# Cummins Electric Truck with Range-Extending Engine (ETREE) Project Final Technical Report

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**PROJECT TITLE:** Electric Truck with Range-Extending Engine (ETREE)

**RECIPIENT ORGANIZATION:** Cummins Inc.

**Partners:** PACCAR, Argonne National Lab, National Renewable Energy Lab, The Ohio State University

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## Disclaimer:

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# Executive Summary:

The Cummins Electric Truck with Range Extending Engine (ETREE) program designed, developed, and demonstrated a range extending electric vehicle that employs an electrified propulsion system installed in a class 6 commercial vehicle (Peterbilt 220).

The program objectives were:

Objective 1: To develop and demonstrate a range extending electric truck that can meet the target objective of 50% reduction in fuel consumption compared to a conventional class 6 commercial vehicle over a wide variety of class 6 drive cycles.

Objective 2: To demonstrate good drivability and performance as well as the ability to accomplish all typical missions in various environmental conditions of a conventional class 6 commercial vehicle.

This project was relevant to industry and the greater public because at the time of the project there were two keys to widespread electrified commercial vehicle adoption yet to be realize:

1. For pure electrified vehicle adoption, battery improvements are needed: Cost must decrease, and energy density must increase.
2. Electric vehicles must overcome fleet operator risks such as: operations in cold climates, hilly terrain, or where majority of conventional trucks are replaced with electrified vehicles.

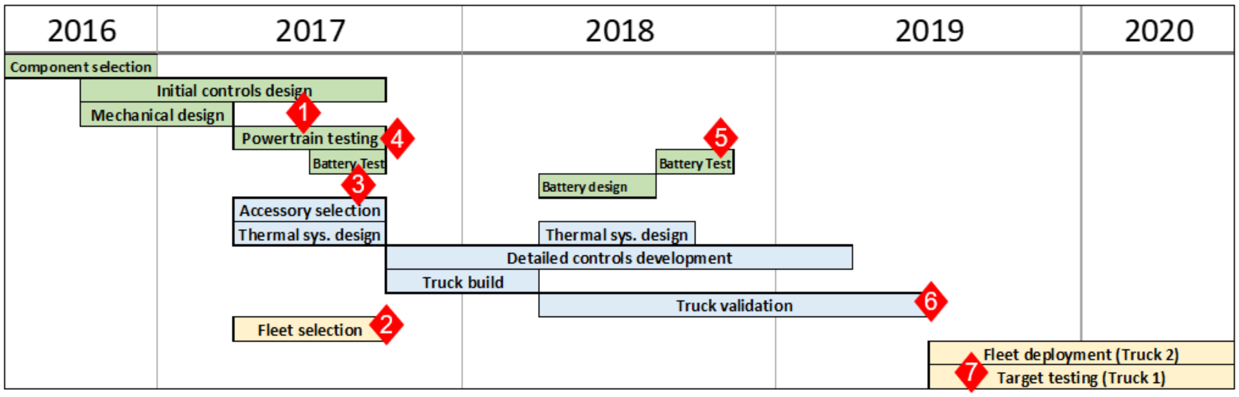
In the near to medium term these adoption hurdles were address by the objectives of this project. A plug-in hybrid vehicle that could be operated in all electric mode for most of its workday optimizing the use of grid energy with the ability to supplement energy demand with the onboard range extending engine. This project's architecture provided ability to match a conventional class 6 commercial vehicle range and performance characteristics prior to the ubiquitous adoption of battery electric vehicle charging infrastructure as well.

Additionally, the vehicles produced as part of this project can be considered a prototype for a commercially viable heavily electrified commercial vehicle because most of the physical hardware used for the project is commercially available in the market today.

The ETREE program met its main objectives and demonstrated 65% fuel consumption reduction as compared to a conventional class 6 vehicle while meeting performance and range expectations. This was achieved by drawing upon the strengths of the assembled team: Cummins, PACCAR, the Ohio State University, Argonne National Laboratory and the National Renewable Energy Laboratory.

## Comparison of Accomplishments to Goals and Objectives:

The Cummins ETREE program consisted of three phases carried out over a four-year period. An overview of key milestones contained within each phase is detailed below in Figure 1. This included go/ no-go milestones that must be met prior to progressing forward in each phase.




| | Milestone | Budget Period | Scheduled Completion | Actual |
|---|---|---|---|---|
| 1 | Fuel consumption reduction objectives met in test cell (go / no-go) | 1 | 6/30/2017 | 6/6/2017 |
| 2 | Fleet demo partner selected | 1 | 6/30/2017 | 8/27/2017 |
| 3 | Battery tested in lab | 2 | 7/31/2017 | 8/7/2017 |
| 4 | Powertrain testing in test cell complete | 2 | 10/15/2017 | 9/22/2017 |
| 5 | Truck 1 operational with updated batteries | 2 | 10/30/2018 | 12/15/2018 |
| 6 | SAE J1526 testing complete & fuel consumption goals met (go / no-go) | 2 | 6/30/2018 | 8/15/2019 |
| 7 | Release truck to first fleet operator | 3 | 7/15/2018 | 1/15/19 |

*Figure 1:Project high level milestone plan*

Phase 1 consisted of system development and simulation to define the architecture, select the components, and develop the system culminating with demonstrating fuel consumption reduction objectives in a test cell.

For phase 1 the go/ no-go milestone was to demonstrate the architectures fuel consumptions reduction target of > 50% in a test cell on the NREL 80 cycle. This cycle was developed by the National Renewable Energy Lab as part of phase 1. It was used for the remainder of the project as the control cycle for results of the project and is believed to capture approximately 90% of class 6 pickup and delivery workday mileage. Powertrain testing was completed at the Cummins technical center in a powertrain test cell shown in Figure 2 below. Test cell data demonstrated the ETREE architecture had a 64.6% reduction in fuel consumption over a conventional powertrain. This data compared well to the simulation results, which predicted a 66.5% reduction. These results completed phase 1 and built confidence for phase 2 milestones.

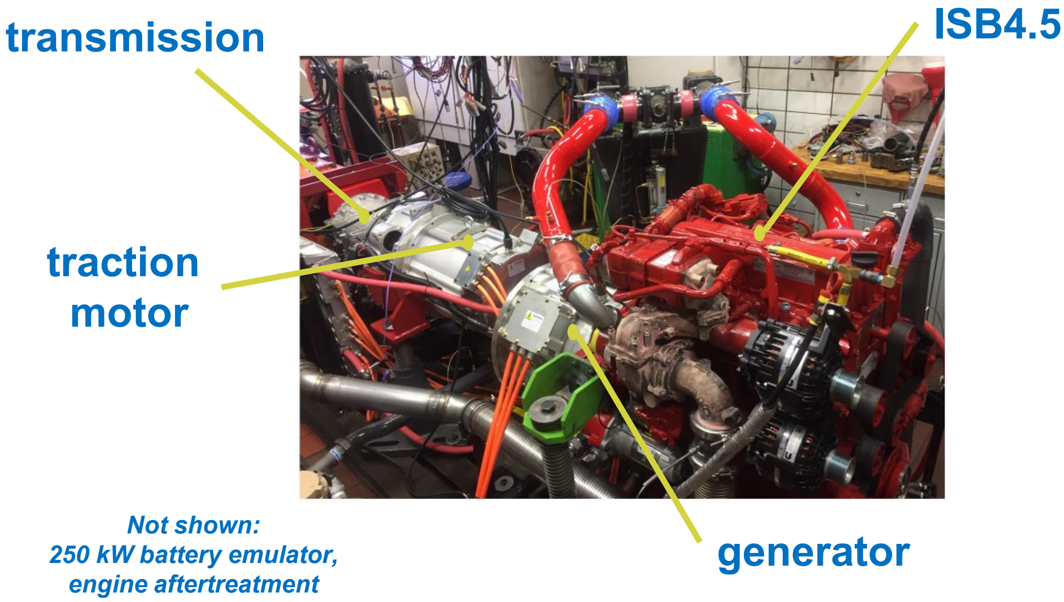



*Figure 2: ETREE powertrain installed in test cell*

Phase 2 consisted of vehicle Integration to integrate and install the systems defined by the architecture in two class 6 vehicles, a Kenworth K270 and a Peterbilt 220 as well as verify fuel consumption and drivability objectives on a test track.

The budget period 2 go/ no-go milestone was to demonstrate the simulation and powertrain test cell 65% fuel consumption reduction results of the architecture on a modified NREL 80 cycle during SAE J1526 testing on actual vehicles. Southwest Research Institute conducted this testing on the ETREE Peterbilt 220 vehicle and a conventional diesel-powered version simultaneous on the Continental test track in Uvalde, Texas. The 2 vehicles shown below in Figure 3 were operated 5 minutes apart with 4850 lbs. of payload and fuel consumption was measured gravimetrically according to the SAE J1526 standard. The results of this testing showed ETREE had a 65.2% reduction in fuel consumed matching well with simulation and powertrain test cell results. This completed phase 2 of the project.

*Figure 3: ETREE vehicle(front) and conventional diesel vehicle staged for J1526 testing*

Phase 3 of the project was to demonstrate the ETREE vehicle's architecture in real world use over a range of workday cycles, weather conditions, and showing its capability equivalent to a conventional class 6 vehicle. Additionally, to show this project had produced a commercially viable product one of the ETREE vehicles was to be operated in an actual fleet hauling freight for 12 months.

The project team completed build and public road commissioning per Cummins development verification protocol for 1 Kenworth K270 and 1 Peterbilt 220 vehicles. As part of this process and over the course of the project more than 10,000 public road miles were accumulated between the two vehicles. These road miles spanned trip distances from 10 to 300 miles in weather conditions spanning all 4 seasons. The trucks were operated in sunshine, rain, and snow in temperature down to 5 degrees Fahrenheit and upwards of 105 Fahrenheit. For the J1526 testing one vehicle was driven from Columbus, Indiana to San Antonio, Texas and back. These trips consummated approximately 1200 miles over 3 days per trip and demonstrated the architectures lack of "range anxiety" and or need for ubiquitous charging infrastructure demonstrating it as a near and medium-term electrification solution for fleets.

One vehicle was deployed into fleet service in January of 2020 for the 12-month trial period. Despite the accumulation of 10,000 road miles prior, an issue was discovered with the high voltage battery management system that would not allow it to initialize in cold temperatures after drivers had left the truck sitting for long periods (> 2hrs). This posed a vehicle "no start" risk in cold temperatures that could possibly strand the operator. Because of this the trial period was put on hold for 2 months until weather conditions turned more favorable. Regrettably during this time in early March 2020, the COVID 19 global pandemic became a major challenge for humanity. Both the fleet and Cummins decided putting a protype vehicle in service during this time posed additional risk to the operators that was unwarranted given the severity of the global pandemic and the demo phase was stopped. In good faith to accomplishing the final milestone Cummins proposed operating the vehicle locally to accumulated mileage for the remainder of project timeline. From July through September 2020 one ETREE truck was operated out of Columbus, IN by an independent driving company on daily or nightly routes between 40 and 175 miles. At the end of the driving period the truck had accumulated an additional 3300 miles of public road driving in the 3-month period. This completed the final milestone for the project.

## Project Objectives:

The primary objectives of this DOE award to Cummins as part of their Medium- and Heavy-Duty Vehicle Powertrain Electrification solicitation was to develop and demonstrated a hybrid class 6 pickup and delivery truck. By using electrification, the project was to improve the Class 6 Peterbilt Model 220 to substantially reduce (>50%) fuel consumption for class 6 pickup and delivery market while meeting requirements of the existing trucks. The project was also to investigate the potential to improve a commercial electrified vehicle using a range extending engine/generator with optimized controls. Hybrid system controls technology development was also a key deliverable of the project focused on battery state-of-charge trajectory management and vehicle integration (electrified accessories, thermal management) systems. Additionally, the project was to demonstrate the architecture capability on road and in fleet use.

## Technical Challenges

The objectives of this projects posed several technical challenges which will be discussed briefly followed sequentially with approaches taken on the project.

In order to meet fuel reduction targets (>50%) outlined in the project objectives and still have a commercially viable product it was critical to architect the electric vehicle and range extending architecture to meet the electric range requirements of a high percentage of the population but not capture the corner use cases. This would allow for a cost-effective high voltage battery system which needed to be fully utilized each workday while leverage the range extending engine to complete the workday. It was important that for each workday the grid energy inputted into the vehicle was fully utilized to meet fuel reduction targets.

Additionally, sizing of the range extending engine was a technical challenge to ensure cost, weight, emissions and efficiency targets were met.

Another technical challenge for the project was executing the developed NREL 80 target cycle in the real world to ensure measurable and repeatable fuel consumption numbers while ensuring that cycle characteristics were met.

While executing the project two additional technical challenges were faced. The first was that the initial prototype high voltage battery supplier for the project supplied samples that validation testing revealed to have design challenges identified in the cell voltage and temperature monitoring boards which did not meet the programs reliability goals and potential posed safety risks. This rendered the samples unusable and caused a 6-month delay to the project. The project team overcame this challenge by developing and integrating a new high voltage battery utilizing production low voltage modules.

Lastly vehicle curb weight for an electrified vehicle tends to be worse because of the added weight of the electrified components as compared to a conventional powertrain. This project's architecture with a range extending engine increased the curb weight penalty further reducing commercial payload capability. This was a challenge for the project to ensure all project objectives and still be able to carry a reasonable commercial payload (6000 lbs.).

## Technical Approach

### Selection of Fleet Demo Partner

A major part of the project revolved around ensuring the product is commercially viable and demonstrating it in real fleet use for the class 6 pickup and delivery market. The project team reached out too many fleets as part of the project to gain insight of the application and fleet operator desires. During this work Frito-Lay was identified as a major fleet in the class 6 pickup and delivery market that operated fixed routes between 15-100 miles all around the united states delivering chips/snack food. Their fleet also utilized Peterbilt 220 vehicles, which was produced by one of the programs partners, PACCAR. Additionally, PepsiCo/ Frito-Lay is a significant proponent and adopter of alternative fueled, including electrified vehicles and one of the largest operators of class 6-7 trucks. They were selected as the fleet demo partner for the ETREE project because of this. The intent of the project was to operate the 1 ETREE demo truck out of their Indianapolis distribution center.

## Understanding Customer Requirements

During fleet consultation several customer requirements(voices) were realized. For the class 5-7 pickup and delivery market, fleet operators want a truck with comparable performance as a conventional truck (startability, gradeability, acceleration, range) and, generally, desire flexibility provided by a range extender. This flexibility being range and ability to operate in any terrain and weather conditions. Fleet operators also desired the capability to operate in pure electric mode for a substantial part of route. This would allow them to meet current and new area regulations for NVH and localized air quality.

Lastly, much of the class 5-7 pickup and delivery fleet operates 1 8-hour shift per day and the vehicle remains primarily unused for the remainder of the day. The vehicles also primarily reside outside during this time at a variety of sites that may not have significant electrical infrastructure available. These items combined with a desire for a reasonable total cost of ownership payback in 3-8 years suggest fleets desire low installation cost and simple electrical infrastructure requirements for the electric vehicle stationary charger (EVSE).

## Translation into Design Requirements

The customer requirements above were translated into project design requirements, which can be seen below in Table 1. These design requirements would be utilized in conjunction with a defined workday cycle to develop the technical architecture for the project.

*Table 1: Project Design Requirements*

| | |
|---|---|
| Fuel consumption reduction | ≥ 50-100% on typical class 6 P & D routes |
| Performance, startability | Equivalent to conventional |
| Gradeability | Equivalent to conventional for at least 10 minutes |
| Max vehicle range | ≥ 270 miles *(fuel + fully charged battery)* |
| All electric range (AER) | 40 miles |
| Payload | ≥ 6500 lb (snack food) |
| Truck body | 24’ box with lift gate |

A critical design requirement for the project was to define an appropriate workday cycle that could be used to simulate, design, and verify the performance and fuel reduction targets for the project. A representative duty cycle for testing needed to capture a full day of operation in both variability and duration. A comparison of average fuel efficiency for a typical 20 to 60-minute dynamometer drive cycle is not adequate to evaluate the performance of the vehicle energy management system designed to minimize total fuel use for an entire workday. For this reason, the National Renewable Energy Lab (NREL) previously developed representative drive cycles for class 6 pickup and delivery operation [1]. NREL investigated real-world driving data in their Fleet DNA database and performed a statistical analysis on the set of conventionally fueled class 6-7 pickup and delivery vehicles to identify the appropriate length and duration of the desired cycle [2]. The study found that 90% of recorded days had less than 80 vehicle miles traveled and 95% of days had less than 100 vehicle miles traveled. Because of this, the primary target cycle was developed to represent an 80-mile workday (NREL 80), and a secondary represented a 100-mile workday (NREL 100). The composite drive cycles were constructed from the individual recorded trips using NREL's Drive-Cycle Rapid Investigation, Visualization, and Evaluation (DRIVE) tool [3]. The NREL 80 is shown below in Figure 4, which was utilized as the workday cycle for the project.

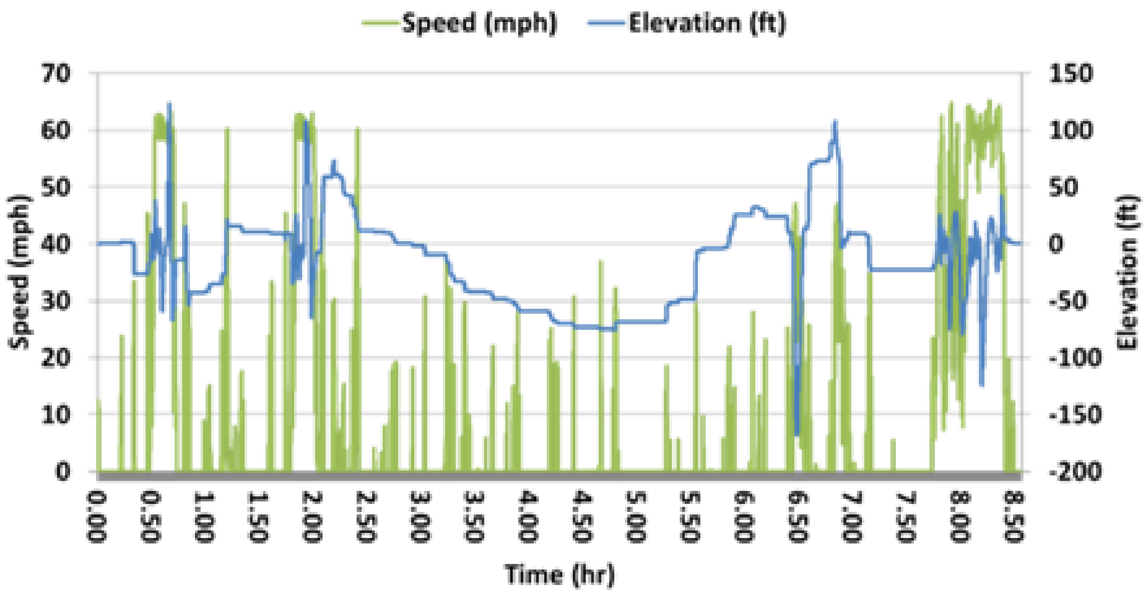



*Figure 4: NREL 80 Mile Class 6 P&D Cycle*

## Architecture

The ETREE project architecture diagram is shown below in Figure 5. The architecture consisted of a downsized Cummins ISB 4.5-liter diesel engine with a full suite of modern aftertreatment as the range extending engine. The ISB 4.5 diesel engine is mechanically coupled to a 130-kW permanent magnet generator. It is to be noted that this combination of engine and generator is oversized compared to the ideal fully optimized version that would be commercially sold for this class 6 application. The ETREE program chose the oversized range extender combination to allow for more flexibility in the demonstration phase of the project. In simplistic terms, for a production version the range extender would be sized to meet power demands of the application while at cruise speed on a level grade. The generator was electrical coupled to a 700-volt nominal DC bus via an Inverter. The electric energy storage for the high voltage DC bus was from a pair of NMC Li-ion batteries assembled in series for a capacity of 122 kWh. A traction inverter electrical coupled a 175-kW permanent magnet electric machine used as the traction drive. The traction motor was then mechanical coupled to an Allison 3000 series ETREE 4 speed automatic transmission with stop-start input.

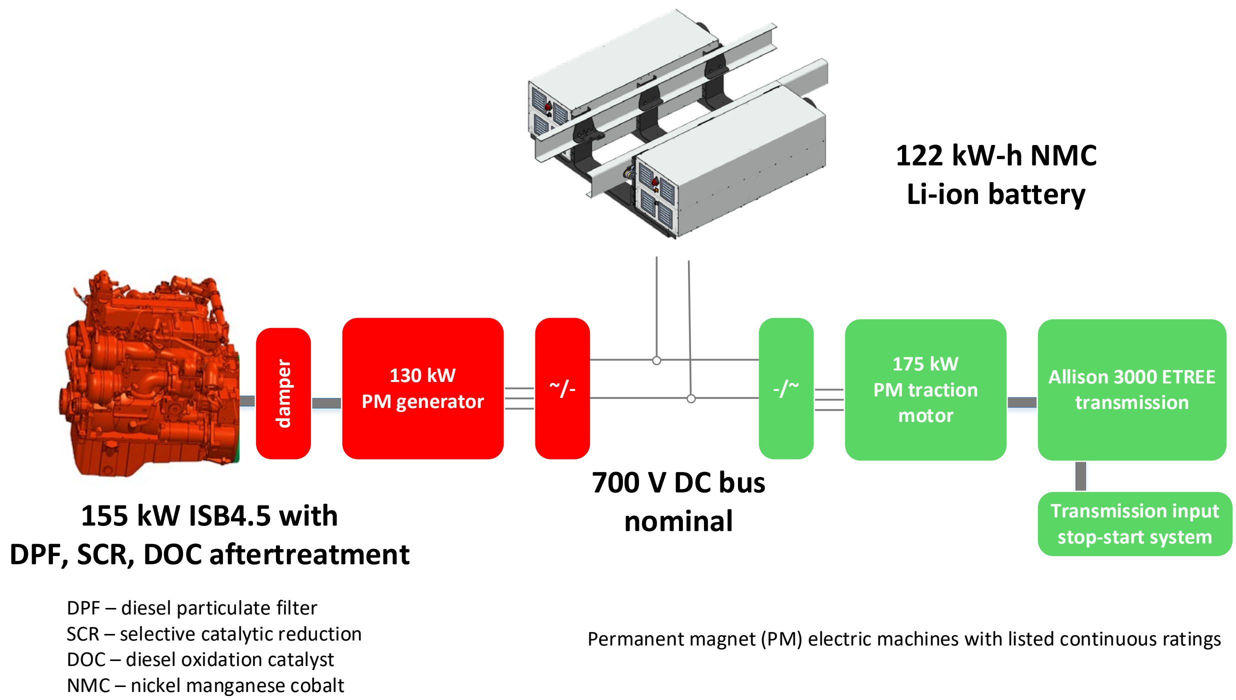



*Figure 5: ETREE Architecture Diagram*

Ancillary components, not shown in architecture diagram above, were selected to meet customer requirements on target duty cycles and support fully electric operation mode. These consisted of all electric power steering, foundation brake air compressor, cabin air conditioning system, and DC-DC converter to charge the low voltage battery system and accessories.

Based on customers desire to have low cost charge infrastructure and knowledge that the vehicle was unused for most of the hours in a typical day, allowing for ample charge time, a J1772 level 2 AC to DC onboard charger was selected for the architecture.

Finally, a key architecture piece, developed as part of the project, was the energy-based range extender controls. The approach was based on a blended philosophy to ensure maximum fuel savings through strategic use of all electrical energy stored in the high voltage batteries each workday.  This SOC trajectory management software maximized daily us of the battery through driver entered and learned parameters via a human machine interface shown below in Figure 6.  Drivers would enter daily desired mileage or routes through this human machine interface.


*Figure 6: Human Machine Interface for Daily Mileage Entry*

## Utilizing the Range Extender to Help Overcome Fleet Operator Concerns

Three approaches were identified where the range extending engine could be used to help overcome fleet operator concerns.

Figure 7 below illustrates a use case where the range extender can be used to provide required system current when battery cell temperatures increase above nominal operating range or long duration discharge rate is exceeded causing battery discharge current limit to decrease below system demands. In this case the range extending engine/generator could provide current to maintain required system performance despite a battery discharge current limitation

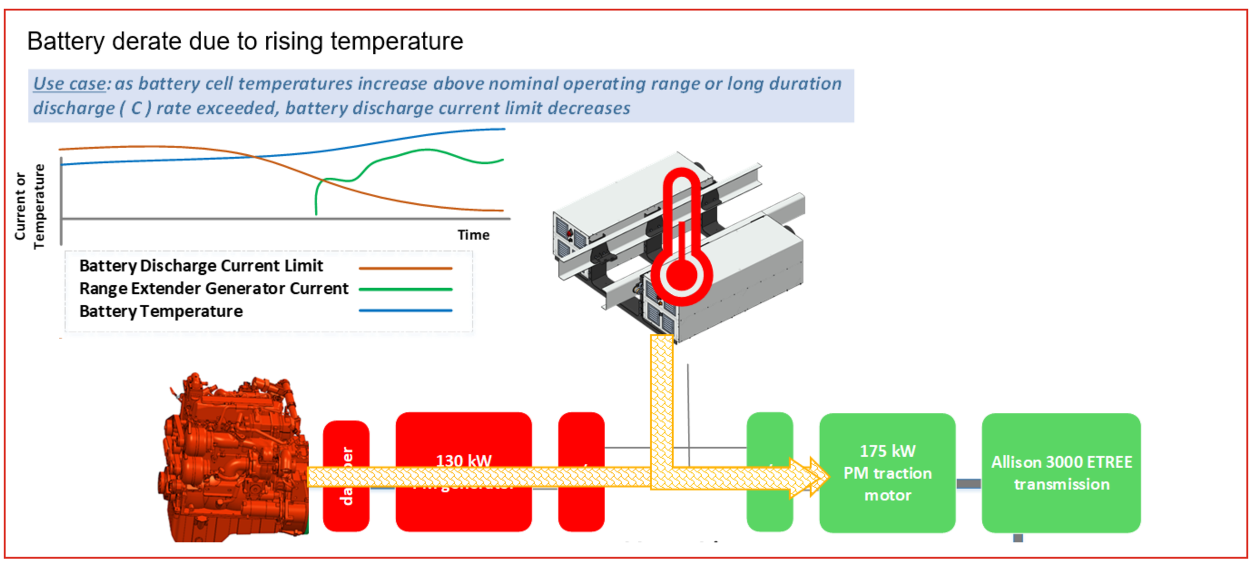



*Figure 7: Battery Derate Due to Rising Temperature Use Case*

The second approach identified to leverage the range extended engine/generator is depicted below in Figure 8. In this case high voltage battery current is not available due to cold overnight temperature soak. The range extender could be utilized immediately in this case to provide system current and start the workday. This supplemental current from the range extending engine/generator would allow the workday to progress until battery temperatures increased enough that high voltage battery current limits were removed.

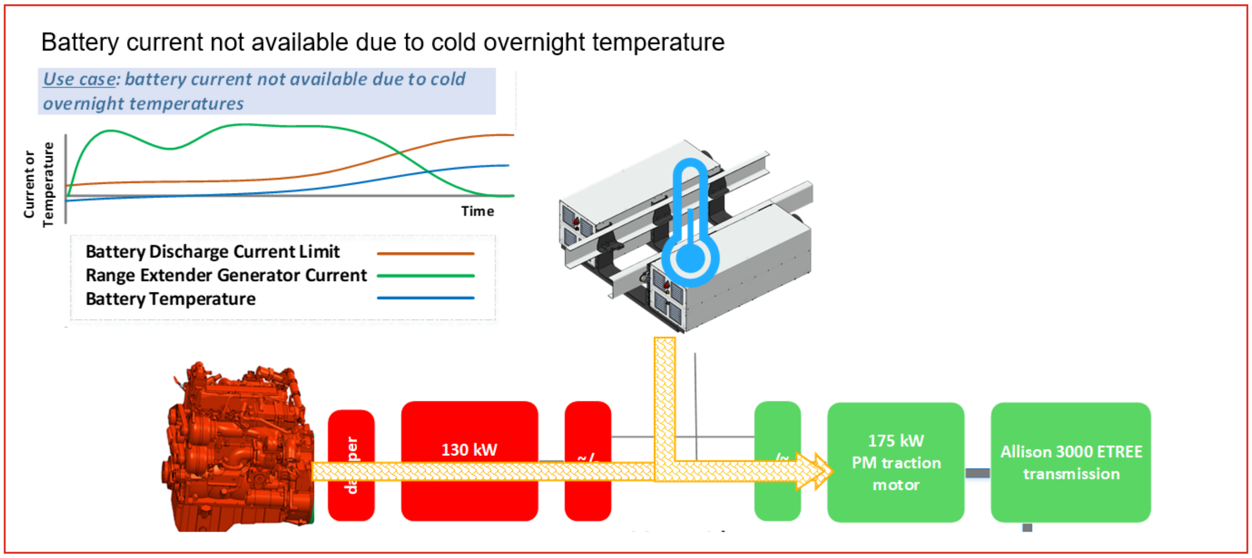



*Figure 8: Battery Current not Available due to Cold Temperature Use Case*

The third approach identified to leverage the range extended engine/generator is depicted below in Figure 9. In this case the high voltage state of charge is low and an electric vehicle stationary charger (EVSE) is not available or the electric grid is down. In this scenario the engine/generator could be utilized to raise the battery state of charge and complete the next workday or complete a workday of significantly higher mileage then normal. This architecture use case was demonstrated on the ETREE truck with a 600-mile workday while in route to Texas for J1526 fuel consumption testing. The truck was driven from Columbus, Indiana to Little Rock, Arkansas in a single day. The limitation for the day being commercial vehicle driver maximum hours of service requirements, not vehicle range.

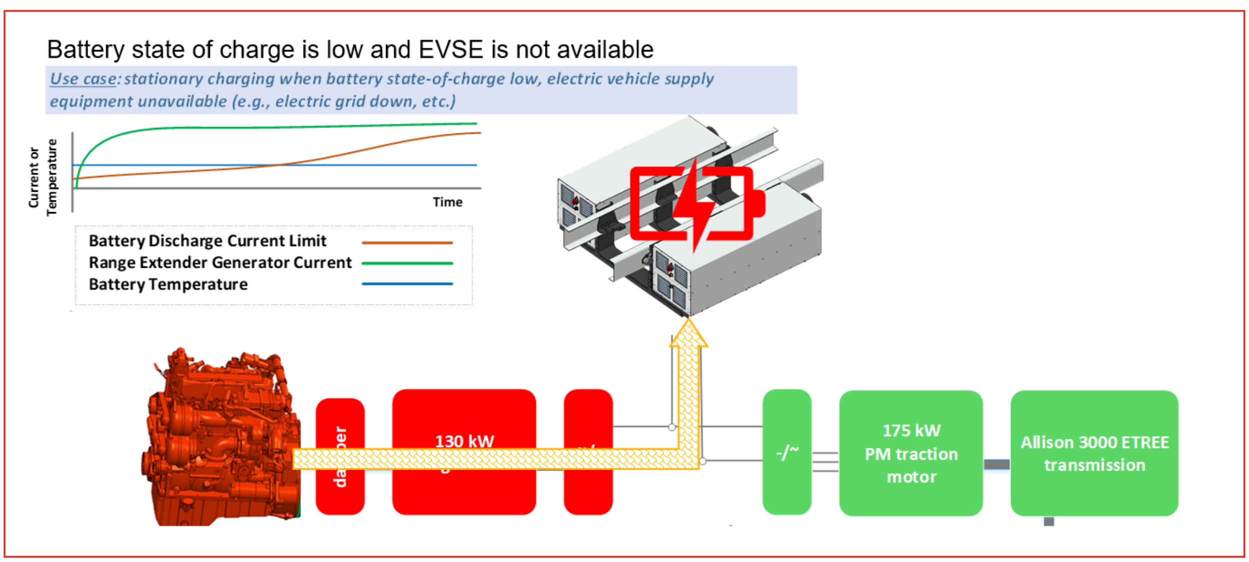



*Figure 9: Battery State of Charge is Low and EVSE not Available Use Case*

# Project Activities:

## Phase I System Development

Phase 1 consisted of system development and simulation to define the architecture, select the components, and develop the system culminating with demonstrating fuel consumption reduction objectives in a test cell.

### Component Selection

The component selection simulation task, a joint cooperative simulation exercise carried out starting in July 2016 by Argonne National Labs, Cummins and Ohio State University (with assistance from NREL). The objective of the component selection simulation task was to select the specific electrified powertrain components (traction motor, associated power electronics, transmission, final drive ratio, and energy storage) to enable the ETREE vehicle to meet its program objectives (both for fuel consumption and performance / drivability).

The assembled team completed the following as inputs into the selection simulation:

- Definition of application requirements (i.e., how the vehicle and system should operate from a customer perspective).
- Selection and data gathering for potential traction motors; these permanent magnet traction motors included those produced by TM4, Parker-Hannifin, and BorgWarner.
- Identification of the set of final drive ratios available on the target vehicle, the Kenworth K270 and Peterbilt 220.
- Gathering of data for two prospective transmissions (Eaton 2-Speed EV Gearbox or Allison 3000 ETREE). These will be paired with appropriate available traction motors.
- Selection and data gathering for potential Li-ion NMC Energy Storage Systems (ESS) from various suppliers.
- Configuration data for the target vehicle (K270) and conventional, baseline powertrain (PX-7 engine with Allison 2100 series transmission).

The above inputs were included in the definition of the technical profile along with the following:

1. Performance metrics (acceleration, gradeability, startability)
2. Payload capacity
3. Identification of desired drive cycles.

A high-level summary of the technical profile is referenced earlier in this report in Table 1.

The technical profile attributes, coupled with the selected vehicles (Kenworth K270 & Peterbilt 220), provide the basis to define the ETREE components. Using simulation, a range of traction motors made by several companies were evaluated against the performance metrics. Additionally, the traction motors (and associated power electronics) were checked to ensure they could be delivered by their suppliers in time to meet the ETREE testing schedule. Along with the traction motors, two transmissions were also evaluated: an Eaton 2-speed EV-targeted transmission (used in the Proterra bus) and an Allison 3000 ETREE with a stop-start system.

The baseline Kenworth K270 has a payload capacity of 10k lb. Certainly, a commercial vehicle with a large energy storage system, using today's technology, will have an empty weight greater than a conventionally powered vehicle, which may limit its payload capacity. In fact, this has been recognized in Europe where alternative fueled commercial vehicles are allowed higher gross vehicle weights (Directive (EU) 2015/719) to offset the additional weight of the alternative fuel (or energy storage) system. However, for operation in the United States, the K270 must not exceed a GVW of 26k lb. After investigating customer requirements, a desired payload capacity of 7.5k lb and a minimum required payload capacity of 6.5k lb was identified. It should be noted that the simulation model for the ETREE vehicle included this weight penalty.

Class 6 commercial trucks, such as the Kenworth K270 have an incredibly varied set of drive cycles and drive a wide range of miles per day as indicated by research and real fleet data provided by the National Renewable Energy Laboratory in Figure 10 below.

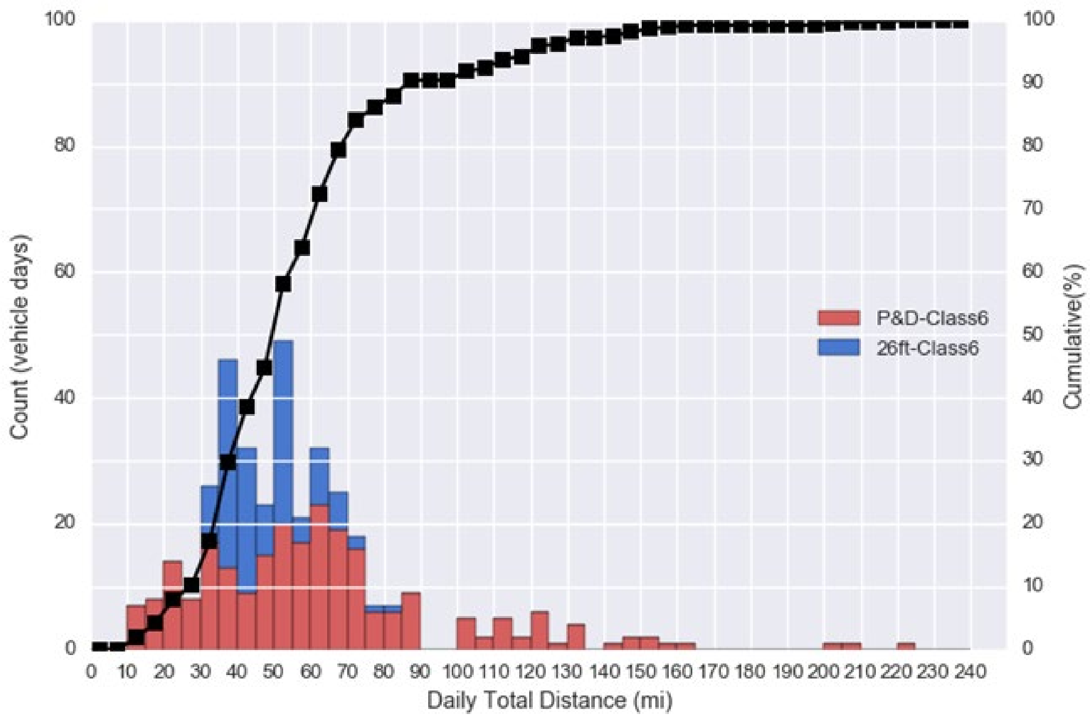



*Figure 10: NREL Class 6 Real World Drive Cycles*

As stated in the project objectives, ETREE is to deliver at least a 50% fuel consumption reduction over a wide range of class 6 drive cycles. The main design choice to meet this objective is in the usable capacity of the energy storage system. Therefore, it is important to select the correct set of drive cycles as part of the design of experiments for the component selection simulation phase. To convert ETREE's program objective of "deliver a 50% fuel consumption reduction over a wide range of duty cycles" to a more specific objective, a composite 80-mile cycle was created by NREL, with the assistance of Cummins to be used as the primary target duty cycle for ETREE during the testing phases. The NREL 80 composite cycle is shown below in Figure 11.

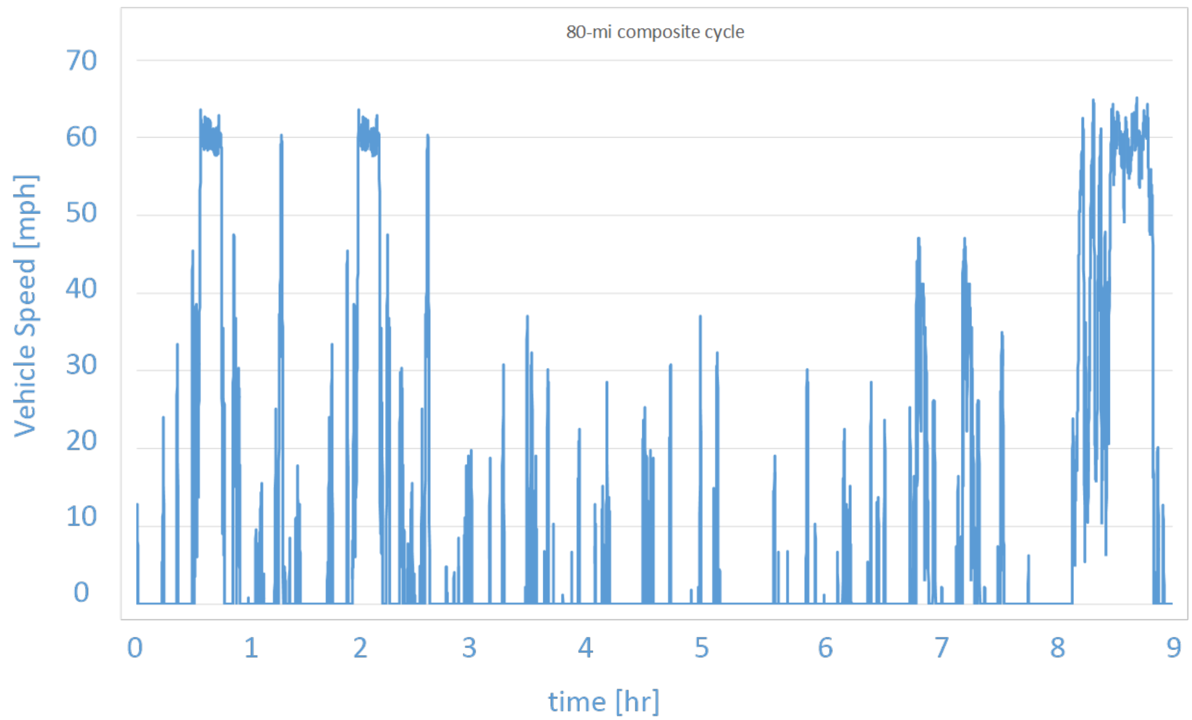



*Figure 11: NREL 80 Composite Cycle*

This cycle, which describes the entire workday of a class 6 pickup and delivery vehicle, also includes key switch events (i.e., where the operator turns the vehicle off when not present) as well as grades representative of a wide variety of the United States.  The cycle has suburban, urban and highway portions as is the result of analyzing and combining a number of real world driving in this type of application.

It is the intention of the ETREE team that this duty cycle, as well as a related 100-mile cycle, which will also be used in testing, will be disseminated to the commercial vehicle industry for use in the future design of class 6 and 7 vehicles.  Existing duty cycles used in the industry (for design and testing) such as HTUF, FTP-72, "Manhattan", and others are not "full workday" cycles; they are snippets of a day. However, the use of an entire workday cycle is a prime consideration when specifying a battery that employs overnight (and opportunistic) charging from the grid.

With the technical requirements and drive cycles defined the team utilized two simulation models to finalize energy requirements and component selection. The MATLAB Simulink models utilized were for a conventional powertrain and a range-extended electric vehicle powertrain respectively.  Both models were forward looking and included a driver model, vehicle dynamics, diesel engine dynamics and fuel efficiency maps, electric machine dynamics and efficiency maps, and battery dynamics and an energy management system.  A large design of experiments was conducted to define the required energy storage system that achieved fuel reduction goals. Based on this work and market available energy storage systems, 125 kWh was defined to meet project goals.  Figure 12 below shows simulation predicted reduction in fuel consumption over the prescribed NREL 80 workday cycle as well as various other real-world class 6 vehicle drive cycles with the selected energy storage system. This data predicted the ETREE architecture would achieve 50% fuel reduction target on more than 80% of the routes.

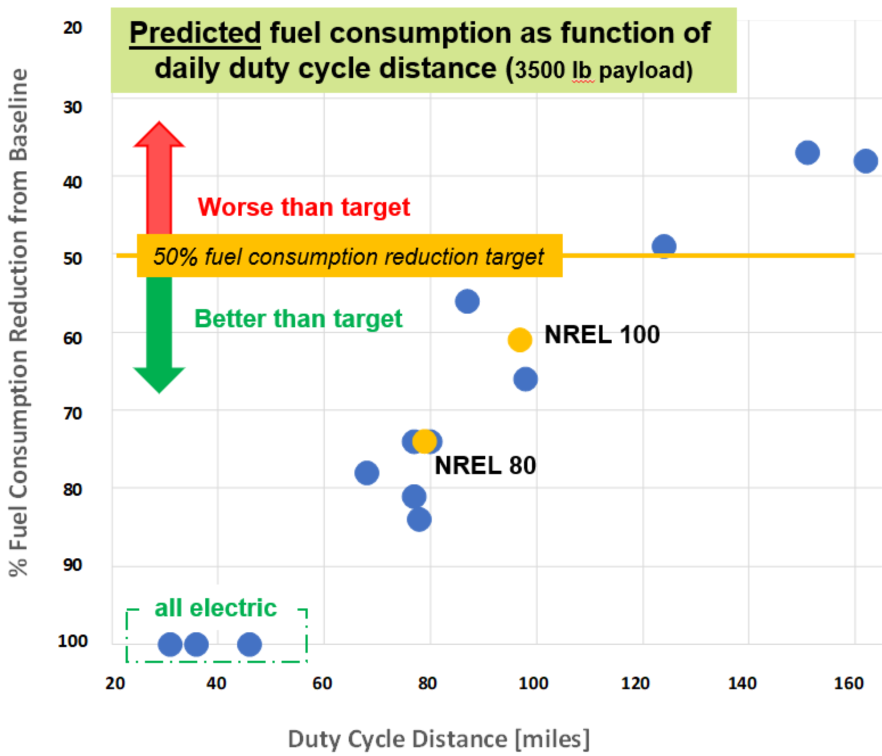



*Figure 12: Simulation Predicted Fuel Consumption Reduction Based on Selected Energy Storage System*

The final component selection, which was based on simulation results and availability of hardware to meet program timing needs is shown below in Table 2.  The final program architecture diagram of key components is detailed earlier in this report as Figure 5.

The completed simulation also defined the path to target for the program to achieve >50% fuel reduction goals moving into test cell testing and demonstration.

Path to target as follows:

- Properly sized energy storage
- Adequate use of kinetic energy recovery (regenerative braking)
- System controls which ensure:
    - End workday with 5-10% of minimum energy storage state of charge
    - Operate range extender engine for best efficiency and, in the case of a diesel, minimize selective catalytic reduction thermal management modes
    - Operate traction motor for best efficiency with assistance of transmission
- Proper selection of drive cycle and fleet operator

*Table 2: ETREE Final Component Selection Table*

| Component | Selection Criteria | Status |
|---|---|---|
| ISB4.5 (Euro6 recal'd to EPA) | Meets vehicle technical profile, meets schedule | Selected |
| TM4 LSG130 (generator) | Meets vehicle technical profile, meets schedule | Selected |
| TM4 LSM200-2100 (traction motor) | Meets vehicle technical profile, meets schedule | Selected |
| Cummins Hybrid System Controller | Meets vehicle technical profile, flexible development | Selected |
| System Voltage (680 VDC nominal) | High power, low loss, production ready components | Selected |
| WABCO EBS | Enhanced regen capability, improved drivabililty | Cancelled |
| Allison 3000 ETREE Transmission | Compared to direct drive motor: higher top speed, higher torque | Selected |
| Energy Storage (125 kW-h Li-ion NMC) | meets cost, weight, energy, power requirements | Selected |
| Other Accessories (DC-DC converter, J1772 level 2 on-board charger, coolant systems, brake compressor, A/C compressor, datalogger, etc.) | | |

## Powertrain Test Cell Verification

The first part of Q1 2017 entailed the testing of the K270's conventional powertrain (ISB6.7 and Allison 2100 as shown in Figure 13) in order to establish baseline fuel consumption results on the target cycles.

This baseline testing also allowed for the development of the testing procedures (including ability to follow the NREL 80-mile target cycle). This work was conducted at the Cummins Technical Center in Columbus, IN.


*Figure 13: Conventional Powertrain in Cummins Test Cell*

Next the ETREE powertrain was tested as shown below in Figure 14.

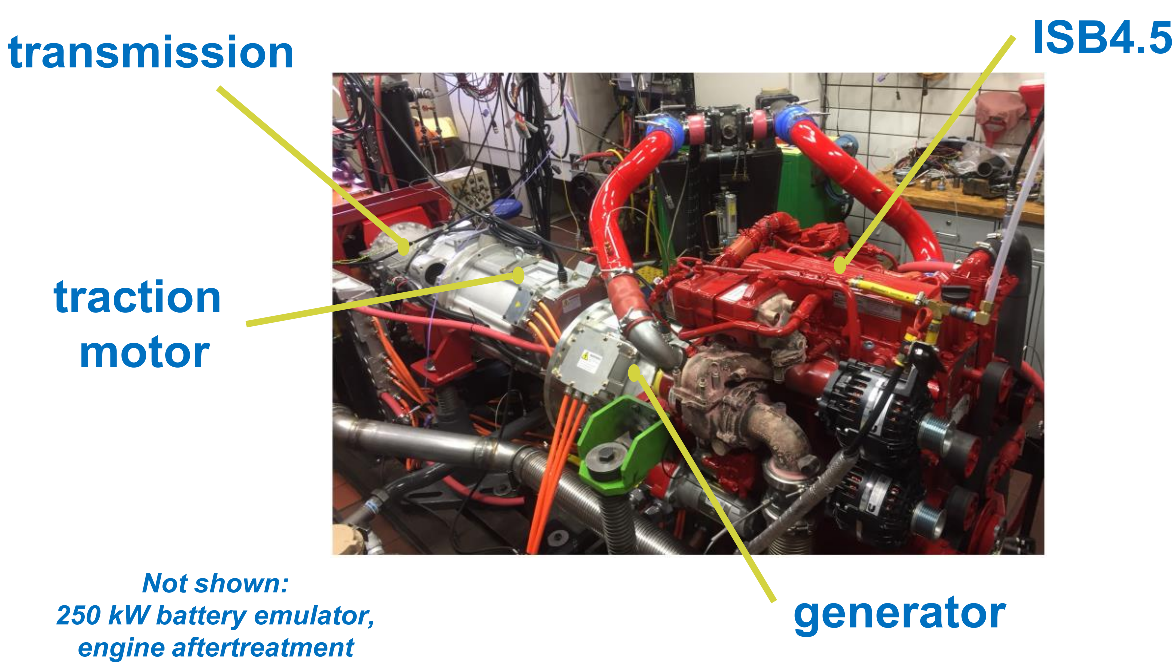



*Figure 14: ETREE Powertrain in Test Cell*

The ETREE powertrain testing consisted of the ISB 4.5L range extending engine mechanically coupled to the 130-kW generator by a specially designed rubber vibration damper that provided appropriate mechanical vibration damping of the 4-cylinder inline diesel engine dynamics to allow the generator to achieve its reliability targets.   The 175-kW traction motor was mechanical coupled to the Allisson 3000 4 speed ETREE transmission, which was sequentially coupled to the test cell dynamometer. The transmission was operated primarily in torque converter lockup mode for efficiency and only 4 of the 6 speeds were utilized for the project to emulate production intent gear ratio coverage. The battery is not part of the test cell.  Instead, a battery simulation (emulator) was used to provide (and accept) high voltage electrical energy.  Current from the generator and from the traction motor is measured going to the simulator.  And, current to the traction motor (and to the generator and/or low voltage starter when these are used, separately, as starters for the range extender).  The difference in current is used to adjust a battery model, which then adjusts the battery simulator DC bus voltage to precisely emulate the battery operation. The battery emulator along with Cummins test cell software was utilized to operate the ETREE powertrain over the NREL 80 and NREL 100 workday cycles.  Results for both the ETREE powertrain as well as the conventional powertrain (baseline) are shown in Table 3 below compared to the predicted simulations results. It is to be noted that all reference to fuel consumption in this report and for the ETREE project is in terms of absolute fuel mass not volume.  Test cell measured fuel reduction on the NREL 80 test cycle indicated a 64.6% fuel reduction for the ETREE powertrain compared to conventional.  This correlated well to simulation results that predicted a 66.5% reduction. On the NREL 100 cycle the testing measured a 47% reduction for the ETREE powertrain compared to simulation prediction of 52.9%.  Although this was slightly below the target of >50% it was still considered an acceptable result for this relatively high energy duty cycle.  These test cell testing results built high confidence that the project fuel reduction target of >50% would be achieved on vehicle especially with the results close correlation with simulation.  Lastly this test result completed the go/ no-go milestone for phase 1 of the project.

*Table 3: Test Cell Fuel Consumption Results Compared to Simulation*

| Duty Cycle | baseline | ETREE | Simulated Fuel Reduction [%] | baseline | ETREE | Tested Fuel Reduction [%] |
|---|---|---|---|---|---|---|
| | Simulated fuel used (lb) | | | Tested: test cell fuel used (lb) | | |
| **NREL 80** | 69.7 | 23.3 | **66.5%** | 68.8 | 24.4 | **64.6%** |
| **NREL 100** | 94.2 | 44.3 | **52.9%** | 90.9 | 48.2 | **47.0%** |

Target >50%

## Phase II Vehicle Integration

Phase 2 consisted of vehicle Integration to integrate and install the systems defined by the architecture in two class 6 vehicles, a Kenworth K270 and a Peterbilt 220 as well as verify fuel consumption goal and drivability objectives on a test track.

### Vehicle Design & Build

In the second phase of the project the project design team at Cummins strategically integrated all the selected components into CAD software, procured necessary design componentry to allow installation of said hardware on vehicle, and documented assembly instructions.  Figure 15 below shows the all-inclusive vehicle design layout in 3d rendering. Note liftgate assembly is not shown in rendering.

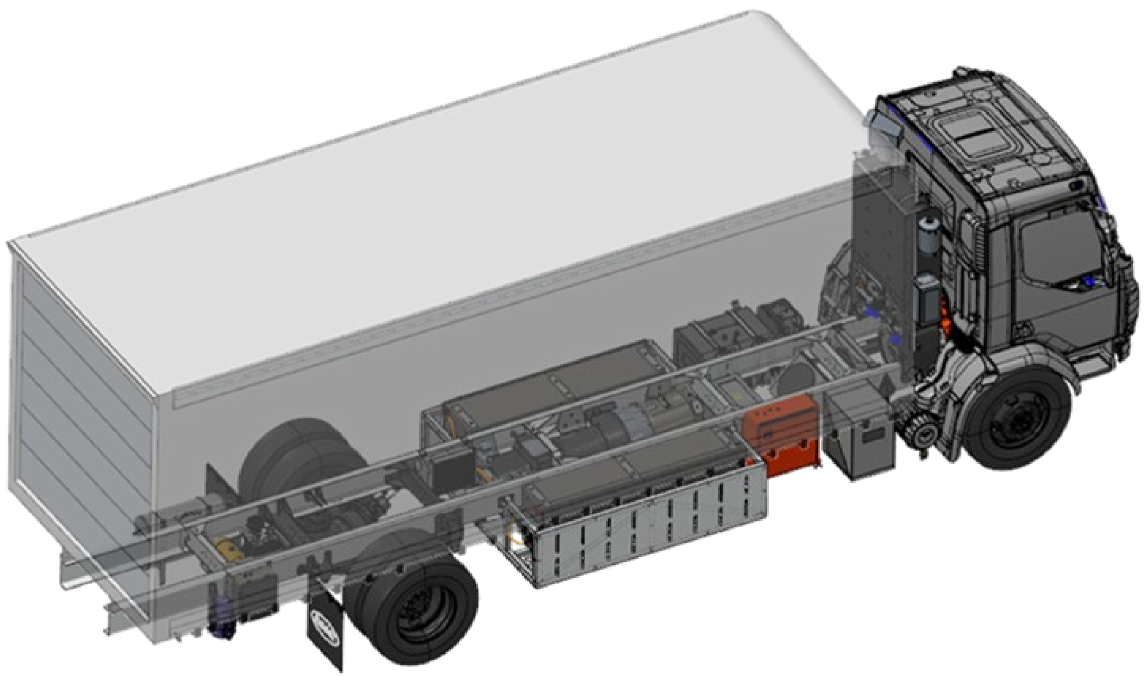


*Figure 15: ETREE Vehicle CAD Layout*

The range extending engine/generator was integrated into the front of the vehicle, shown in Figure 16, in approximately the same location as the conventional powertrain would be installed. This location allowed ample packaging space as well as the ability to retain the stock vehicle cooling package which was being repurposed.

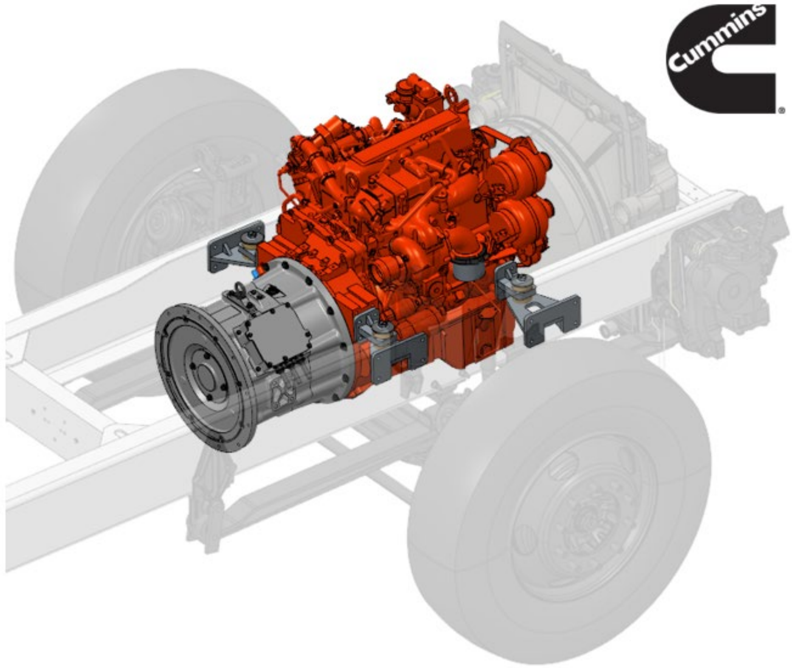



*Figure 16: Range Extending Engine Placement*

The traction drive system assembly, which consisted of the 175kW traction motor adapted to an Allisson 3000 ETREE transmission was placed in between the frame rails approximately mid chassis as shown in Figure 17. This placement was chosen to allow for good driveline geometry and dynamics. Additionally, this provided space in between the frame rails forward of the traction machine that usually would be consumed with a conventual transmission and driveline. This space was utilized to place a module that housed the 6-phase traction invertor and the high voltage DC to DC converter.

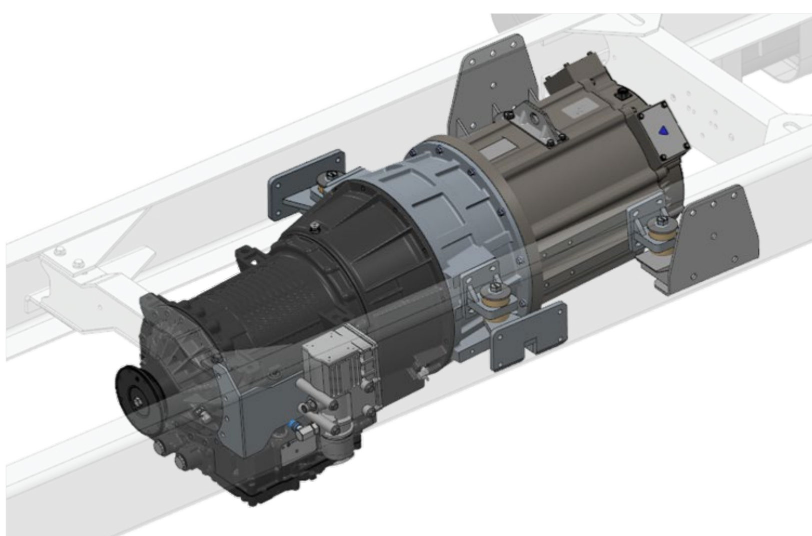


*Figure 17: Traction Drive System Placement*

Another key design layout item designed by the team was the modular back of cab assembly. This integrated directly behind the cab of the vehicles and housed several components making for an efficient use of vertical space. Within this assembly, Figure 18 below, the following were housed: Range extender full suite Selective Catalytic Reduction aftertreatment, On board J1772 AC to DC charger, 130 kW generator 3-phase invertor, coolant to coolant heat exchanges, qty 3 electric water pumps, the system electronic control module, and a fuel fired heater.

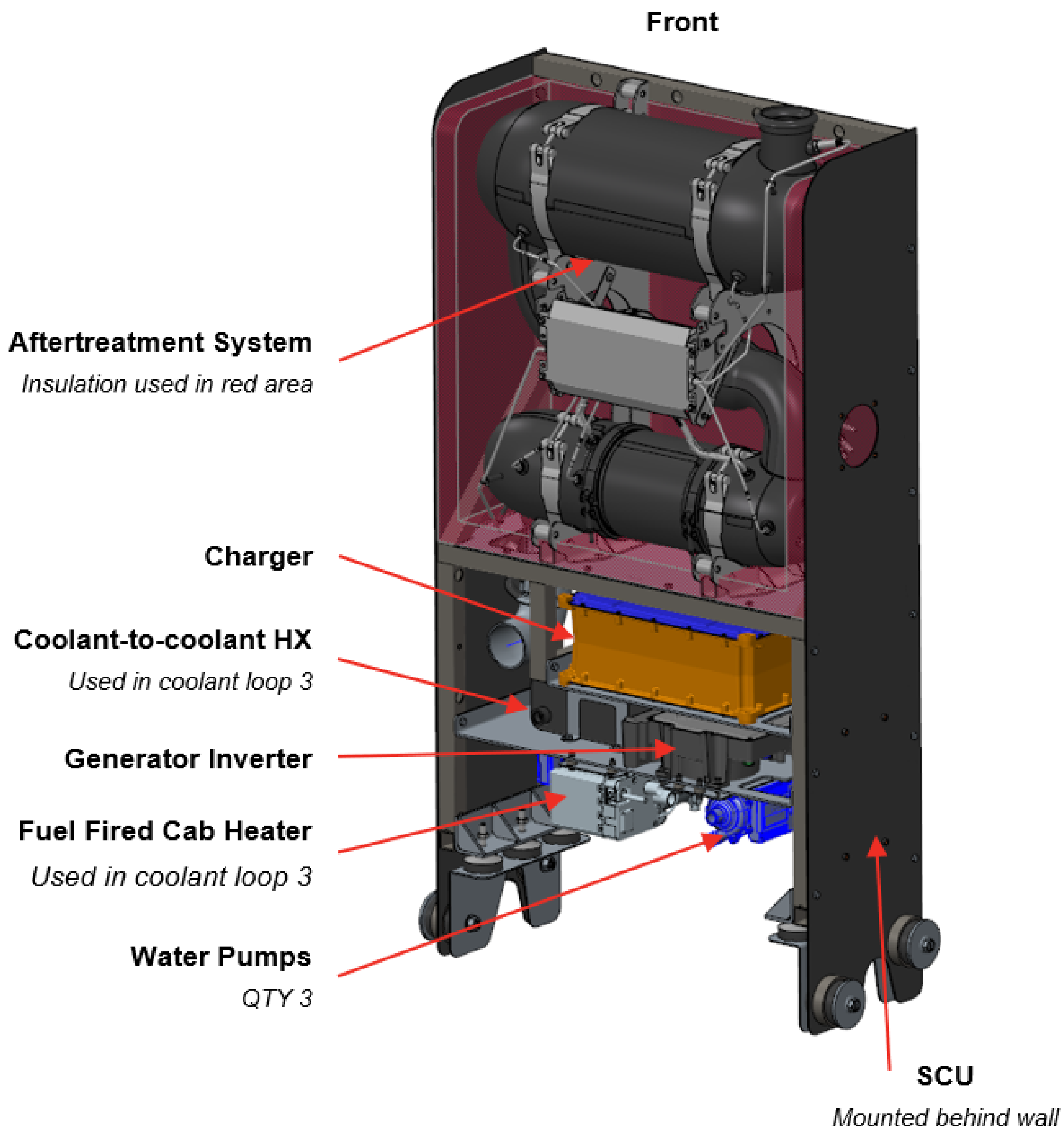



*Figure 18: Layout of Modular Back of Cab Assembly*

The high voltage battery pack, which consisted of two sub packs electrically connected in series to achieve the prescribed voltage was placed on the outside of the frame rails slightly rearward of mid chassis as seen in Figure 19 below.  This was a key part of the architecture layout because of the significant weight impact the high voltage batteries and mounting bracketry had to the chassis and weight bias(~1775kg).  Placement needed to be as rearward as possible to limit the impact on the front axle weight, which was rated at 10,000 lbs.

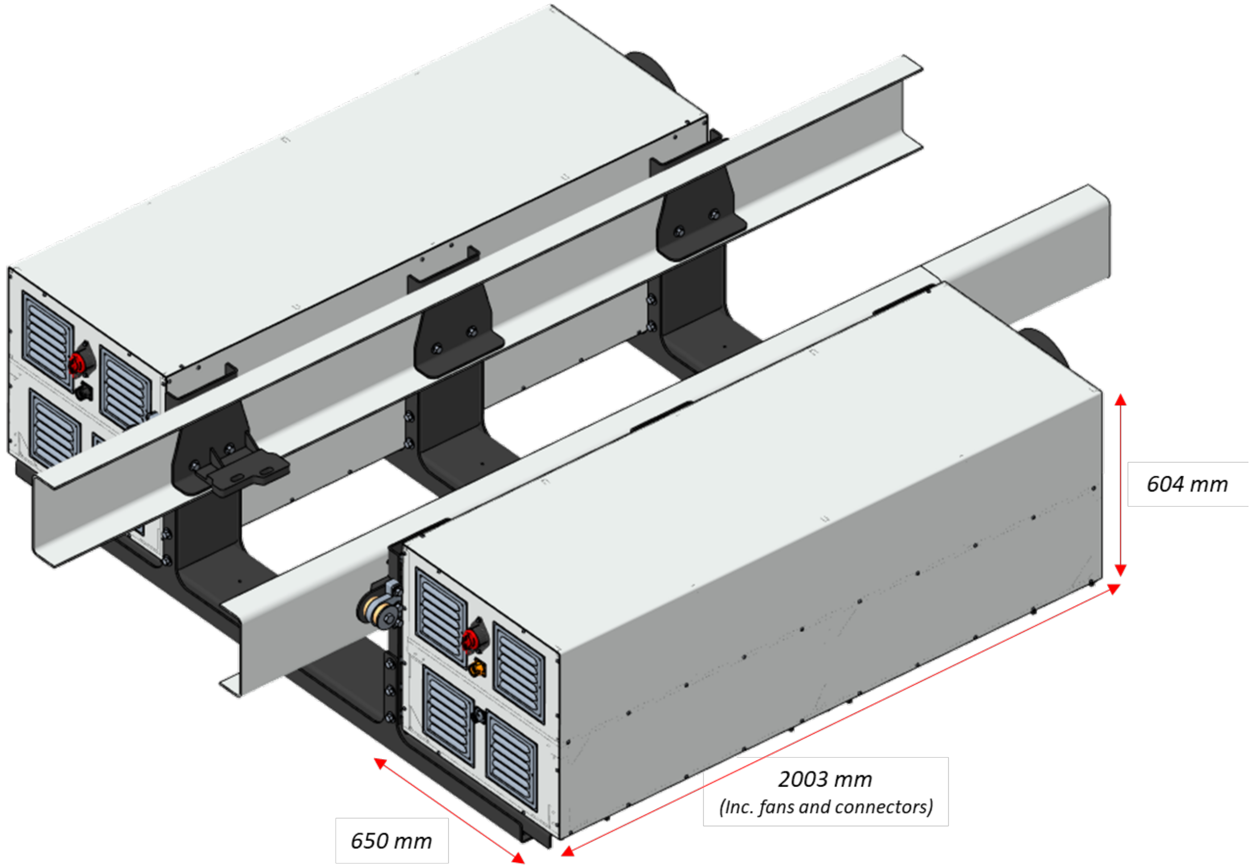



*Figure 19: ETREE High Voltage Battery Mounting*

Other electrified accessories can be seen in Figure 20 below. In this top rendering view placement of the following can be seen: Charge port on rear passenger side, foundation brake air compressor and DC to AC invertor in middle rear frame rail, high voltage DC junction box on outside passenger frame rail just aft of mid chassis, low voltage DC junction/fuse box on outside passenger front frame rail, 3 cooling loop heat exchangers and fans placed in various locations inside the frame rails, and power steering pump, fuel, and diesel exhaust fluid (Def) tanks placed on driver side outside front frame rail.

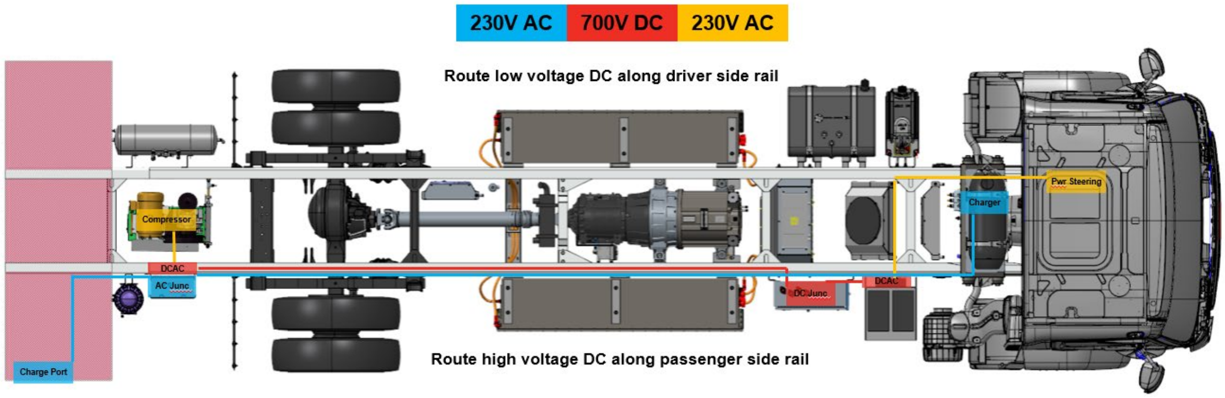



*Figure 20:Top View Vehicle Rendering*

The vehicle layout for the ETREE trucks posed both space and weight integration challenges.  As can be seen from the layout rendering this architecture required packaging both an electrified powertrain as well as a conventional one, which made space optimization key.  Not displayed are the additional high voltage cables, low voltage cables, and coolant pluming which required clever utilization of space and routing to ensure bend radii and flow restriction targets were adhered to and achieved.

The thermal management system(s) for the ETREE vehicle was split into 3 cooling loops based on component flow and temperature requirements.  Cooling loop 1 served the power electronics, Cooling loop 2 served the traction and generator motors, and cooling loop 3 served the range extending engine and the Allison transmission. Schematics for each cooling loop (1,2,3) are shown below in Figure 21, Figure 22, Figure 23 respectively.

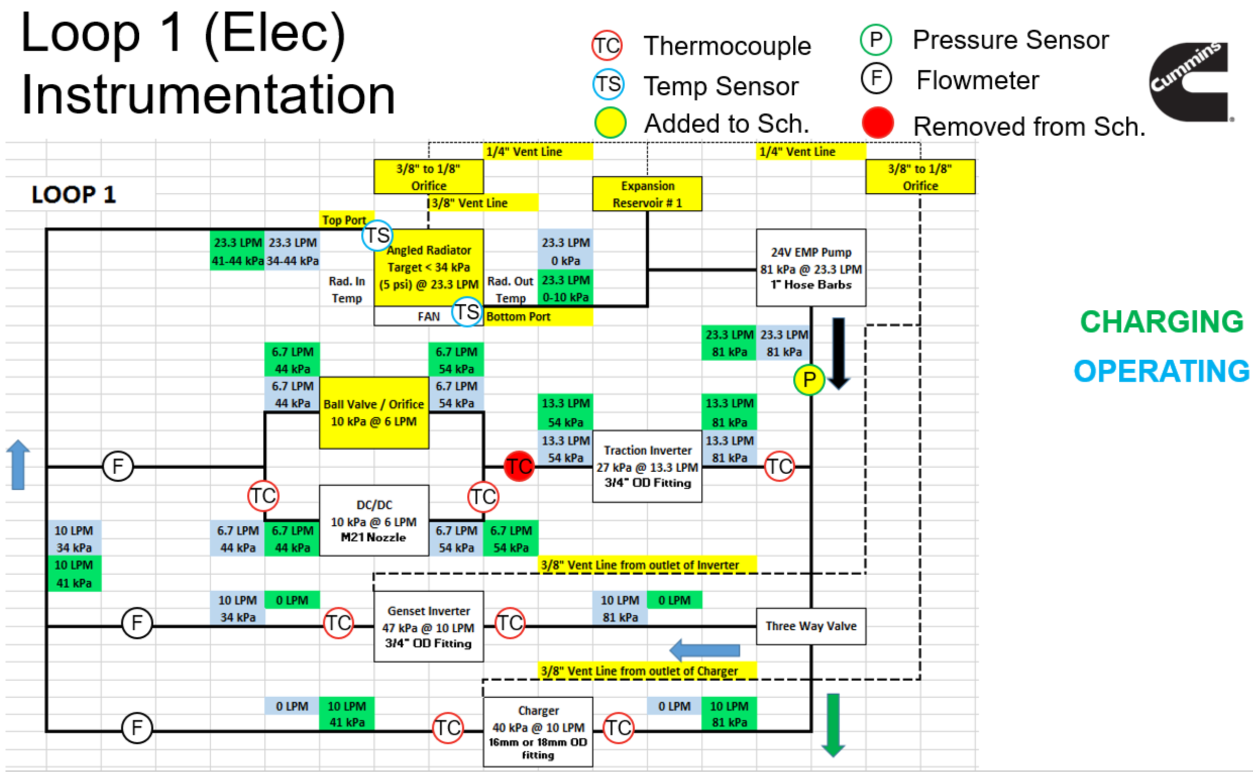



*Figure 21: Cooling Loop 1- Power Electronics*

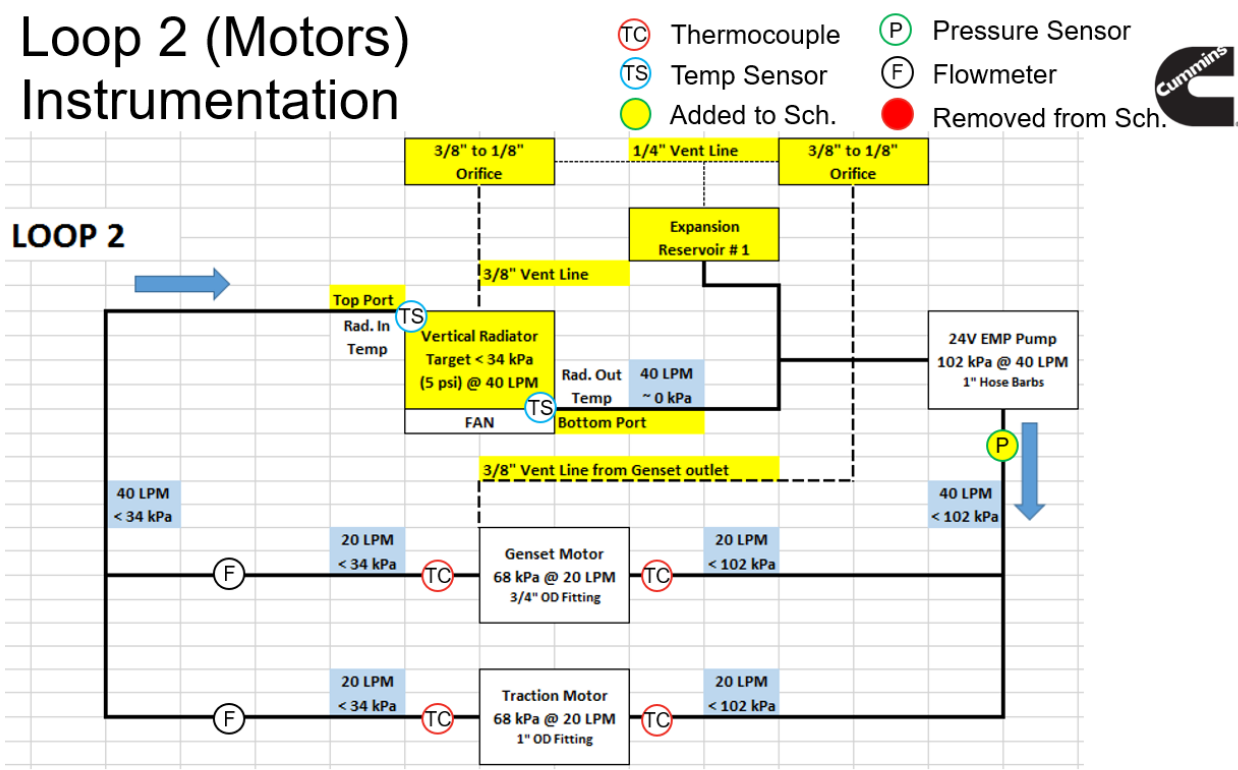



*Figure 22: Cooling Loop 2 Electric Machines*

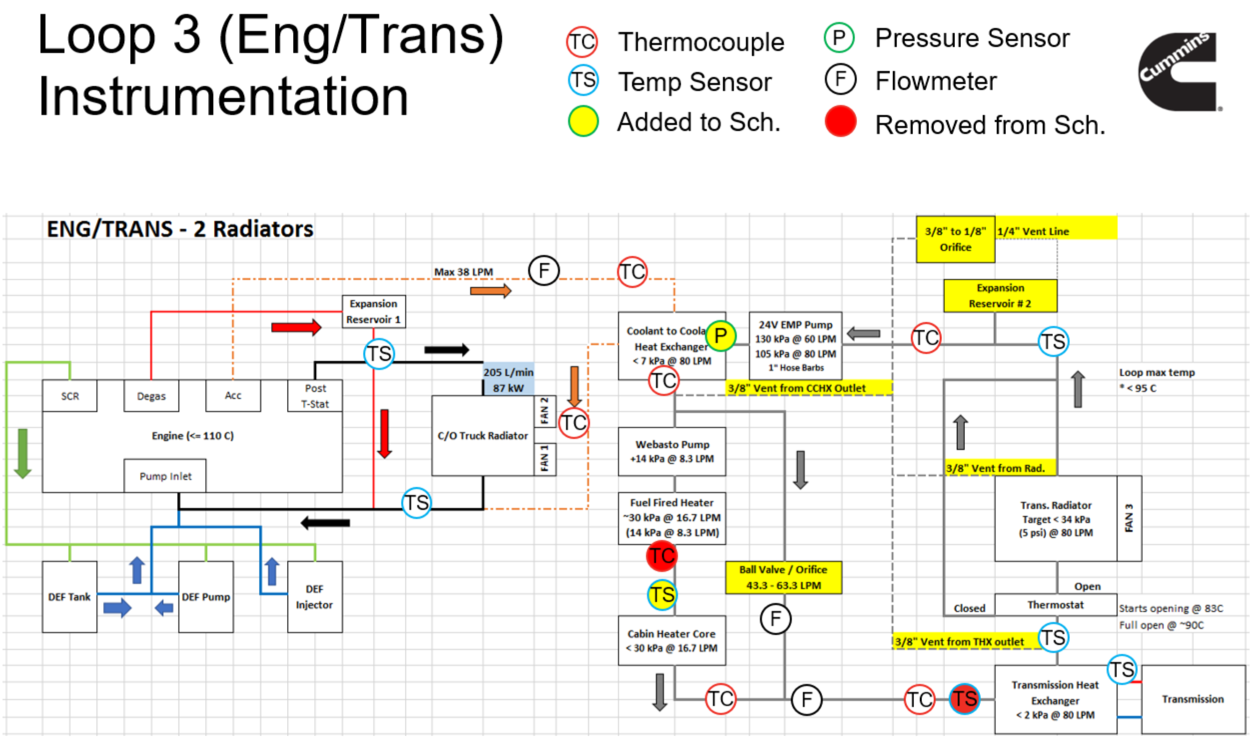



*Figure 23: Cooling loop 3 Range Extending Engine & Transmission*

With the design layout finalized and the components procured the two vehicles were assembled at a facility in Columbus, IN. The completed Kenworth k270 is displayed in Figure 24 below. A flatbed was installed initially to allow for testing with a variety of payloads (concrete blocks) prior to the 24 ft van body installation.

*Figure 24: ETREE K270 with Flatbed for Validation Testing*

## Vehicle Verification & Validation

Once vehicle builds were complete commissioning of the systems and controls commenced immediately. As the first ETREE truck was complete and system verification commenced it was revealed that the original high voltage ETREE battery was not reliable and prone to incorrect cell voltage & temperature readings. These incorrect sensor readings would result in the battery management system opening the battery contactors. Further analysis indicated that it would be very difficult and expensive to correct these deficiencies. Therefore, a plan was developed to build a new battery based on production 44V modules made by a company, Brammo, which is now owned by Cummins. This caused a 6-month program delay.

The alternate high voltage battery has 123 kw-h in total energy with slightly more than 100 kw-h useable. This battery size will enable ETREE to meet, and exceed, the fuel consumption reduction demonstrated in the test cell during the phase 1 of the project.

The battery consists of two enclosures, each with slightly more than 60 kw-h of total energy capacity. Figure 25 shows the driver side enclosure; each enclosure contains seven 200 A-h modules along with a sealed junction box (shown in red). The driver side junction box contains main and pre-charge contactors and master battery management system controller while the passenger side box contains a fan controller and negative side contactor.

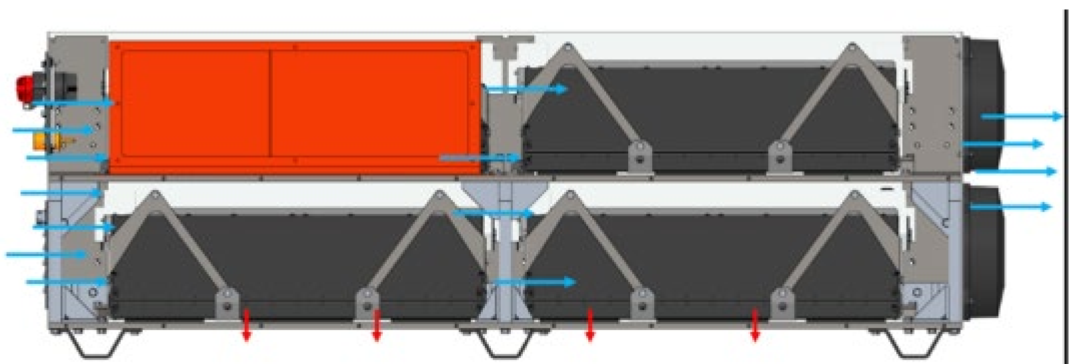


*Figure 25: ETREE Alternative High Voltage Battery Driver side*

The alternative battery design was sent to the Battery Innovation Center in Newberry, Indiana to test its performance on a simplified NREL 80 cycle to ensure it could meet performance requirements of upcoming J1526 fuel consumption testing and fleet use. The battery was able to meet performance requirements of the simplified NREL 80 cycle testing as shown in Figure 26. Based on these results the alternative battery was installed on both trucks and vehicle verification testing resumed.

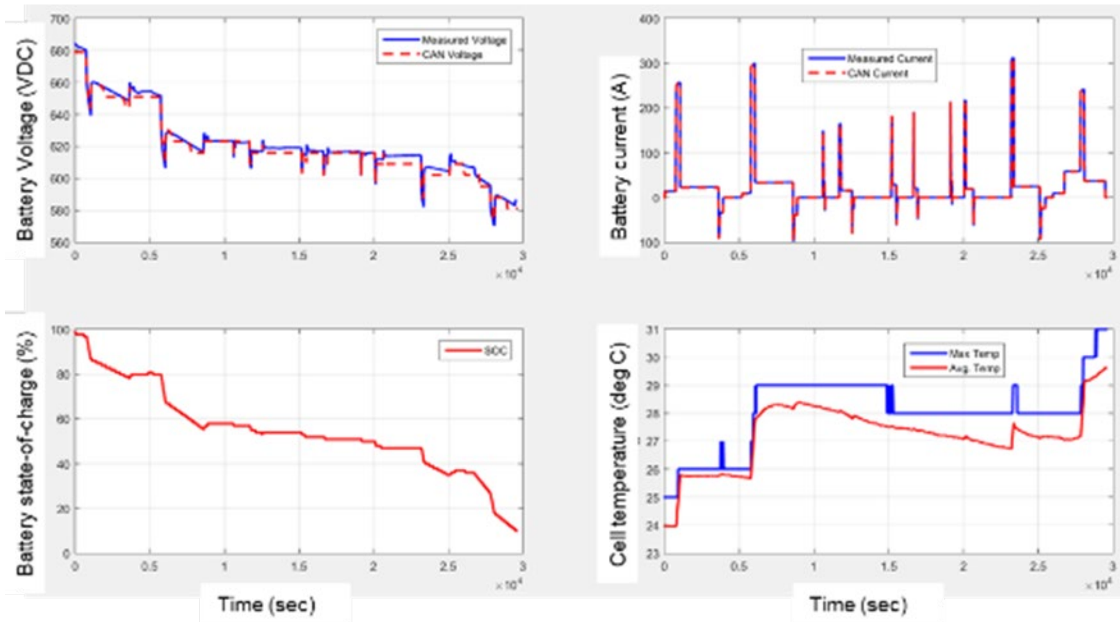



*Figure 26: Alternate Battery Testing Results*

While the alternative batteries were being built and tested a vehicle operating mode was developed utilizing the range extender without a battery to supply power to the vehicle DC high voltage bus. This testing allowed various systems to be tested and test track speeds up to 50 mph were reached. Operating without the battery, so-called “voltage control mode” by the range extender, can be a useful limp-home feature in the event of an energy storage system failure. Operating in “voltage control mode” is similar to a non-plug-in series hybrid operation albeit without energy storage for use as DC bus capacitance. Proper balancing of DC bus energy and consumption is absolutely required.

Truck validation continued on a local test track following Cummins internal protocol for prototype vehicle verification and validation to ensure safe on road use. At a high level this consisted of 500 test track mileage accumulation and the following validation tasks completed at 25,000 lbs:

- Level road acceleration performance (calibrated to be slightly better than a baseline diesel truck)
- Battery contactor control
- EV-only truck operation
- J1772 level 2 EVSE charging system operation
- Truck operation with active range extender
- Transmission shift quality including operation of stop-start system
- Validation of J1939-71 signals
- Validation of braking system
- Drivability with moderate levels of regeneration (negative torque)
- Operation of human machine interface and integration with range extender control

With key tasks complete a standard Cummins product safety hazard analysis (PSHA) for electrified vehicles was conducted and reviewed. At the conclusion of this PSHA ETREE vehicles were declared safe and allowed to operate on public roads for continued mileage accumulation.

The Peterbilt 220 truck was sent to a body builder in Groveport, Ohio to install the 24-foot van body. When this work was complete the ETREE truck demonstrated its range extending architecture's flexibility by driving 200 miles from Groveport, Ohio to Columbus, Indiana without needing to be charged or fueled.

The ETREE trucks accumulated more than 10,000 miles of on road use spanning multiple states and environmental conditions over the course of the project.  This was a key piece of the project to demonstrate the vehicles ability to operate under a variety of real conditions.  To demonstrate the capability of the ETREE trucks to meet or exceed conventional vehicle range and performance the project decided to drive one of the trucks across the United States for the J1526 fuel consumption testing in Uvalde, Texas instead of ship it.  This trip began at the Cummins Technical Center in Columbus, Indiana and ended 3 days later at Southwest Research Institute in San Antonio, Texas.  The ETREE truck accumulated 1150 miles over the 3-day trip with the first day mileage being approximately 600 miles.  A map of the trip can be seen in Figure 27.

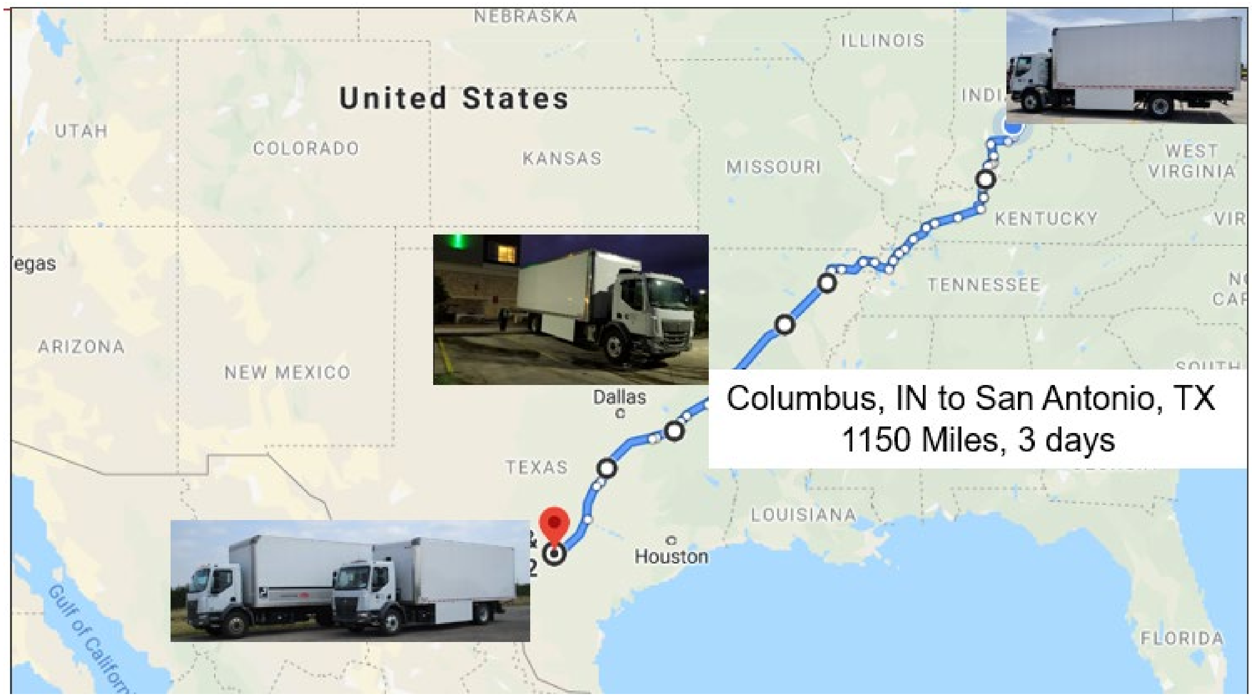



*Figure 27: ETREE 1150 Mile Trip*

## Vehicle SAE J1526 Fuel Reduction Testing

The major milestone for the ETREE project and the go/no-go for phase 2 was to demonstrate the fuel reduction goal of >50% compared to a conventional class 6 vehicle on a simplified NREL 80 cycle.

The ETREE target duty cycle is a workday cycle consisting of real-world vehicle trajectories obtained, by NREL, from similar trucks operating in the field.  This combination of length of time and variable trajectories presents challenges when attempting to test on a test track.  To overcome these issues, Cummins and NREL has developed a test track-suitable duty cycle with similar characteristics to the target NREL 80 pickup and delivery cycle but with less second-to-second variance.  And, the modified duty cycle has been reduced to two sections with total driving time less than four hours. NREL modified the cycle by “adaptive decimation” method to strategically reduce the complexity of the speed profile while minimizing the overall impact to key cycle metrics—kinetic intensity, driving average speed, stops per mile, etc. Table 4 shows a comparison of kinetic intensity and driving average speed for the original cycle and decimated cycle [5].

*Table 4: Comparison of Kinetic Intensity and Driving Average Speed*

| | **Kinetic Intensity ($mi^{-1}$)** | **Driving Average Speed (mph)** |
|---|---|---|
| NREL 80, original | 0.359 | 31.9 |
| NREL 80, decimated Δ7.5 mph (as defined) | 0.266 | 32.7 |
| NREL 80, decimated Δ7.5 mph (as driven, conventional vehicle) | 0.395 | 32.6 |
| NREL 80, decimated Δ7.5 mph (as driven, REEV) | 0.367 | 33.1 |

To improve the tracking of test duty cycles, Southwest Research Institute (SwRI) has developed a Direct Electronic Vehicle Control (DEVCon) automated system which modulates accelerator pedal and service brake (while the vehicle is on a test track). The ETREE team believes this semi-autonomous system is important test technology that can improve testing results when complex (and closer to “real world”) duty cycles are involved. Therefore, SwRI was selected as the responsible party for the J1526 testing; they installed and tuned their system on both ETREE truck 1 and the baseline truck. The test was conducted on an 8.5-mile oval test track in Uvalde, TX, shown in Figure 28.

*Figure 28: Uvalde, Test Track: Courtesy of Southwest Research Institute*

The two trucks (Figure 29) were operated each day on the same test cycles separated by 5 minutes on the test track. Each truck was ballasted with 4850 lbs. of payload for testing to mimic real world cargo. The two trucks did not share the same curb weight, with ETREE being significantly heavier due to electrified componentry. Specification of each truck as tested are listed in Table 1.


*Figure 29:Convential Truck (Left) & ETREE Truck (right)*

*Table 5:Convential and ETREE Truck Specifications as Tested*

| Test Vehicle | Kenworth REEV (A) | Peterbilt 220 (B) |
|---|---|---|
| Unit Number | ***1832*** | ***681269*** |
| Make | Kenworth | Peterbilt |
| Model | K270 | 220 |
| Year | 2018 | 2015 |
| VIN | 3BKJHM6X8JF581832 | 3BPPHM6XXFF590608 |
| Vehicle Mileage | 3,100 | 93,100 |
| Driver | Thomas | Chris |
| Cargo Box Size (Height, Width, Length) | 8.5'H x 101"W x 24.5' L | 9'H x 101"W x 26' L |
| Number of Axles | 2 | 2 |
| Number of Drive Axles | 1 | 1 |
| Engine Make | Cummins | Cummins |
| Engine Size (liters) | 4.5 | 6.7 |
| Engine Family | ISB | PX-7 |
| Differential Ratio | 5.29 :1 | 5.57:1 |
| Test Weights- Steer (pounds) | 9620 | 8020 |
| Test Weights- Drive (pounds) | 15780 | 14080 |
| Test Weights- Total (pounds) | 25400 | 22100 |
| SOT Weights (pounds) | 20580 | 17220 |
| Weight Added (pounds) | 4820 | 4880 |

A driver was present in each truck to steer the vehicle around the 8.5-mile track with 3-mile radius turns. The driver steering input in this case is negligible and was not considered. This was the first instance of testing on an electrified vehicle and the first J1526 test for this system. The system provided consistent and repeatable velocity vs. time data (Figure 30) between the two vehicles over the course of testing.

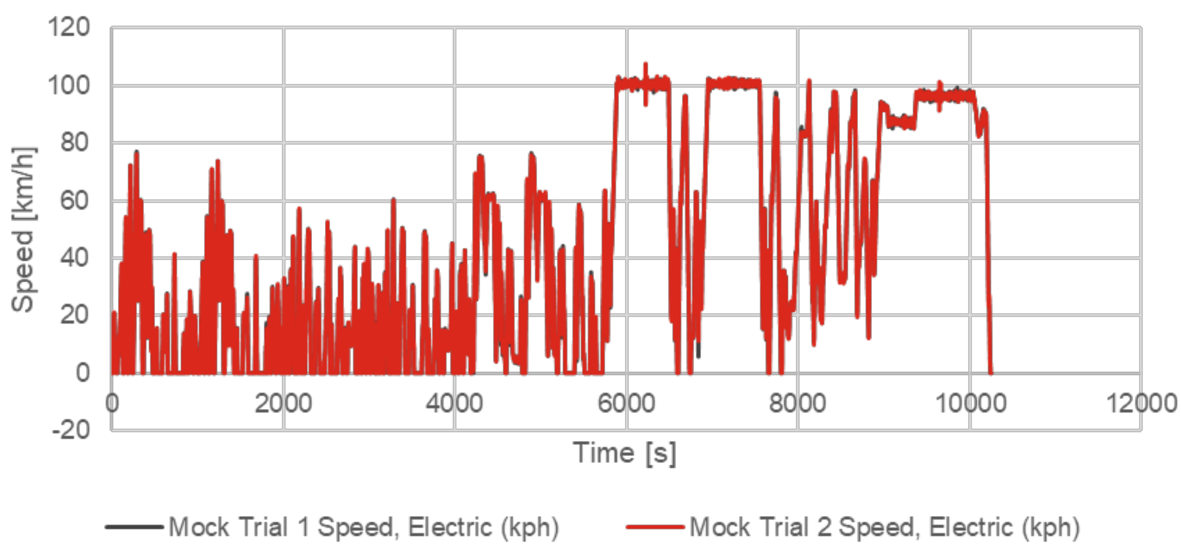



*Figure 30: Cycle to Cycle Speed vs. Time Data*

Southwest Research completed three runs of testing on the modified NREL 80 test cycle on the 8.5 test track with the DEVCon system. Review of the data deemed testing valid according to intent of the J1526 standard. Table 6 shows the result of **65.2%** reduction in fuel consumption as measured via gravimetric method according to J1526 standard averaged over three runs. This was an excellent result for the program and completed phase 2 of the project along with achieving the major milestone for the project.

*Table 6: J1526 Fuel Consumption Test Results*

| Vehicle A Compared to Vehicle B with 95% Confidence Interval | Result | | Conf. Int |
|---|---|---|---|
| Average Difference in Fuel Quantity | 46.46 | ± | 1.27 |
| % Less Fuel Consumed by Veh A | **65.2%** | ± | 1.8% |
| Is fuel consumption proven different w/ at least 95% confidence? | **Yes** | | |

| | ETREE | Conventional | | |
|---|---|---|---|---|
| | **Vehicle A Qty Fuel** | **Vehicle B Qty Fuel** | **Delta Qty Fuel (lbs)** | **Fuel Reduction (%)** |
| **Run 1** | 24.4 | 70.38 | 45.98 | 65.33 |
| **Run 2** | 24.42 | 71.42 | 47 | 65.81 |
| **Run 3** | 25.48 | 71.88 | 46.4 | 64.55 |

NREL 80 modified test cycle as driven was inputted back into simulation to compare results with measured test results. This comparison is shown in Table 7. The fuel consumption reduction percentage shows an excellent match between test 65.6% and simulation 65.8%. Kinetic Intensity is slightly higher during testing but average speed for the cycle is the same. This difference is because of the driver model used in simulation compared to the DEVCon system used in testing. There is 8% difference in fuel consumed between test and simulation. This discrepancy is attributed to the following:

- Simulation assumes a flat surface with no grade, but this is not true for testing
- Accessory load is not accurately modeled for either vehicle in simulation
- Test engine efficiency was lower in actual testing at 36.9% compared to simulated 40.53%

*Table 7: Modified NREL 80 Simulation & Test Results Comparison*

| | NREL 80 (sim) | NREL 80 (Test) |
|---|---|---|
| Max. Speed (mph) | 65 | 64 |
| Aerodynamic Speed (mph) | 50 | 50 |
| Average Speed (mph) | 33 | 33 |
| Kinetic Intensity (1/km) | 0.17 | 0.26 |
| Mileage Covered | 77 | 77 |
| Vehicle Weight (lb) | 25,400/21,200 | 25,400/21,200 |
| SOC Start | 97% | 97% |
| SOC End | 25% | 25% |
| ETREE Fuel Consumption (lb) | 21.5 | 24.4 |
| Conventional FC (lb) | 63 | 71 |
| FC Reduction (%) | 65.8 | 65.6 |

## Phase III Vehicle Demonstration

The ETREE Peterbilt 220 truck was released in fleet service to Frito Lay in January of 2020. The truck completed daily missions with comparable performance to the conventional vehicles. However, after a short trial period it became apparent that the combination of the route characteristics, which included shut down times up to 4 hours, and a cold temperature induced high voltage battery communication issue would not allow for a successful demonstration in winter. The long shut down period between stops combined with a prototype high voltage battery heater circuit that produced CAN bus noise potentially would put the truck into a “no start” condition. This issue could be fixed with a hardware cycle, but project time and budget constraints would not allow for this hardware cycle to take place. It was determined to pause the demonstration until springtime when ambient temperatures were higher, and this issue would not pose a challenge. Figure 31 shows the ETREE truck parked outside while charging at the fleet partner’s distribution center. In the 2$^{nd}$ quarter of 2020 the ETREE truck was intended to be deployed back in service at Frito Lay in Indianapolis, IN. However, because of the global COVID 19 pandemic the decision was made to not place the truck back into service to prevent additional risk to operating staff during the pandemic. At the onset of the quarter this was perceived to be a temporary challenge for the ETREE project to accumulate fleet miles but as COVID 19 continued to be a global issue through the end of the Q2 2020 it was apparent that an alternate solution was needed. The program executed an alternative solution to operate the truck through an independent driving company for 3 months during Q3 2020. From July through September 2020 the ETREE truck was operating out of Columbus, Indiana by an independent driving company on daily or nightly routes between 30 and 175 miles. At the end of the driving period the truck had accumulated 3300 miles of public road driving in the 3-month period. This completed the final milestone for the project. Figure 32 below shows estimated fuel consumed vs. mileage driven for some of the routes from this period. It is worth noting two distinct clusters of data in the 70-90 mileage range. These clusters were caused by driver behavior differences operating the truck and entering incorrect information into the human machine interface. Both items should be addressed at a real fleet through driver training.

*Figure 31:ETREE Charging outside at fleet partner distribution center*

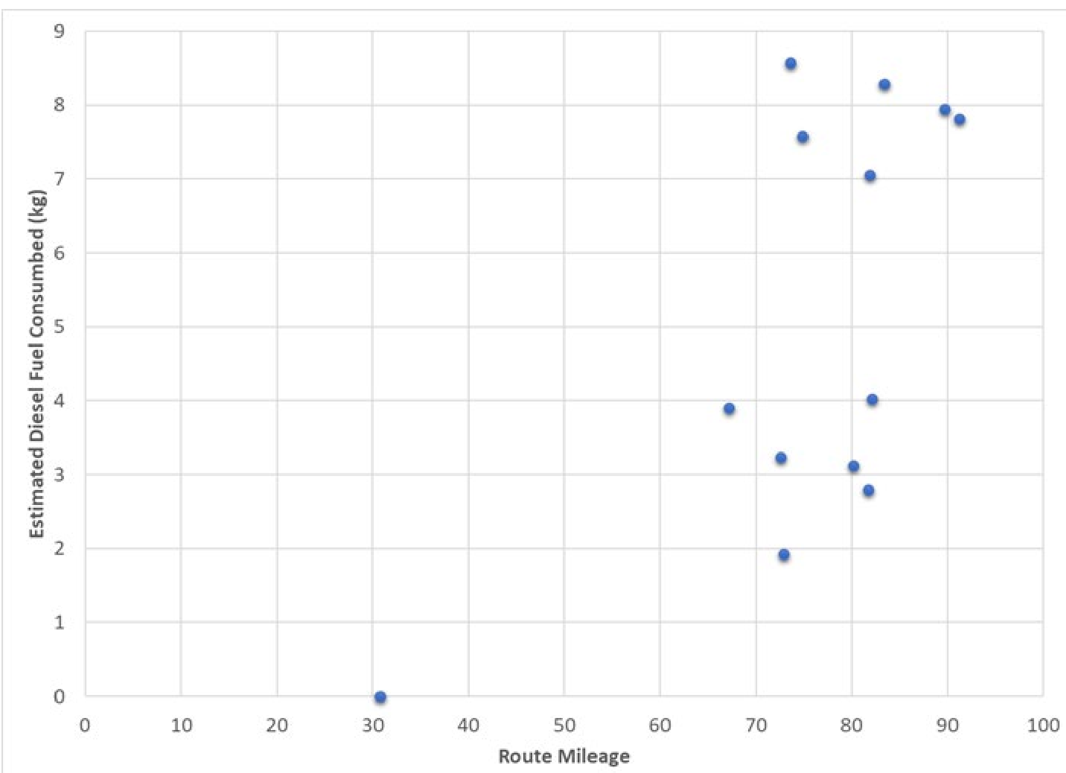



*Figure 32: Estimated fuel consumed vs. mileage driven while operating on local routes*

# Summary & Conclusions

Initially the project team utilized partners in academia and at national laboratories to develop an applicable workday cycle, the NREL 80. This cycle was curated based off real fleet data and is representative of 90% of mileage traveled for the class 6 & 7 pickup and delivery market. The NREL 80 cycle was then utilized in simulation and a variety of design of experiments to define an architecture that would yield 65% fuel reduction for the ETREE project compared to a conventional diesel powertrain.

Next components were procured, assembled, and tested in a test cell at the Cummins Technical Center on the NREL 80 cycle. Test cell testing measured a 64.6% reduction in fuel consumed over a conventional diesel powertrain. The project team then integrated the architecture into two class 6 trucks. Over the course of the project the two class 6 trucks accumulated over 10,000 miles of on road use spanning all four weather seasons, multiple states, and use conditions including a short fleet trial hauling real freight. One of the trucks was driven 1150 miles over the course of three days from Columbus, Indiana to San Antonio, Texas to complete J1526 fuel consumption testing with Southwest Research Institute at the Continental test track in Uvalde, TX. Controlled J1526 fuel consumption testing was carried out on one ETREE and conventional truck at the 8.5-mile oval test track utilizing the Southwest Research Institute DEVCon semi-autonomous drive system for NREL 80 cycle repeatability. Data from three runs of J1526 testing on a modified NREL 80 cycle yielded a measured 65.2% fuel reduction of ETREE compared to a conventional truck. This was the major milestone for the project.

In summary the range extending engine architecture with optimized state of charge trajectory management controls demonstrated in this project can fully utilized grid energy daily while meeting range, performance, and robustness expectations of a conventional powertrain vehicle. It is a viable near to medium term solution for a commercialized electric vehicle product to meet fleet operator needs in the class 6 pickup and delivery market.

# Project Presentations & Publications

## Industry Outreach

SAE COMVEC Technology Demo at the Indianapolis Motor Speedway Q3 2019

ETREE lunch and learn industry outreach with Greater Indiana Clean Cities held at Work Truck Show in Q1 2020

greater Indiana clean cities coalition

## Publications

Duran, A., Li, K., Kresse, J., and Kelly, K., “Development of 80- and 100- Mile Work Day Cycles Representative of Commercial Pickup and Delivery Operation,” SAE Technical Paper 2018-01-1192, 2018, doi:10.4271/2018-01-1192.

Jeffers, M., Miller, E., Kelly, K., Kresse, J., Li, K., Dalton, J., Kadar, M., Frazier, C., “Development and demonstration of a class 6 range-extended electric vehicle for commercial pickup and delivery operation”, SAE Technical Paper 2020-01-0848, 2020.

The following technical paper, based on ETREE project work, was presented at the 2019 Innovations in Mobility Conference:
Title: Opportunities and Challenges of Internal Combustion Engine Range Extenders in Commercial Vehicles
Primary Author: Ke Li
The following technical paper, also based on ETREE project work, was presented at the 2018 ASME Dynamic Systems and Controls conference:
Title: Battery Discharge Strategies for Energy Management in Electrified Truck for Pick-up and Delivery Application
Primary Author: Mukilan Arasu
Additional Authors: Qadeer Ahmed and Giorgio Rizzoni

# References


1. Duran, A., Li, K., Kresse, J., and Kelly, K., "Development of 80- and 100- Mile Work Day Cycles Representative of Commercial Pickup and Delivery Operation,"

SAE Technical Paper 2018-01-1192, 2018, doi:10.4271/2018-01-1192.

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3. National Renewable Energy Laboratory, "DRIVE Analysis Tool Generates Custom Vehicle Drive Cycles Based on Real-World Data," https://www.nrel.gov/docs/fy13osti/54507.pdf, April 2013.

4. SAE International Surface Vehicle Recommended Practice, "SAE Fuel Consumption Test Procedure (Engineering Method)," SAE Standard J1526, Rev. Sep. 2015.

5. Jeffers, M., Miller, E., Kelly, K., Kresse, J., Li, K., Dalton, J., Kadar, M., Frazier, C., "Development and demonstration of a class 6 range-extended electric vehicle for commercial pickup and delivery operation", SAE Technical Paper 2020-01-0848, 2020.


# List of Figures

## List of Tables