Long-Range Battery Electric Vehicle with Megawatt Wireless Charging

Project ID: elt262

Principal Investigator:
Brian Lindgren
Kenworth Truck Company

DOE Vehicle Technologies Program
2021 Annual Merit Review

Overview

Timeline
- Start Date: 1 Oct 2019
- End Date: 12 Dec 2022
- 50% Complete

Budget
- Total Project Funding: $8M
- DOE share: $5M
- Partner Cost Share: $3M

Barriers
Broad acceptance of battery-electric power for heavy trucks is hampered by:
- Range
  Typical today is 100-150 miles/day
- Re-Charge Time
  Typical today is 2-10 hours

This project will research, develop and demonstrate a Class 8 tractor and charging system capable of two-shift operation exceeding 400 miles per day. The tractor will have range of up to 200 miles and can be recharged in 30 minutes.

Project Partners
A strong and diverse team has been assembled:
- **Kenworth Truck Company** – Heavy Truck OEM
- **UPS** – Global Transportation & Logistics Fleet
- **Utah State University** – Academic Institution with Extensive Wireless Charging Expertise
- **WAVE** – Technology Startup Producing & Deploying Wireless Chargers For Heavy Vehicles
- **Seattle City Light** – Local Government-Owned Utility
- **Portland General Electric** – Local Public Utility
- **Romeo Power**– Battery System Manufacturer

Relevance

Impact

Heavy-Duty BEVs are struggling to gain acceptance by trucking fleets.

- Increasing the range of heavy trucks will allow fleets to more easily **integrate BEVs into daily routes**
- Reducing the charge time will allow fleets to **operate BEVs in two-shift operations**
- Minimizing battery size while maximizing daily range will allow a **smaller increase in initial purchase price** and a **smaller reduction in payload capability** compared with today's diesel powertrains
- Wireless power transfer will allow **safe and efficient** extreme fast charging with **minimal driver interaction** (no large, heavy cable to wrestle)

Objectives

- **Reduced energy use** throughout the BEV system to improve kW-h/mile
  - Baseline test vehicles were measured at an average of 2.65 kW-h/mile
  - System efficiencies in traction motor/inverter, power steering, air compressor and thermal management were explored and will be validated
- **Megawatt-rate wireless power transfer**
  - Design and demonstrate safe and efficient wireless charging at megawatt rate
  - Develop batteries and charge profile to allow adding 170+ miles of freeway range in 30 minutes

Milestones

Target	Description	Achieved	Responsible
Sep 2020	Design parameters for the single-stage AC-AC converter	Oct 2020	USU
Dec 2020	Preliminary infrastructure plans for charging sites	Dec 2020	USU, WAVE, UPS, SCL, PGE
Dec 2020	**Go/No-Go** Proof-of-Concept charger operation to validate the coil design, control system function, and thermal management	Mar 2021	USU
Mar 2021	Chassis layout: location of components, weight distribution, and high-voltage cable routings	Mar 2021	KW
Jun 2021	Charging site equipment design is completed	At risk	USU, WAVE, UPS, SCL, PGE
Sep 2021	Key charger components characterized and validated	On target	USU, WAVE
Dec 2021	Grid electrical power supply in place at charging sites	On target	SCL, PGE
Dec 2021	**Go/No-Go** Demonstrate full-scale megawatt wireless charger system in off-vehicle operation	At risk	USU, WAVE
Mar 2022	Vehicle is assembled and fully operable	On target	KW
Jun 2022	Demonstration of the system operation with one megawatt wireless charging on site	On target	(All)
Sep 2022	Confirm operations exceed 400 miles per day	On target	(All)

KW: Kenworth

PGE: Portland General Electric

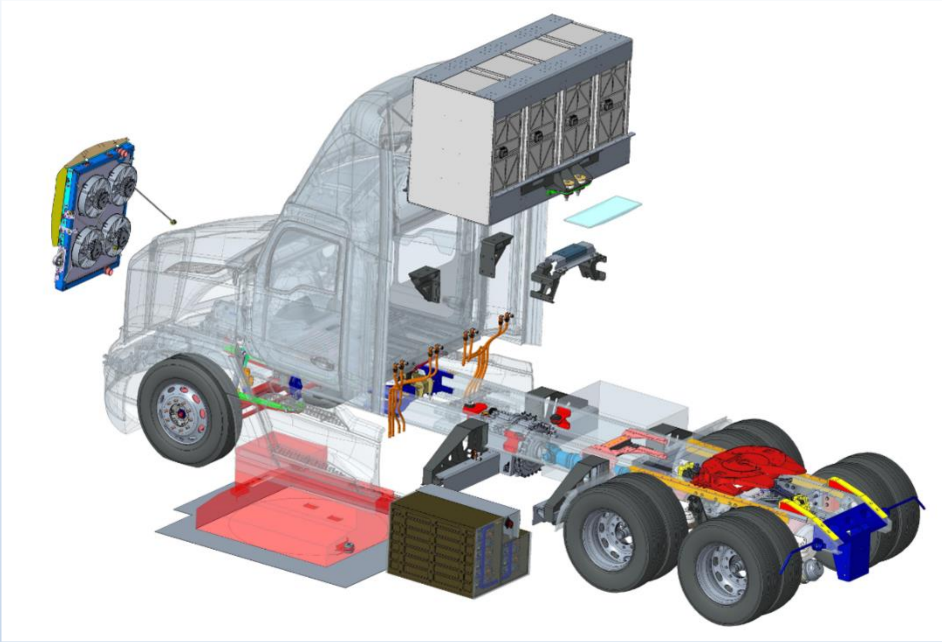
SCL: Seattle City Light

USU: Utah State Univ

Approach

Develop a Class 8 BEV tractor optimized for regional-haul use and wireless extreme fast charging

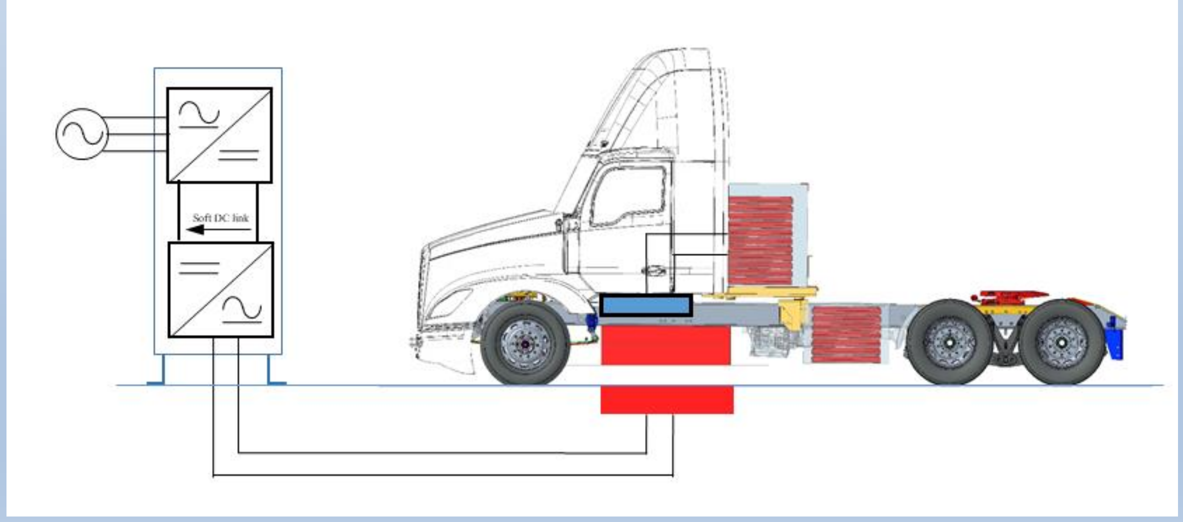
- Usable energy of >500 kW-h allows range up to 200 miles on a single charge
- Fast-charge capability at up to 1.5C rate allows up to 400 miles per shift and 2-shift operation



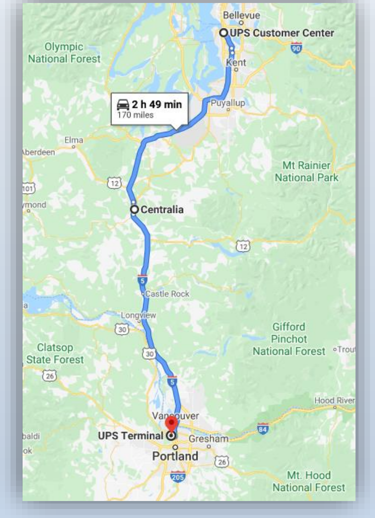
Develop a wireless charging system capable of safely & efficiently charging at up to megawatt rate

- Megawatt wireless charging supports 1.5C rate, allows re-charge on driver's lunch break
- Engineered magnetic field containment ensures system meets ICNRP safety standards
- DC-DC efficiency expected to be 92-95%

ICNRP = International Commission on Non-Ionizing Radiation Protection



Previous Accomplishments

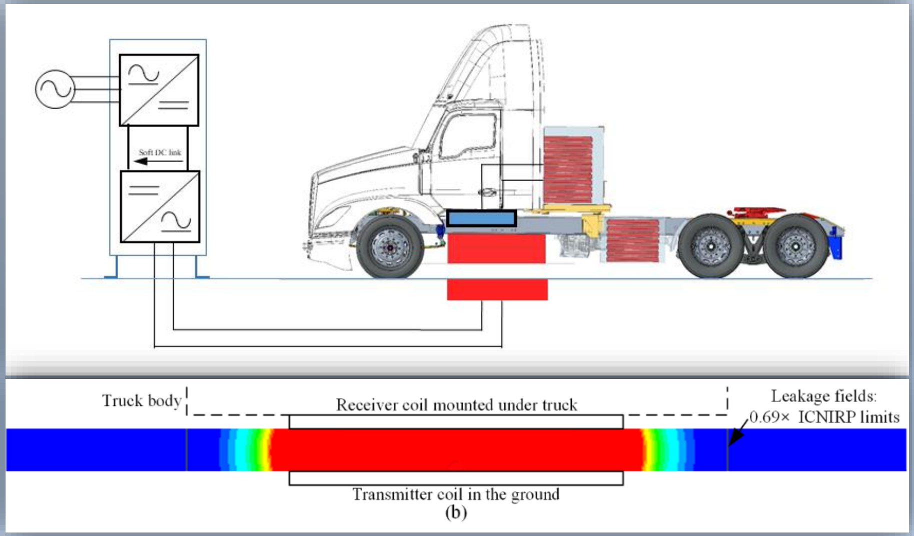


Energy Storage Requirements:

- Obtained data from Seattle to Portland in range-extended electric tractor-trailer
- Included power requirements for the traction motor system plus all accessory drives such as cooling pumps and fans, power steering, air compressor, HVAC, etc.
- Conservative value for energy consumption one-way Seattle to Portland = 462 kW-h
- Selected battery system capacity of 660 kW-h
  - One-way energy use is <70% of total capacity: allows operation between 20% SOC and 90% SOC
  - Megawatt charging yields 1.5 C-rate, which is upper end for NMC cells

Magnetics & Electronics Design and Simulation:

- Significant simulation and investigation
- Design meets vehicle parameters and charging requirement
- ANSYS simulation results yield path forward for a scaled prototype pad and shield
- Development and testing plans complete
- Initial weight and space calculations complete

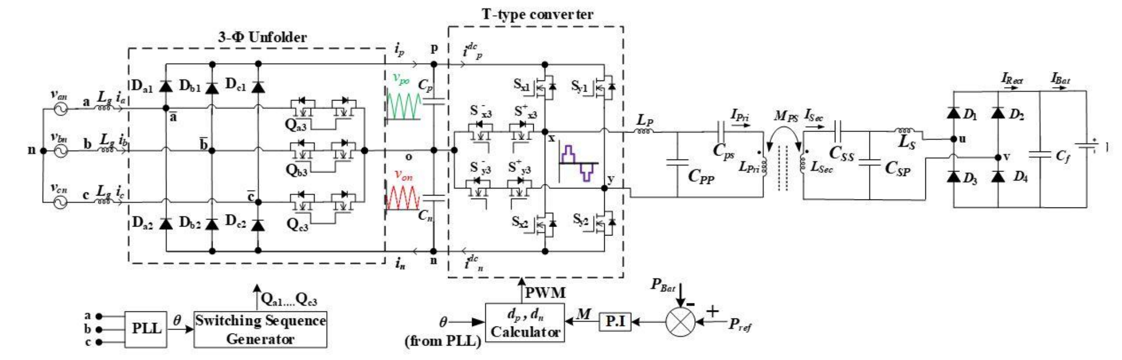


Magnetic Field Plot Showing Leakage Meets ICNRP Regulations

Accomplishments- Wireless Charger Design

Key system parameters:

- 660 kWh battery @ 1.5 C charging rate
- 390 to 475 kWh of energy in 23 to 29 minutes @ 1 MW
- 480V 3-φ AC input (Grid voltage)
- 649 V –755 V DC output (Battery voltage)
- 8 inverter modules x 125 kW per module
- >90% targeted efficiency
- Leakage fields <15 µT (ANSI 14117 standard)
- Air gap of 300 mm
- Receiver weight < 3125 lbs

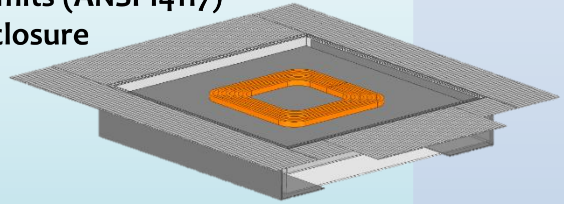


Unfolder + T-type converter

- Single stage AC-AC
- High Efficiency
- No bulky DC link capacitors

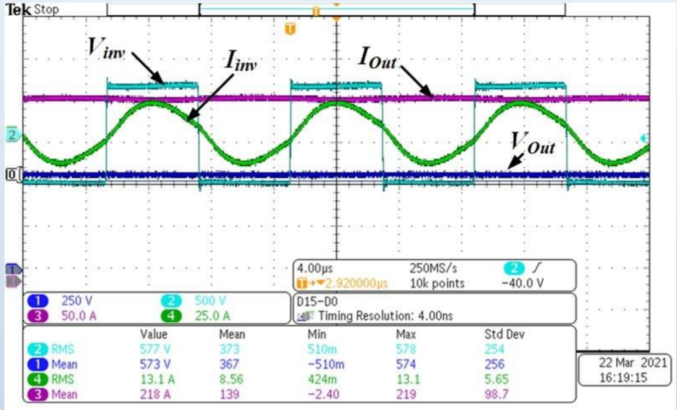
Magnetics design:

- Key design features
  - Power transfer achieved at large air gap (300 mm)
  - Meets public safety field exposure limits (ANSI 14117)
  - Integrated electronics in the pad enclosure
  - Allocated pad space: 5' x 5'
  - Estimated weight < 3125 lbs
  - Operating frequency: 85 kHz
- Key innovations:
  - Developed new optimization method that considers circuit topology and magnetics design to find optimal designs for maximum performance
  - Design avoids complex interleaving which significantly simplifies cooling design
- Designs evaluated:
  - Active field cancellation vs passive field cancellation
  - Various aluminum shield designs to minimize impact of truck chassis

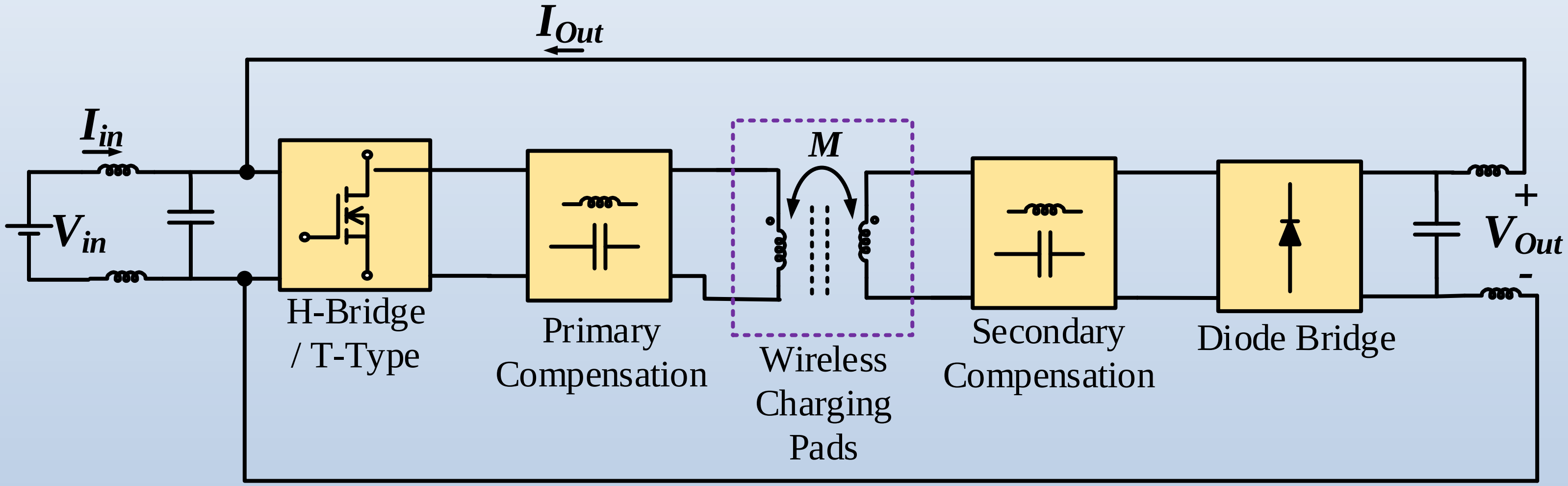


- **Matching battery charge profile required 8 modules vs 4.**
- **Established all component parameters in design phase.**

Accomplishments- Wireless Charger Testing



Parameter	Value
V_{out}	573 volts
I_{out}	218 amps
Output Power	125 kW
Losses	9.66 kW
DC-DC Efficiency	93%



- **Successfully tested one module (125kW) through charge plates.**
- **Achieved 93% DC-DC efficiency in initial test**

Accomplishments- Battery Charge Profile

Charge Profile:

- CP-CV (Transition at 72.5%SOC or 45oC or 0.9C) / 0.9C CC-CV
- CP-CV Maximum Current Limit of 1.5C
- Peak CV Charge Setpoint 4.1V/cell
- 0.9C Peak CV Charge Setpoint at 4.15V/cell

Conditions

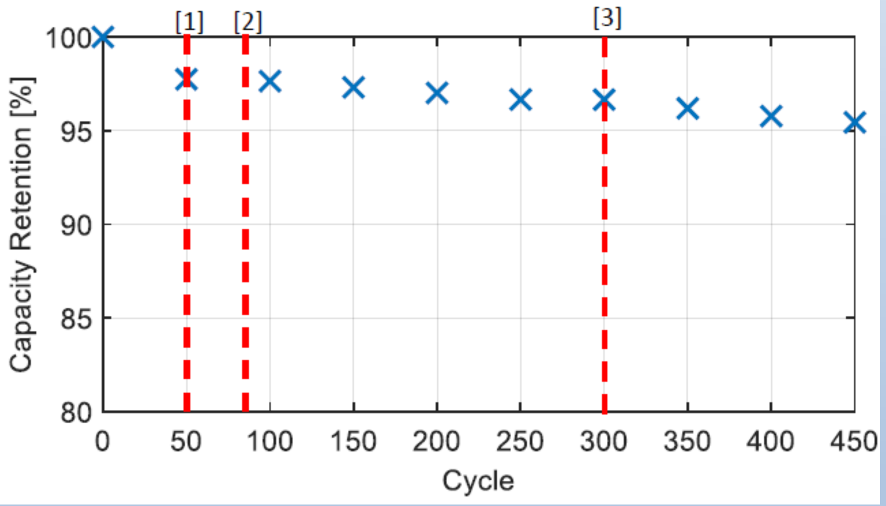
- Tested one 11-kW module (total system will comprise 66 modules) – results for total pack are extrapolated
- 25°C Initial Temperatures for Cells and Coolant
- 25°C Ambient
- 2.5 LPM Coolant Flow Rate

SOC = State Of Charge
CC = Constant Current
CV = Constant Voltage
CP = Constant Power

ROMEOPOWER

Initial SOC (%)	Total Charge Time
10	29.78 min.
15	34.52 min.
20	47.01 min.

Aging test data



- **Successfully demonstrated capability to achieve 462 kW in 30 minutes or less**
- **Determined cooling requirements for charge cooling**

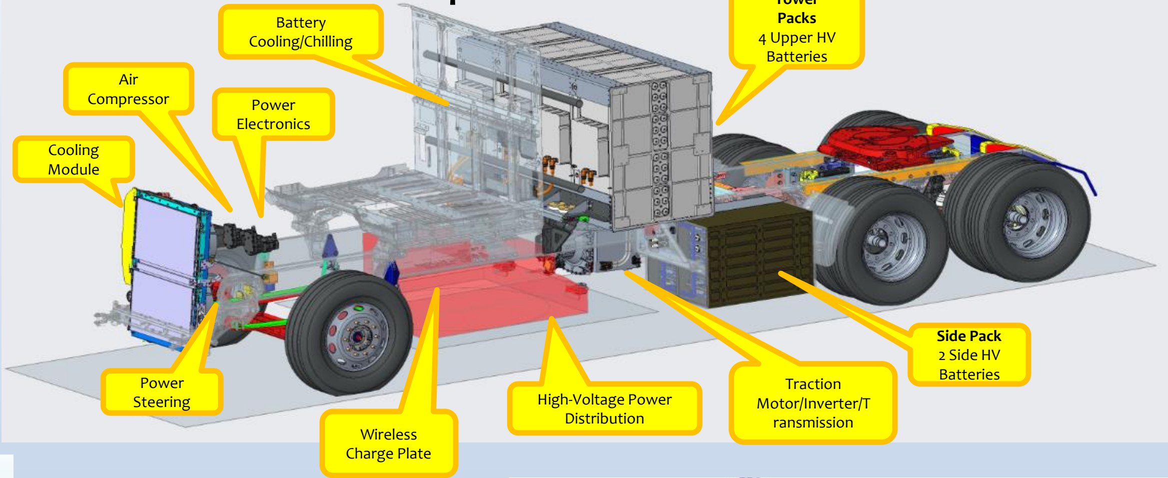
Accomplishments- BEV Design

Key vehicle attributes:

- Kenworth mode: T680 Daycab
- Wheelbase: 220”
- Traction motor power: 350 kW continuous
- Two voltage buses: 650V and 12V. All components >1 kW are 650V
- Estimated tare weights:

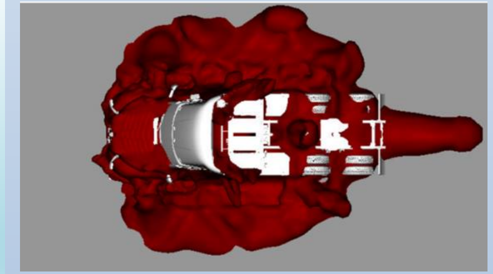
Front	13,000 lbs
Rear	14,000 lbs
Total	27,000 lbs

Chassis component locations

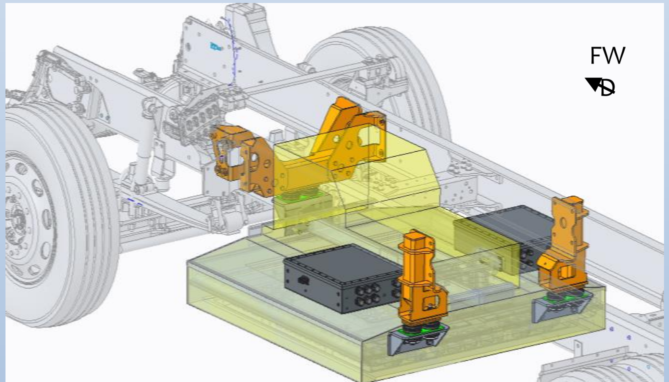


Thermal systems attributes:

- One WEG radiator; 2 refrigerant condensers; 1 large 650V fan
- Batteries cooled by chilled Water/Ethylene Glycol (WEG), each of 6 packs in parallel
- Cab HVAC shares refrigerant with battery system; heaters separate
- Charger cooled by WEG radiator; simulation shows adequate cooling when charging at 1 MW rate



Airflow during charging



Charge plate mounting

Current status:

- All components on order; many received
- Chassis is being fitted with components
- Pacing item is motor/inverter/transmission – expected mid-June

- **Tractor is expected to be drivable in August 2021**

Prior AMR Comments/Questions

Was energy consumption from SuperTruckII used in this project?

- No, because we needed energy consumption for a specific route (Seattle to Portland and return). A range-extended electric truck was driven on the route, and electrical energy consumption measured. SuperTruckII data were used as a comparison to ensure that results were reasonable.

It was not clear why wireless charging is preferred at this level of power transfer and vehicle specialization.

- Cable-connected charging at megawatt rate was expected to require a very large cable size (for 1500+ amps), and was expected to need to be a cooled cable. A cooled connector would need to be developed. High-Voltage, High-Current connections may require an electrician to connect, especially at union facilities. Wireless charging avoids these issues.

The cost of the battery and the incremental wireless infrastructure looks cost prohibitive

- Cost remains a concern. The battery system chosen utilizes high-production-volume NMC cells, a choice intended to optimize battery cost, size and weight. Wireless chargers at lower rates have shown commercial advantages, but this remains to be uncovered during this project at megawatt rate.

Collaboration and Coordination

A strong and diverse team of partners has been established:

Kenworth Truck Co.
division of PACCAR – Prime Recipient
Heavy Truck OEM. Project leadership and vehicle devlopment

UPS
Global Transportation and Logistics Fleet.
Providing location for charging equipment; will operate test vehicle in fleet operations

Utah State University
Academic Institution with Extensive Wireless Power Transfer Expertise.
Wireless Power Transfer design & development

WAVE
Technology Startup Producing & Deploying Wireless Chargers for Heavy Vehicles.
Build and commercialize Wireless Power Transfer equipment

Seattle City Light
Local Government-Owned Public Utility.
Providing grid power and consultation at Seattle charging site

Portland General Electric
Local Public Utility.
Providing power and consultation at Portland charging site

Romeo Power
Battery Technology Company.
Battery development

Remaining Challenges and Barriers

Technical Challenges:

- Achieving the required energy transfer in the desired time without over-voltage or over-current in the battery system remains a concern. Early testing results indicate this can be achieved when the batteries are new; aging of the batteries may slow charge times.
- Thermal management of the batteries during charging is a concern. Simulation and analysis indicates the cooling system is properly designed, but testing may reveal unexpected issues.
- Electrical noise from the charger may affect CAN communications. Steps are being taken to reduce noise and to shield communication lines, but issues may arise once the full vehicle is in operation.
- Complete charging system efficiency including ground-side cooling and vehicle-side cooling may be low enough to reduce the attractiveness of this technology.
- This project will develop a proof-of-concept system of one BEV tractor and two wireless chargers for a total cost of $10M. Can this technology be produced at affordable costs when scaled to higher volumes?

Barriers:

- COVID has resulted in global component shortages and delivery delays. This has slowed progress in building the chassis and the charging system.

Proposed Future Research

2021 FY:

- Characterize the single stage AC-AC converter operation, transmitter coil and receiver coil, compensation tank and receiver diode bridge in terms of electric performance and thermal behavior.
- Complete the design and installation plans for each charger site (Seattle and Portland), and start the permitting process.
- Begin commercialization of the charging system.
- Complete the build of the vehicle and initiate functional testing (using 150 kW plug-in charger).

2022 FY:

- Complete the build of the charging equipment.
- Demonstrate the charging system off-vehicle at megawatt rate.
- Complete the installation of the grid power supply and charging equipment at each charging location.
- Install the charging receiver plate on the vehicle and validate power transfer to battery system.
- Commence commercial operations with the BEV tractor and wireless charging system.

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

Summary

Technical Accomplishments:

- Validated through physical testing that 462 kW-h of energy can be added to a 660-kW-h battery system in 30 minutes or less.
- Validated through physical testing that one inverter module (125 kW) can transmit power across a 300-mm [11.8 in] air gap at 93% DC-DC efficiency.
- Developed thermal management systems for the vehicle side to cool the charge plate, batteries, traction motor/inverter/transmission, auxiliary device motors and power electronics, in addition to cab HVAC. Conducted air flow and coolant flow simulations to show adequate cooling in expected worst-case scenarios.
- Completed vehicle layout and detail design drawings, and placed orders for all components.
- Developing vehicle control system to manage on-board components and systems – 50% complete.

(End of presentation)