NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL is a national laboratory of the U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

In-Use Fleet Evaluation of Fast-Charge Battery Electric Transit Buses

Robert Prohaska, Kenneth Kelly, and Leslie Eudy

Background

With support from the U.S. Department of Energy's Vehicle Technologies Office, the National Renewable Energy Laboratory (NREL) conducts real-world performance evaluations of advanced medium- and heavy-duty fleet vehicles. Evaluation results can help vehicle manufacturers fine-tune their designs and assist fleet managers in selecting fuel-efficient, low-emission vehicles that meet their economic and operational goals.

In 2015, NREL launched an in-service evaluation of 12 battery electric buses (BEBs) compared to conventional compressed natural gas (CNG) buses operated by Foothill Transit in West Covina, California. The study aims to improve understanding of the overall usage and effectiveness of fast-charge BEBs and the associated charging infrastructure in transit operation. To date, NREL researchers have analyzed more than 148,000 km of in-use operational data, including driving and charging events.

Foothill Transit purchased the BEBs with grant funding from the Federal Transit Administration's Transit Investments for Greenhouse Gas and Energy Reduction Program.

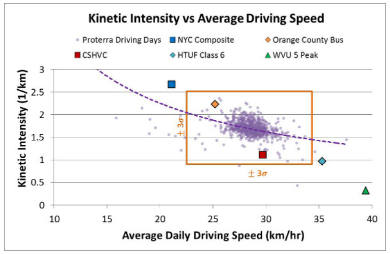
Data Collection, Analysis, and Reporting

Proterra provided NREL with 148,605 km of 2-Hz in-use operation data from 12 BEBs in the Foothill Transit fleet. These data were from four separate time periods to balance out the potential effects of seasonality and changes in ridership.

NREL's data analysis results are published in technical reports, conference papers, and online at *www.nrel.gov/transportation/fleettest.html*. Project data are also stored in the Fleet DNA clearinghouse at *www.nrel.gov/fleetdna*, allowing for comparison of vehicle performance across platforms, vocations, and projects.

Drive Cycle Characterization

One metric used to describe the drive cycle of a particular vehicle is kinetic intensity, a relative measure of driving aggressiveness based on the relationship between the energy used for vehicle acceleration versus the amount of energy used to overcome aerodynamic drag. Comparing daily average kinetic intensity to average driving speed, there is very little variation in the data set—99.7% of all the values fall within the orange rectangle representing values within ±3 standard deviations from the mean.



Kinetic intensity versus average driving speed for all BEBs, with standard test cycles shown

Test Vehicle Specifications

Bus Manufacturer	Proterra
Bus Model	BE35
Total Length	10.67 m (35 ft)
Total Height	3.28 m (10.75 ft)
Wheelbase	6.02 m (237 in.)
Curb Weight	12,555 kg (27,680 lb)
Gross Vehicle Weight Rating	16,928 kg (37,320 lb)
Passenger Capacity	35 seated and 18 standing
Battery Manufacturer/Model	Altairnano/TerraVolt 368
Battery Type	368-V lithium titanate
Battery Energy/Capacity	88 kWh/60 Ah
Number of Packs	8 (6 floor and 2 roof)
Motor Manufacturer/Model	UQM/PP220
Motor Power – Nominal	120 kW (161 hp)
Motor Power – Peak	220 kW (295 hp)
Fast-Charging Peak Power	500 kW
Cabin Air Conditioning	Thermoking REH-M6
Cabin Heater	11-kW electric resistance

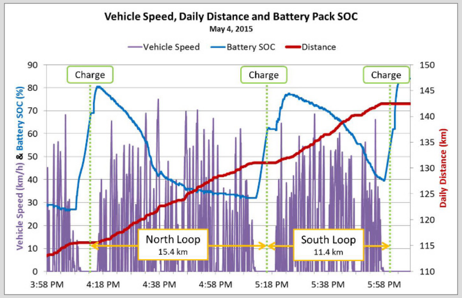
Proterra BE35 fast-charge BEB. *Photo by Leslie Eudy, NREL 36043*

GPS route data showing charging stations at Pomona Transit Center. *Photo by Robert Prohaska, NREL 37695*

Road Grade Impacts

This typical drive cycle speed trace for a BEB operating on Line 291 shows three separate charge events with an average duration of 5 to 6 minutes. The purple line shows the speed trace of the bus and the blue line shows the battery pack state of charge (SOC); both of these metrics use the left vertical axis. The red line, with the vertical axis on the right, shows cumulative distance. The change in slope of the battery SOC curve on the portion of the figure labeled "North Loop" shows varying discharge rates, which can be attributed to the modest road grade on Line 291, as the north end of the loop is approximately 92 m above the Pomona Transit Center.

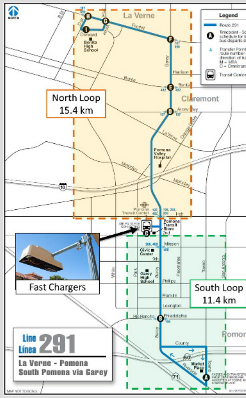
The first portion of the North Loop, starting at approximately 4:18 p.m. with a battery pack SOC of 80%, shows a faster discharge rate (steeper slope of the blue line) due to the bus gaining elevation. The second half of the North Loop has a slower discharge rate (shallower slope of blue line) as the bus returns to the Pomona Transit Center with a battery pack SOC of approximately 32%. While 92 m is not a significant amount of elevation change over 7.7 km (approximately half of the North Loop), there is a noticeable effect on the power required to operate the BEB, which demonstrates the importance of road grade when considering energy storage requirements.



Vehicle speed, battery pack SOC, and distance for one typical loop on Line 291, with three charge events shown

Foothill Transit's Line 291

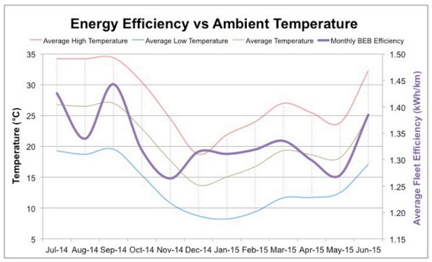
In 2014, Foothill Transit fully electrified one route in its service area—Line 291—and is investigating the feasibility of electrifying other routes as well. The transit agency's electric buses can fully charge in less than 10 minutes via two 500-kW fast chargers located midway along the 26.8-km route at the Pomona Transit Center. The buses are programmed for easy docking—wireless communications govern the speed and stop locations of the buses, and the overhead charger connects without input from the driver.



Ambient Temperature Impacts

The BEBs demonstrated an overall average efficiency of 1.34 kWh/km, which equates to 7.43 km per diesel liter. The overall fleet average efficiency includes the energy required to operate all accessory loads, such as the heating, ventilating, and air conditioning (HVAC) system, and fluctuates in response to average temperature.

The monthly BEB fleet efficiency fluctuates relative to average temperature, with efficiency dropping when temperatures are higher and air conditioning is used, and also when temperatures drop and electric heaters are used. The months of highest efficiency have average high temperatures less than 25°C and average low temperatures greater than 11°C, requiring the least amount of energy to maintain passenger thermal comfort.



BEB energy efficiency versus mean, mean maximum, and mean minimum temperatures.

Summary

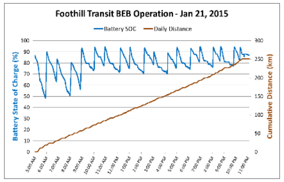
Study findings emphasize the importance of understanding how a vehicle's drive cycle (i.e., the kinematics or motion of the vehicle) and operating environment influence its overall duty cycle (i.e., operational cycle) and how that duty cycle impacts the overall performance of advanced vehicle technologies.

While the BEBs demonstrated an energy efficiency of 1.34 kWh/km, road grade and non-tractive energy demands, such as heating and air conditioning, can have a significant effect on overall energy efficiency and must be taken into account when determining the feasibility of deploying advanced technologies.

Optimization Opportunities Based on Battery SOC Data

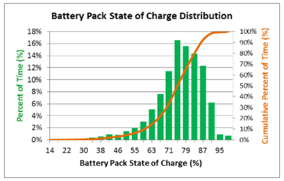
The BEBs are charged on route at the Pomona Transit Center an average of 12.5 times per day via overhead conductive chargers, transferring on average 19.48 kWh of energy per charge with an average charge duration of just 4.99 minutes. The average charging energy delivered equates to only 22% of the 88 kWh of total energy storage, indicating possible opportunities for battery pack downsizing, less frequent charging, or longer routes.

BEB docked at 500-kW overhead fast charger at Pomona Transit Center. *Photo by Leslie Eudy, NREL 36044*



Typical day of BEB operation on Line 291, showing average battery pack SOC and cumulative distance traveled

On a typical day, a single BEB travels 250 km and is charged 18 times, with the battery SOC never dropping below 45%. This charging behavior is consistent with the larger fleet operation where the average battery pack SOC is 75.4% and the battery pack rarely drops below 50% SOC. The battery pack SOC distribution curve in the graph on the left indicates opportunities to optimize deployment of the BEBs as the buses spend less than 6% of their time at an SOC less than 55%.



Vehicle-reported SOC for all BEBs over the entire data-reporting period

Operationally, the buses could be charged less frequently on route, which would allow drivers to get back on schedule if they are delayed. Systematically, there is a potential opportunity to reduce the size of the energy storage system on the vehicles running this particular route to reduce weight and purchase price.

Future Work

Future research will compare Line 291, which is serviced exclusively by BEBs, to a broader set of Foothill Transit routes using in-use data collected from conventional CNG buses randomly dispatched throughout the Foothill Transit service area. Through modeling and simulation, researchers will identify other routes suitable for electrification. In addition to benchmarking the operational efficiency of BEBs against CNG buses using in-field data, researchers will perform controlled chassis dynamometer testing to characterize efficiency over a range of drive cycles.

NREL also plans to further investigate the impacts of HVAC requirements on energy efficiency and identify areas for improvement.

Contact: Robert Prohaska
Robert.Prohaska@nrel.gov
www.nrel.gov/transportation/fleettest.html

The authors acknowledge Lee Slezak and David Anderson of the U.S. Department of Energy's Vehicle Technologies Office for their support.