2019 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Cummins Electric Truck with Range-Extending Engine (ETREE)

Project ID: ELT189

Principal Investigator:
John Kresse
Cummins, Inc.

June 12, 2019

Project Overview

TIMELINE

- 4 year project
- Project start date: July 2016
- Project end date: June 2020
- Percent complete: 85%

BARRIERS

- EV-based commercial vehicle which meets needs of class 6-7 pickup & delivery fleets:
  - Complete the route regardless of environmental conditions with little to no performance degradation
  - Robust, cost-effective powertrain which emphasizes use of grid electricity

BUDGET

Project (overall):	$7,816,364
DOE Share:	$4,126,570
FFRDC:	$355,708
Contractor funding:	$3,053,829
Funding received (1/2019):	$3,730,605

PARTNERS

- Cummins
  - PACCAR
  - Argonne National Lab
  - National Renewable Energy Lab
  - The Ohio State University

Objectives

(1)

- Using electrification, improve the Kenworth K270 & Peterbilt Model 220 to substantially reduce fuel consumption for the **class 6 pickup & delivery market** while meeting requirements of the existing trucks
- Investigate the potential to improve a commercial EV using:
  - range extending engine / generator with optimized controls
  - multi-speed transmission
  - electronic braking system with brake blending
- Develop hybrid system controls technology focused on battery state-of-charge trajectory management and vehicle integration (electrified accessories, thermal management) systems
- Define and verify requirements for range extending electric trucks applicable to class 6-7 pickup and delivery application

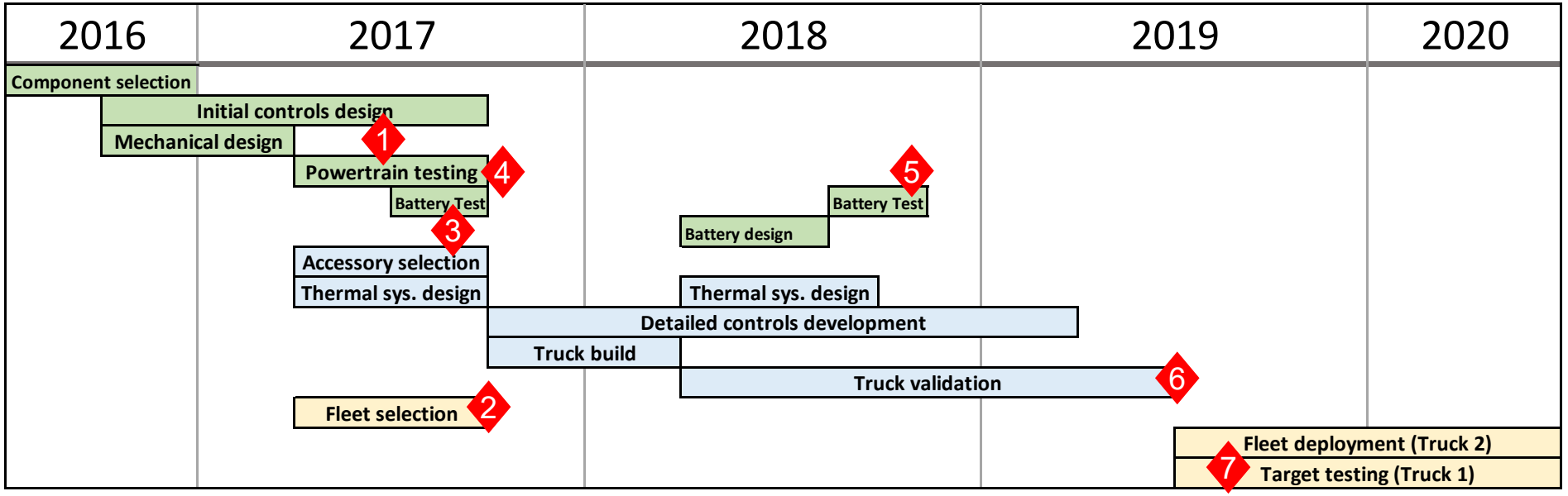
1. Courtesy of PACCAR Inc

Relevance of ETREE project

- Two keys to widespread electrified commercial vehicle adoption
  1. For pure EV, battery improvements are needed: cost(↓) & energy density(↑)
  2. Must overcome fleet operator risks such as: operations in cold climates & hilly terrain, or where majority of conventional trucks are replaced with EV
- In the near- to medium-term, solved by: a PHEV w/ low-cost range extender (REx) to provide route flexibility
  - Proven to work over wide variety of missions & environmental conditions
  - Manufactured, serviced, certified, delivered, integrated using standard commercial vehicle processes
- Vehicle developed in this project can be considered a prototype for a commercially viable heavily electrified commercial vehicle
- ETREE will deliver equivalent continuous performance (transmission output torque and power) and range as conventional class 6 truck

EV – electric vehicle PHEV – plug-in electric vehicle REx – Range Extender

Milestones & Plan



	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	
7	Release truck to first fleet operator	3	7/15/2018	

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

Approach

Selection of Fleet Demo Partner

- **Frito-Lay** selected as primary ETREE demo partner
  - Operates fixed defined routes, 15-100+ mi/day, delivering chips/snack food
  - ETREE Peterbilt Model 220 will operate on (typically) 50-80 mi/day routes from the Indianapolis distribution center
- 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

"The Range Extended capability of the ETREE vehicle is of great interest to PepsiCo. It provides real world opportunity for zero emission driving and also the ability to drive extended miles when needed, with no interruption"

- Mike O'Connell (VP Fleet, Supply Chain and Sustainability) PepsiCo

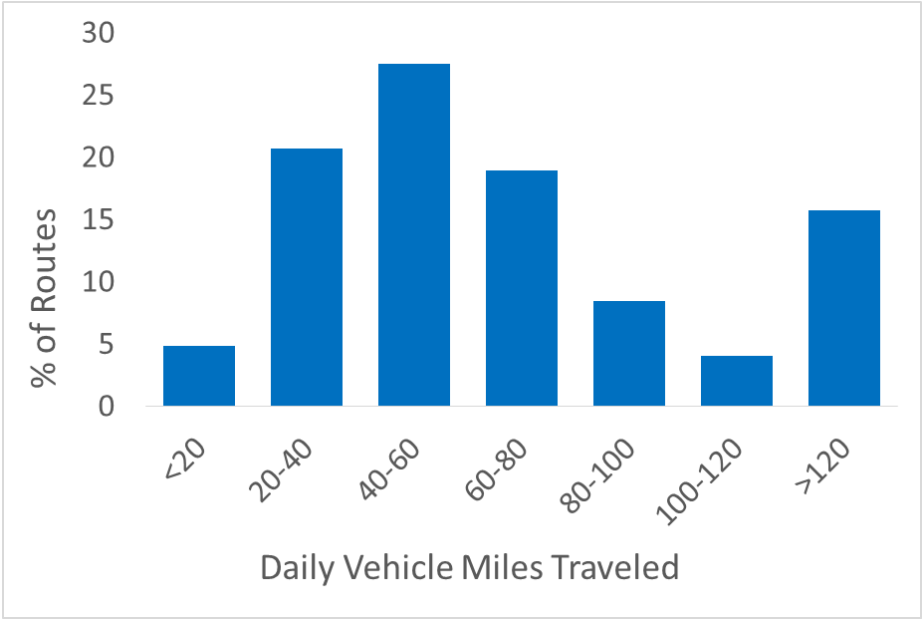
Logos courtesy of PepsiCo, Inc.

Approach

Understanding Customer Requirements

- For class 5-7 pickup & delivery, fleet operators want truck with:
  - comparable performance as conventional and, generally, desire flexibility provided by a range extender
  - capability to operate in pure electric mode for substantial part of route
- Also: require low installation cost of charging infrastructure (EVSE), trucks often stored outside & may not have dedicated EVSE per truck

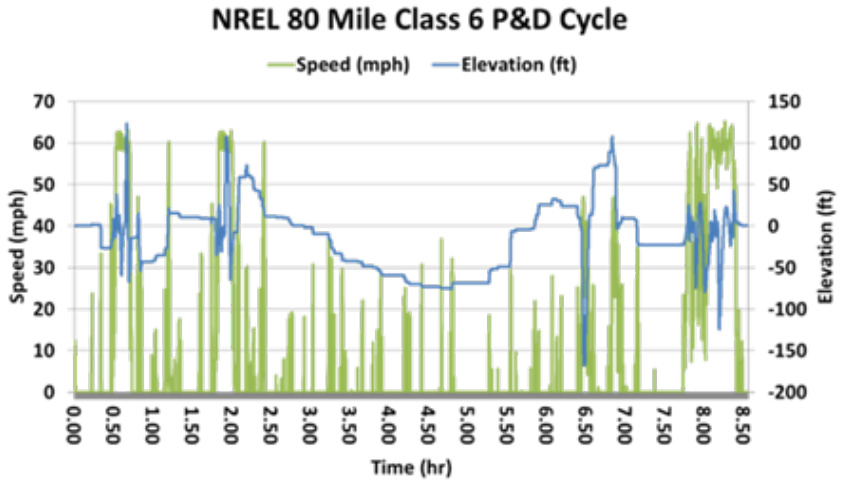
*combined NREL FleetDNA class 5-7 P & D and Cummins data



Approach

Translation into 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

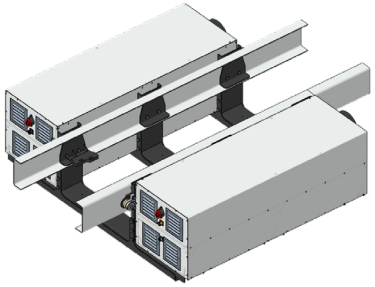


- **NREL 80 mile developed as the ETREE target cycle**; represents 70-80th percentile of required energy of representative drive cycles*
- Secondary target duty cycle developed: NREL 100 mile cycle

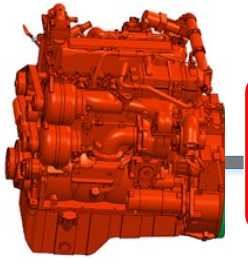
*Duran, A., Le, K., Kresse, J. and Kelly, K. "Development of 80- and 100- Mile Work Day Cycles Representative of Commercial Pickup and Delivery Operation," SAE Technical Paper 2018-01-1192

Approach
Architecture

Architecture & ancillary components selected to meet customer requirements on target duty cycle(s)



122 kW-h NMC Li-ion battery



damper

130 kW PM generator

~/-

620 V DC bus nominal

-/~

175 kW PM traction motor

Allison 3000 ETREE transmission

Transmission input stop-start system

155 kW ISB4.5 with DPF, SCR, DOC aftertreatment

DPF – diesel particulate filter
SCR – selective catalytic reduction
DOC – diesel oxidation catalyst
NMC – nickel manganese cobalt

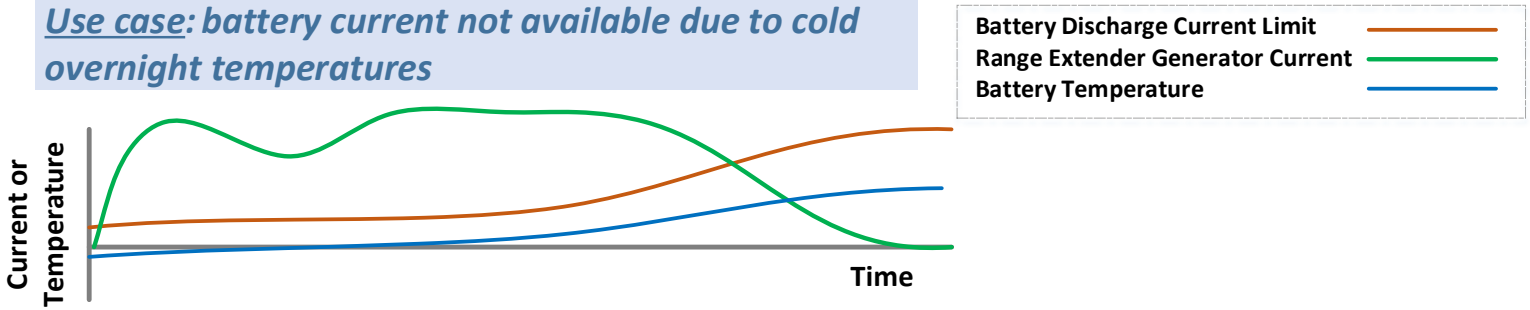
Permanent magnet (PM) electric machines with listed continuous ratings

- **J1772 level 2 EVSE** [supports low cost infrastructure]
- **Energy-based range extender control** to ensure optimal usage of grid energy
- **Electrified accessories** [supports electric-only operation]

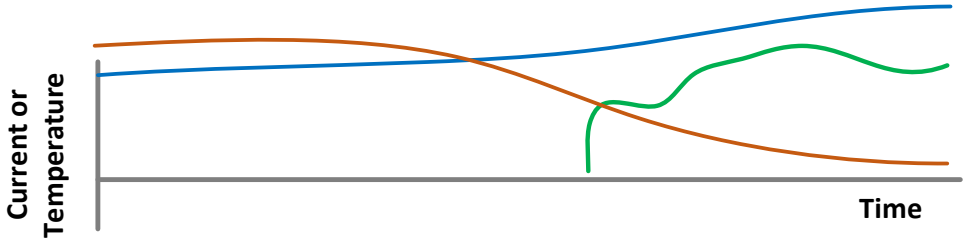
Approach

Using the range extender to help overcome fleet operator concerns

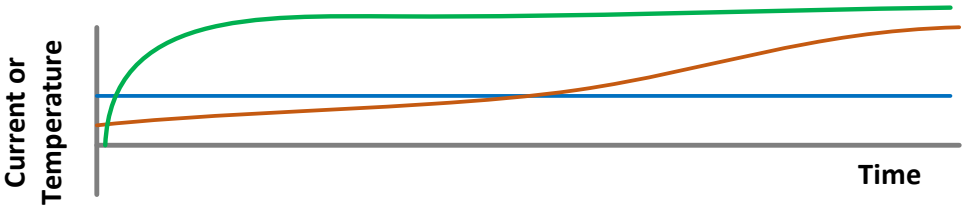
***Use case**: battery current not available due to cold overnight temperatures*



***Use case**: as battery cell temperatures increase above nominal operating range or long duration discharge (C) rate exceeded, battery discharge current limit decreases*



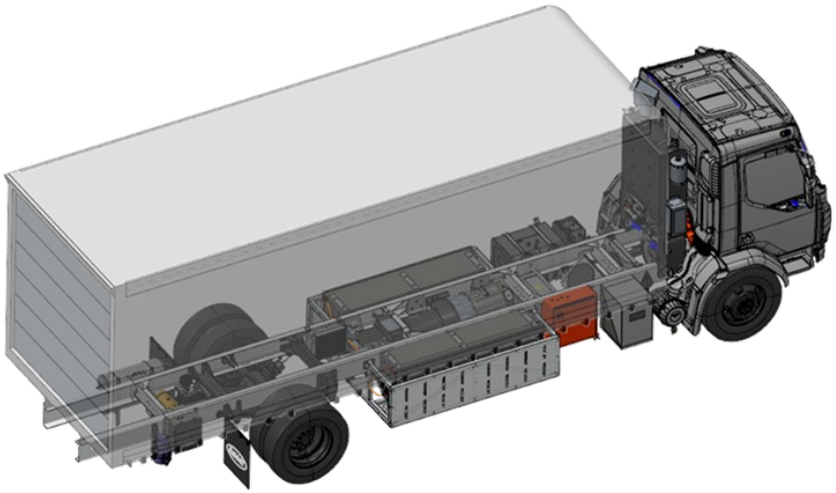
***Use case**: stationary charging when battery state-of-charge low, electric vehicle supply equipment unavailable (e.g., electric grid down, etc.)*



Likely not most efficient for fuel consumption, but used to support upcoming EV-only zone activity

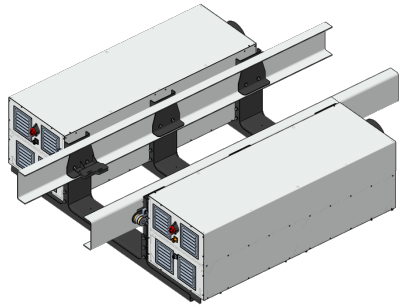
Technical Progress

Vehicle design & build



temporary flat-bed used for initial testing only;
J1526 testing and fleet deployment will use van body

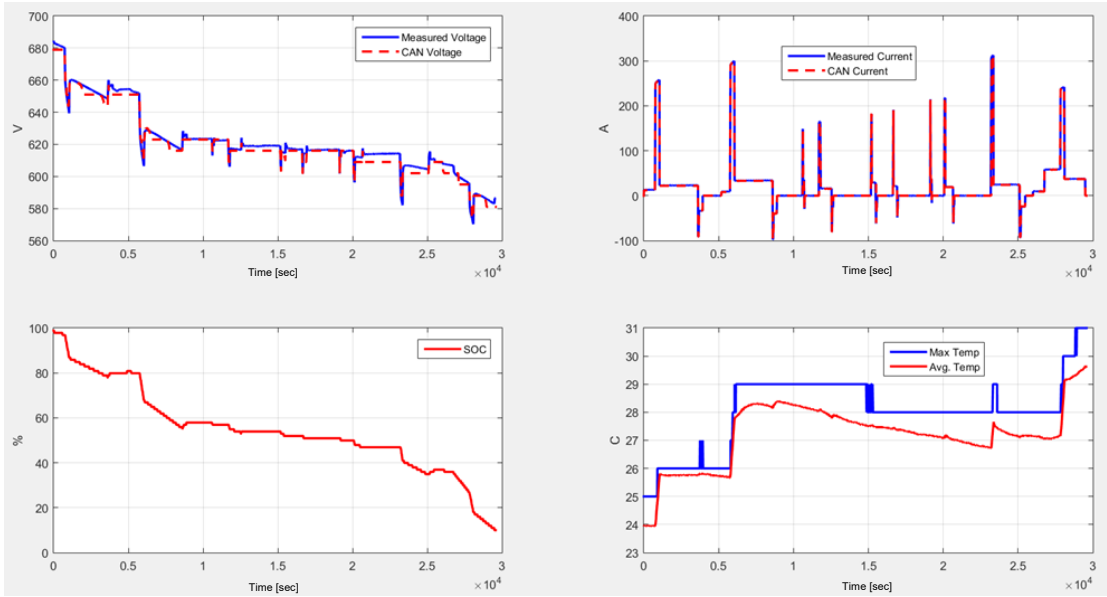
Technical Challenge
Updated battery



- In May 2018, validation testing revealed original battery had cell voltage and temperature monitoring boards which did not support the project's long-term reliability goals
- Decision was made to develop new high voltage battery pack using production low voltage modules (modules support being added in series)

Lithium-ion NMC/G battery
122 kW-h total energy
Integrated crash protection
80 kW charge rate limit
Production cell voltage & temperature monitoring sensors
Production battery management system
Air-cooled (fans & venting)

Updated battery characteristics



Battery-only test results on work-day test cycle

Technical Challenge

Maximize daily use of battery

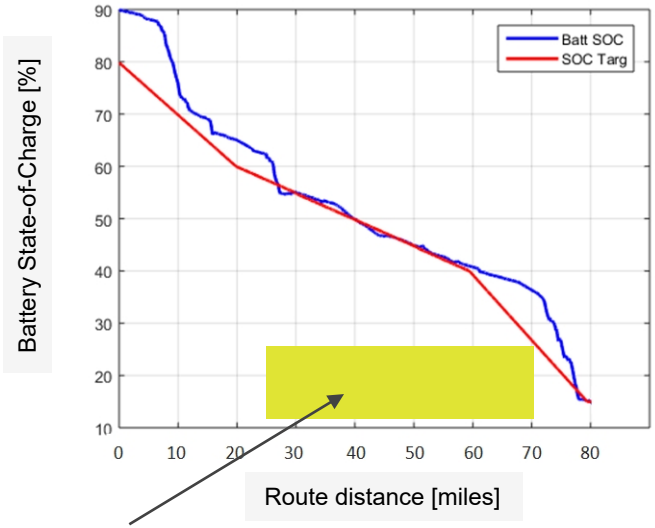
- Using route information (driver entered & learned parameters), range extender control:
  - Reduces fuel consumption
  - Maximizes battery life
  - Manages aftertreatment temperature
  - Meets performance metrics

Range extender power capability < (Traction motor + accessory) max required power; employing only a charge depleting / charge sustaining is not an option without sustained risk of reduced vehicle performance*. ETREE is using:

mix of charge depleting, charge sustaining and blended operation

HMI enables driver to enter route distance

State-of-Charge (SOC) trajectory during work day



***Operation near minimum state-of-charge leaves truck susceptible to derated performance**

Technical Progress

Initial test track results and predictions

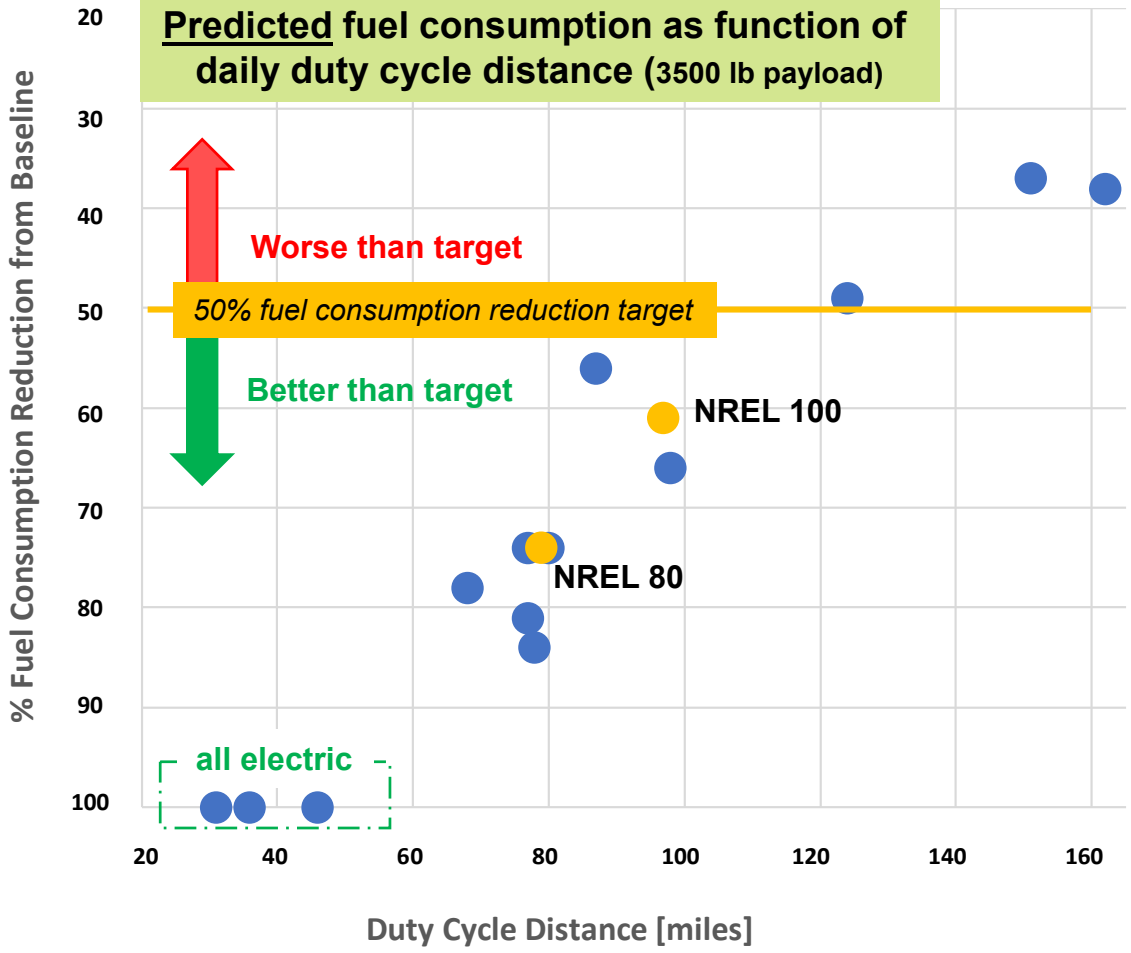
Initial test track results
approximated **NREL 80 duty cycle, 5200 lb payload, $T_{ambient}$ = 13 – 20 degC**

Test 1	
SOC change	86 to 20%
Baseline fuel used (predicted)	24.95 kg
ETREE fuel used (measured)	7.23 kg
% improvement	69.0 *

Test 2	
SOC change	86 to 20%
Baseline fuel used (predicted)	25.64 kg
ETREE fuel used (measured)	9.77 kg
% improvement	61.9 *

**Difference between tested and predicted primarily due to reduced SOC depth-of-discharge for these particular tests – goal is to fully utilize 75% DOD in typical operation*

Predicted fuel consumption as function of daily duty cycle distance (3500 lb payload)



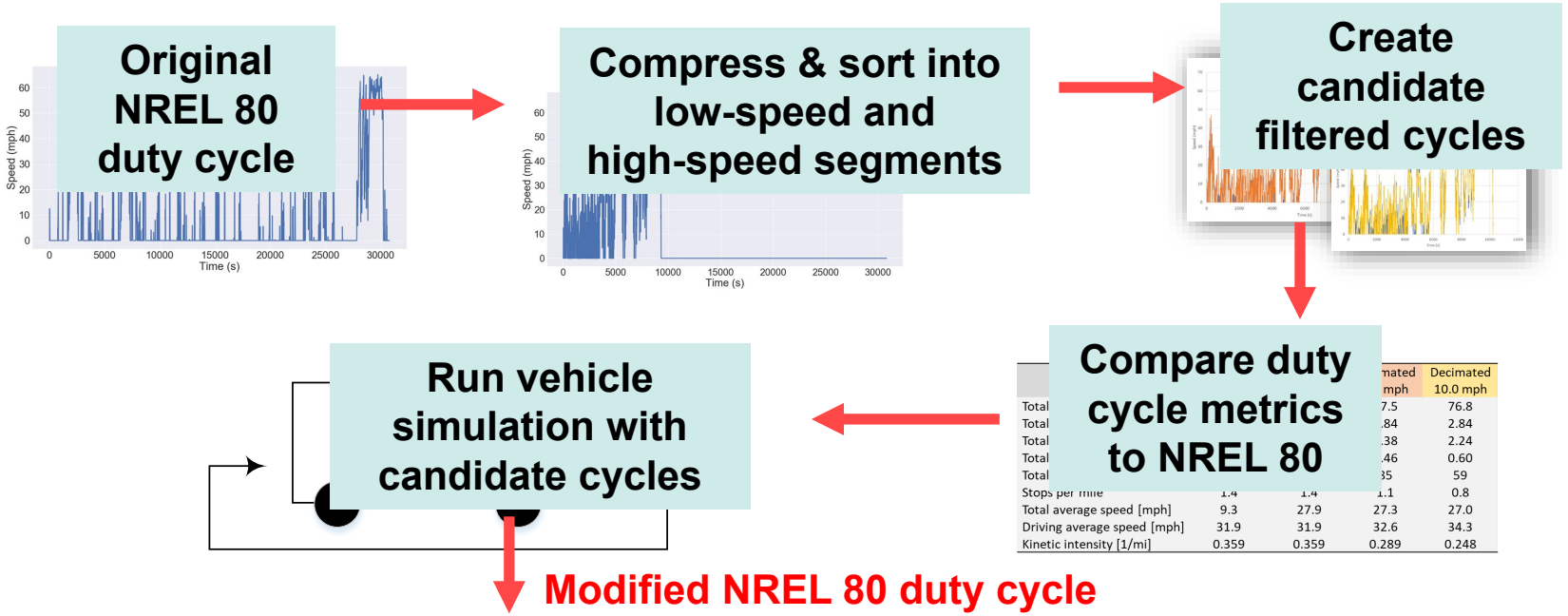
Level road acceleration performance verified to be slightly better than conventional (incl. ETREE weight penalty)

Technical Challenge
J1526 Testing

Objective: J1526 testing with representative results from the NREL 80 target cycle

Challenge: NREL 80 target cycle is work day cycle (8+ hours long) with challenging speed trajectories to drive on test track

Solution: Test track-compatible duty cycle & SwRI* semi-automated testing system



			Decimated 10.0 mph
Total		7.5	76.8
Total		.84	2.84
Total		.38	2.24
Total		.46	0.60
Total		35	59
Stops per mile	1.4	1.1	0.8
Total average speed [mph]	9.3	27.3	27.0
Driving average speed [mph]	31.9	32.6	34.3
Kinetic intensity [1/mi]	0.359	0.289	0.248

On test track, SwRI semi-automated testing system which controls accelerator pedal and brake to track desired trajectory; system reduces testing variation and improves results

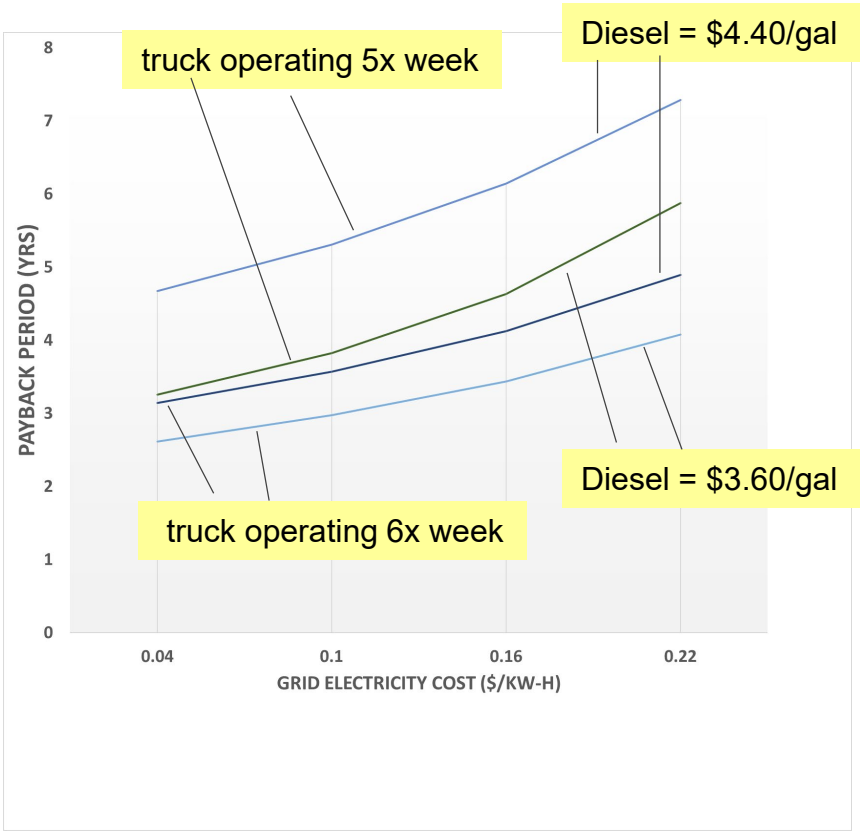
*SwRI = Southwest Research Institute

Commercial viability

- To minimize payback period and maximize commercial viability:
  - **maximize battery use** by 1) selecting routes with appropriate distance and energy requirements & 2) operating 6x/week
  - **minimize cost of grid electricity:** use off-peak charging or consistent electric vehicle grid charging cost plan

That [demand charge] is the scary part… the big risk and unknown. It's hard for fleet managers to live in a variable world. The move from diesel to electricity is a learning curve.[1]

- ~3-year payback period is possible:
  - ETREE operating 6x/week
  - daily VMT: 55 - 110 miles
  - grid electricity cost ≤ 14¢/kW-h
- Updates to ETREE for production:
  - Lower cost & smaller range extender
  - Right-sized powertrain components
  - Serial production batteries



(1) PACIFIC GAS AND ELECTRIC COMPANY COMMERCIAL ELECTRIC VEHICLE RATE PROPOSAL PREPARED TESTIMONY, Electric Power Research Institute, *Nov 5, 2018*

Response to Reviewers' Comments from 2018 AMR

- *This project is not an applicable solution for the current fast-changing environment because it is overly complicated and oversized, and noted that by the time it could become any kind of marketable solution, it will be outdated.*

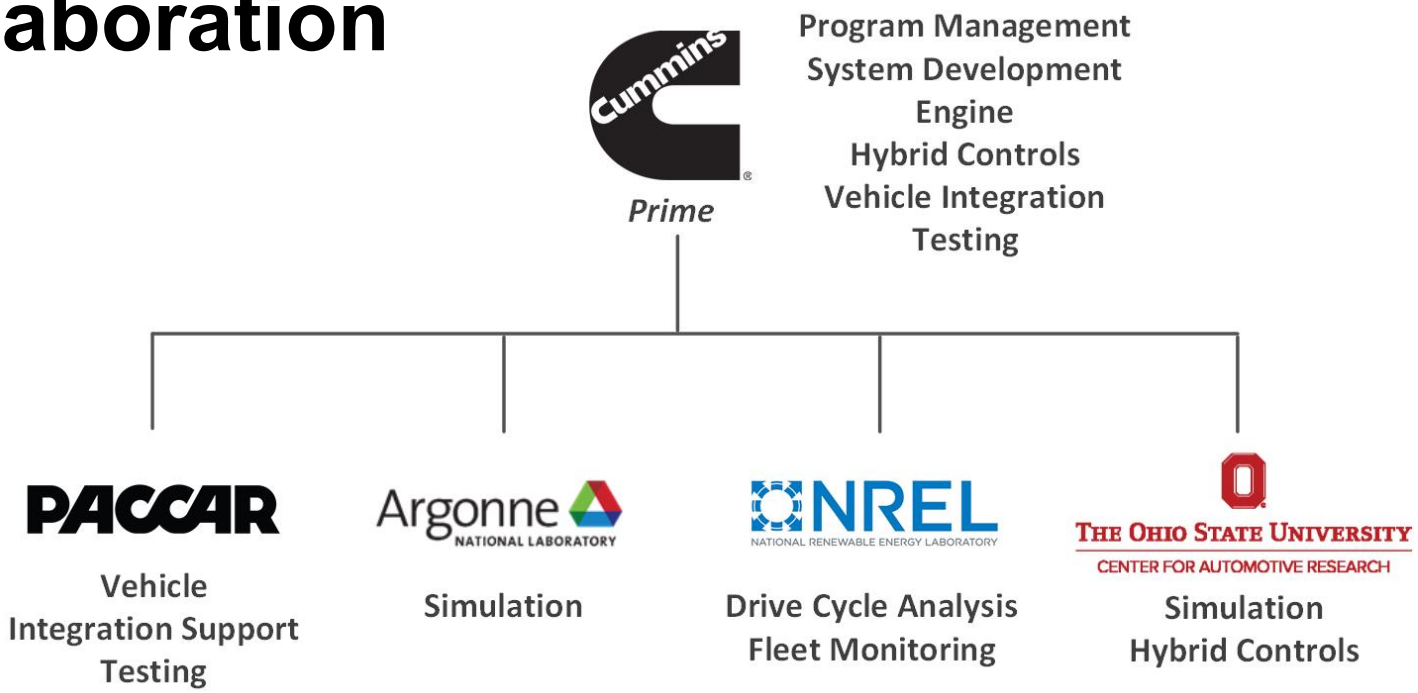
We believe the architecture is simple: a high energy battery with series range extender. We agree many of components are oversized (and too costly) for production, however, more appropriately sized (and cost effective) components are becoming available and can be selected for production. The controls, architecture and, most importantly, learning about customer requirements & how this system will meet their needs are all applicable. We believe an electric truck w/ an appropriately sized, cost effective range extender (operated on easily available fuel unlike H2 and not requiring substantial electric grid infrastructure improvements unlike fast charging) has a very good potential to be a part of the solution in meeting fleet customer electrification needs.

- *The reviewer commented that the project team needs to overcome the battery concerns, and added that the project did not address the potential performance concerns under cold weather conditions.*

Updated battery has continued to pass its validation tests including limited cold weather operation (overnight cold soak < -10degC); however, as previously described (slide 10), range extender can be used to augment current to traction motor if battery current limited after cold soak

- *A couple comments regarding needing a better explanation of commercial viability* ***[see previous slide]***

Collaboration



Key Suppliers	Allison Transmission - transmission, stop-start system
	WABCO - electronic braking system
	Analytical Engineering, Inc. - vehicle build assistance
	Southwest Research Institute - J1526 testing resources
	Morgan Corporation - van body
	Battery Innovation Center - battery testing

- Trucking industry outreach with Greater Indiana Clean Cities in Q3 2019

greater Indiana clean cities coalition

All logos courtesy of their respective owners.

Remaining Challenges & Future Research

- Truck 1
  - SwRI Uvalde, TX test track J1526 (6/2019)
    - Translation of NREL 80 to test track cycle
    - Budget Period 2 Go/no-go milestone
  - Continued testing at Cummins
    - Portable emissions measurement system (PEMS)
    - Range extender virtual downsizing
    - Electronic braking system (EBS) validation
  - PACCAR Technical Center (10/2019)
- Truck 2: Frito-Lay, Indianapolis (7/15/2019 – 6/30/2020)
  - Investigate use of electric-only operation in certain geographic areas (“geo-fencing”)
- Analysis & Future Research
  - Range extender sizing study per class of truck, duty cycles, batteries, geo-fencing requirements, etc.
  - Continued research on state-of-charge management using fleet management data, traffic, weather, etc.

(1)

(2)

1, Courtesy of Southwest Research Institute
2, Courtesy of PACCAR Inc.

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

Summary

- Team has developed an electrified powertrain capable of meeting the project objectives
  - Delivers greater than 50% fuel consumption reduction for a wide range of class 6 pickup and delivery drive cycles with substantial EV-only capability
  - Comparable performance to conventional Kenworth K270
  - Verified, in powertrain test cell testing & preliminary vehicle testing, fuel consumption reduction target can be achieved
- Vehicle testing is progressing to meet Budget Period 2 go / no-go milestone of J1526 testing with Southwest Research Institute
- Deployment to PepsiCo/Frito-Lay in Q3 2019

Technical Papers

(1) *Duran, A., Le, 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.*

(2) *Arasu, M., Ahmed, Q. and Rizzoni, G., "Battery discharge strategies for Energy Management in electrified trucks for Pick-Up & Delivery application", ASME 2018 Dynamic Systems and Control Conference, DSCC2018-9116, 2018.*

(3) *Arasu, M., Ahmed, Q. and Rizzoni, G., "Optimizing Battery Cooling System for a Range Extended Electric Truck", SAE Technical Paper 2019-01-0158, 2019.*

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

Q+A


Cummins