County Connection Battery Electric Bus Demonstration—Preliminary Project Results

Overview of NREL Work

The U.S. Federal Transit Administration (FTA) funds a variety of research projects that support the commercialization of zero-emission bus technology. Recent programs include the National Fuel Cell Bus Program, the Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) Program, and the Low or No Emission Vehicle Deployment (Low-No) Program. To evaluate projects funded through these programs, FTA has enlisted the help of the National Renewable Energy Laboratory (NREL) to conduct third-party evaluations of the technologies deployed under the FTA programs. NREL is a U.S. Department of Energy (DOE) national laboratory focused on renewable energy and energy efficiency research.

NREL works with the selected agencies to evaluate the performance of the zero-emission buses compared to baseline conventional buses in similar service. The evaluation effort will advance the knowledge base of zero-emission technologies in transit bus applications and provide "lessons learned" to aid other fleets in incrementally introducing next generation zero-emission buses into their operations. NREL developed this preliminary-results report to quickly disseminate evaluation results to stakeholders. Detailed evaluation results will be published in future reports.

Fleet Profile—County Connection

County Connection—formally known as Central Contra Costa Transit Authority (CCCTA)—is a public transit agency that provides fixed-route and paratransit service in the San Francisco Bay Area. Headquartered in Concord, California, County Connection provides transit service to 11 surrounding jurisdictions, including Clayton, Concord, Danville, Lafayette, Martinez, Moraga, Orinda, Pleasant Hill, San Ramon, Walnut Creek, and unincorporated central Contra Costa County. The service area covers approximately 200 square miles and contains more than 482,000 residents. The agency operates 25 weekday routes (including 7 express routes) and 10 weekend routes with a fleet of 121 transit buses.

County Connection Battery Electric Bus Project

County Connection was awarded a grant from the FTA in 2012 as part of FTA's Clean Fuels Grant Program. The $4.32 million grant was used to purchase four all-electric Gillig buses and two electric vehicle charging stations. The four trolley-replica electric buses operate on Route 4—a free circulator route through downtown Walnut Creek with a layover stop at the Bay Area Rapid Transit (BART) station. The buses replaced a fleet of diesel trolley replicas that had reached the end of their expected service life. FTA awarded a 2016 Low-No Program grant to County Connection to purchase four additional electric buses to expand the service. These buses are expected for delivery in early 2018.

Bus Technology Descriptions

County Connection's battery buses are 29-ft trolley-replica buses built by Gillig with a BAE Systems electric propulsion system. The agency installed two charging stations: plug-in chargers at the facility for overnight charging and a WAVE inductive charging pad at the BART stop on the Walnut Creek route for wireless charging during scheduled layovers at this stop. The 50-kW WAVE charger uses inductive power transfer between a power-transmitting plate embedded in the road surface and a receiving plate mounted to the bottom of the bus.[1]

NREL is collecting data on two diesel bus fleets as baseline comparisons: a fleet of seven model year 2014 Gillig diesel buses and a fleet of three model year 2002 Gillig trolley-replica diesel buses. Table 1 provides selected specifications for each bus type.

Performance Evaluation Results

The results presented here focus on data from the evaluation clean point established in June 2017 through December 2017. The primary baseline comparison is the fleet of model year 2014 diesel buses. This conventional bus fleet is County Connection's best match to the battery bus fleet with respect to size and age. These buses are randomly dispatched on all routes and therefore have a different duty cycle than the battery buses operating only on the Walnut Creek route. The older diesel trolley-replica buses have been operated on the Walnut Creek Route since 2002 and therefore are the best match to the battery buses in duty cycle, which is important for the fuel economy comparison.

Bus Use and Availability

Bus use and availability are indicators of reliability. Lower bus usage may indicate downtime for maintenance. Since first going into service the battery bus fleet has accumulated more than 48,000 miles. Figure 1 shows the average mileage per month for the battery and diesel bus fleets. The average monthly mileage for the data period is 993 miles for the battery buses and 2,246 miles for the diesel buses. This difference is due

Table 1. System Descriptions for the Battery, Diesel, and Diesel Trolley Buses

Vehicle System	Battery	Diesel	Trolley
Number of buses	4	7	3
Bus manufacturer	Gillig	Gillig	Gillig
Bus year and model	2016	2014 29x102	2002 20x102
Length (ft)	29	29	29
GVWR (lb)	34,500	30,000	30,000
Motor or engine	BAE Systems, HDS200	Diesel engine, Cummins ISL-9	Diesel engine, Cummins ISL-280
Rated power	160 kW nominal, 200 kW peak	280 hp @ 2,200 rpm	280 hp @ 2,000 rpm
Energy storage	Xalt, nickel manganese cobalt, 100 kWh	None	None

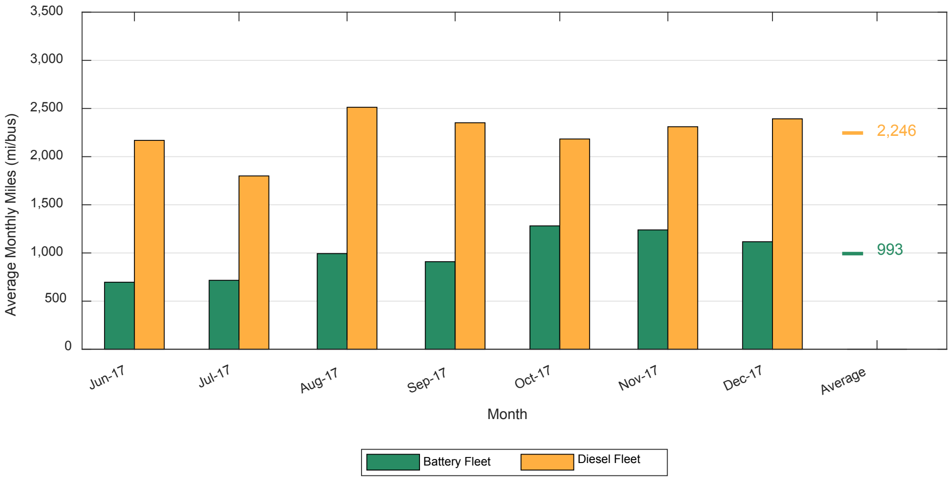

Figure 1. Average monthly mileage per bus for County Connection's battery and diesel bus fleets

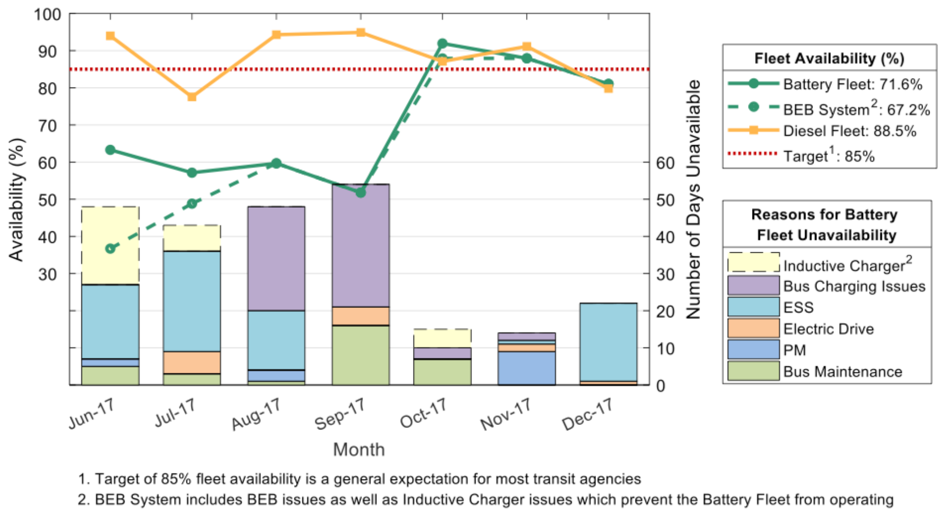

Figure 2. Monthly availability for the battery and diesel fleets and reasons for unavailability for the battery fleet

[1]WAVE projects web page: http://wave-ipt.com/projects/

to the planned operation of the two fleets on different routes and does not indicate a limitation of the battery bus technology. The Walnut Creek route is a slow-speed circulator route, which results in lower mileage accumulation than on other routes.

Availability is measured as the percentage of days the buses are available for service out of days that the buses are planned for operation. Transit agencies typically target 85% availability for their fleets to allow for time to handle scheduled and unscheduled maintenance. County Connection's planned operation for the battery bus fleet is 7 days per week; the diesel buses are primarily operated on weekdays.

The line series in Figure 2 show the monthly availability for the battery and diesel bus fleets. The overall availability is 71.6% for the battery bus fleet and 88.5% for the diesel fleet. The stacked columns in Figure 2 display the number of days of unavailability by category for the battery fleet only. During the early portion of the evaluation, County Connection experienced several issues with the on-route inductive charging system. County Connection considers the battery buses and on-route charger part of a system—when the inductive charger is not available, the buses cannot operate. Figure 2 includes a green dashed line to show the monthly availability of the battery electric bus (BEB) system, and the category of inductive charger is included in the list of reasons for unavailability. When the buses and charger are combined as a system, the overall availability is 67.2%. The availability has increased over time as the team has addressed the early implementation issues. In addition to the inductive charger issues, County Connection had problems with the battery management system on two buses. Software updates appear to have addressed the issue.

Figure 3 shows the overall fraction of time the buses were available for service as well as the fraction of unavailable days, categorized by vehicle system, for each bus fleet. For the battery fleet, the primary issues causing unavailability were the energy storage system (ESS) followed by charging issues. Most of the downtime for the diesel buses was split evenly between preventive maintenance (PM) and general bus maintenance, followed by a few engine issues.

Reliability

The transit industry measures reliability as mean distance between failures, also documented as miles between roadcalls (MBRC). Table 2 provides the MBRC for the battery and diesel buses categorized by total roadcalls and propulsion-related roadcalls. Total roadcalls include all chargeable roadcalls. Propulsion-related roadcalls

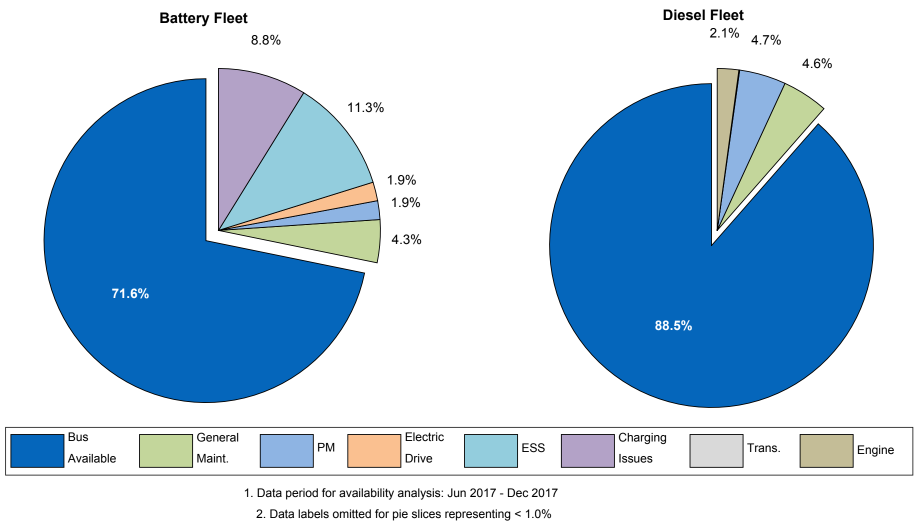

Figure 3. Overall availability for the battery fleet and diesel fleet

Table 2. Roadcalls and MBRC

	Battery	Diesel
Total mileage in data period (Jun-Dec 2017)	27,809	110,042
Average miles accumulated per bus	6,952	15,720
Total roadcalls	10	3
Overall MBRC	2,781	36,681
Propulsion-related roadcalls	7	1
Propulsion-related MBRC	3,973	110,042

A roadcall, or revenue vehicle system failure, is defined as a failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule. If the problem with the bus can be repaired during a layover and the schedule is kept, this is not considered a roadcall. The analysis described here includes only roadcalls that were caused by "chargeable" failures. Chargeable roadcalls include systems that can physically disable the bus from operating on route, such as interlocks (doors, air system), engine, or things that are deemed to be safety issues if operation of the bus continues. They do not include roadcalls for things such as problems with radios, fareboxes, or destination signs.

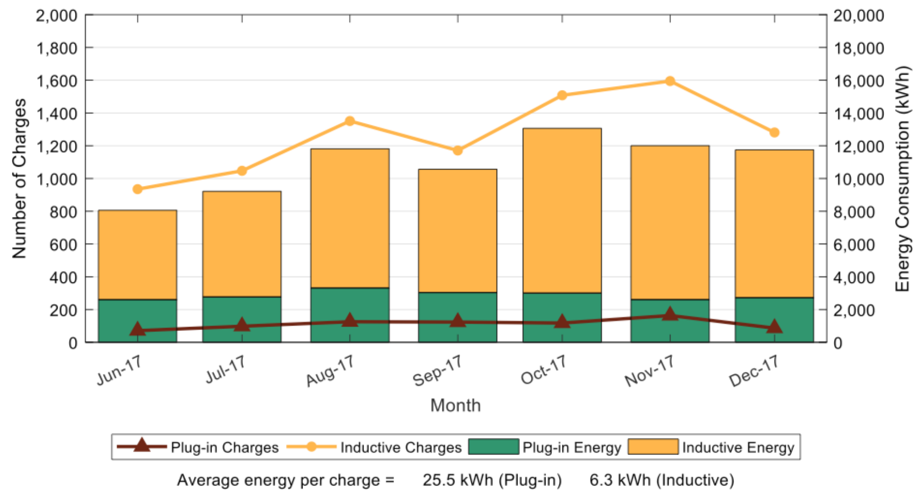

Figure 4. Monthly total energy use and number of charges for the battery fleet

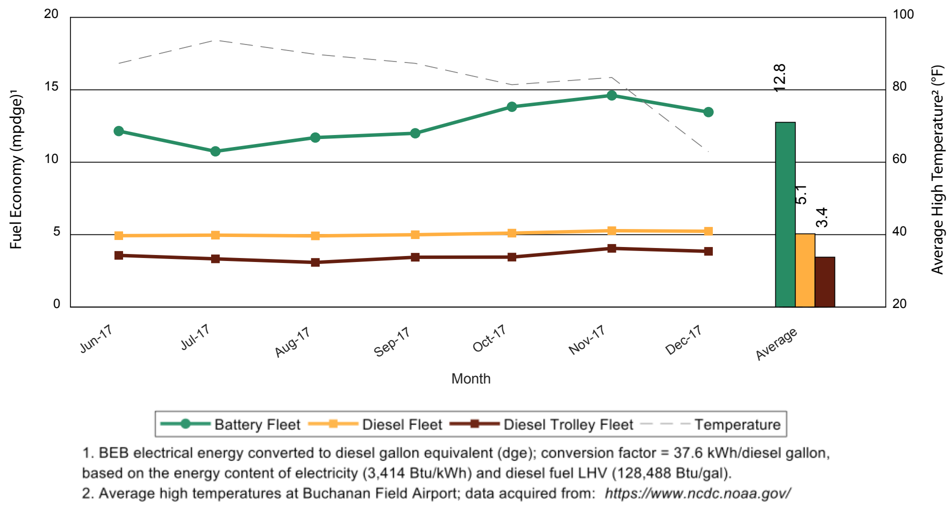

Figure 5. Monthly average fuel economy for the battery, diesel, and diesel trolley fleets

include all roadcalls due to propulsion-related systems including the battery system (or engine for a conventional bus) and the electric drive, fuel, exhaust, air intake, cooling, non-lighting electrical, and transmission systems.

DOE and FTA have not established performance targets specific to electric drive buses; however, the MBRC targets for fuel cell electric buses are based on typical conventional buses and could be considered appropriate for any advanced technology. The ultimate target for bus-related MBRC is 4,000. At this point in the project, the battery buses are still below the overall MBRC target. This is partly due to low mileage accumulation, in which case a single roadcall has a major effect on the MBRC.

Energy Use and Fuel Economy

County Connection's battery fleet is charged each night at the depot through a plug-in charger and receives supplemental charging at the inductive charger on the Walnut Creek circulator route. Figure 4 shows the total energy consumption and number of charges by month, separated by inductive and plug-in charging. The battery buses receive 74% of their energy from the on-route inductive charger.

Figure 5 shows the monthly average fuel economy, in miles per diesel gallon equivalent (mpdge), for the battery, diesel, and diesel trolley fleets. To compare the fuel economy of the bus fleets on an equivalent energy basis, NREL converted kWh of electricity to diesel gallon equivalent (dge) using a conversion factor of 37.64 kWh/diesel gallon. The monthly average high temperature is included in the figure as a reference for seasonal variations in the fuel economy that occur due to additional heating or cooling on the bus. The figure includes monthly fuel economy for both diesel baseline bus types. The standard diesel fleet is randomly dispatched on all routes. The overall system speed for County Connection is 14.8 mph including express routes. The battery buses and diesel trolley buses operate on County Connection's slowest-speed route at 6.1 mph. Because it operates at a similar speed to the battery fleet, the diesel trolley fleet represents a better comparison of conventional bus fuel economy to battery bus fuel economy, despite the difference in age. NREL analyzed fuel economy data for the diesel trolley buses from 2002 to 2007 to ensure there was no significant age-related decline in average fuel economy for the fleet that would adversely impact this comparison.

The battery buses use an average of 2.95 kWh of energy per mile, which equates to a fuel economy of 12.8 mpdge. The battery fleet's fuel economy is 3.8 times higher than that of the diesel trolley buses operated on the same service route and 2.5 times higher than that of the diesel buses operated on all the County Connection routes.

Operation and Maintenance Costs

NREL collected all work orders for the battery and diesel fleets to analyze the maintenance costs. Accident-related repairs, which are extremely variable from bus to bus and not related to propulsion technology, were eliminated from the analysis. Maintenance work covered under warranty was also removed from the calculations. For consistency, the maintenance labor rate was held at a constant $50 per hour; this does not reflect an average rate for County Connection. Table 3 shows the maintenance costs by vehicle system for each bus fleet. The systems with the highest percentage of maintenance costs for the battery electric and diesel buses, in order from greatest to least, were cab, body, and accessories; propulsion-related maintenance; and PM inspections.

The most important comparison is the propulsion-related costs because the propulsion system is the primary difference between fleets. The propulsion-related category includes repairs for engine, fuel, exhaust, electric motors, battery modules, propulsion control, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, and transmission. The propulsion-related cost per mile for the battery buses was 37% lower than that of the diesel buses. PM inspection costs include the labor for scheduled maintenance. Costs for the other systems should be similar from fleet to fleet.

NREL also analyzed data on the cost of operation for the battery and diesel buses. Operation costs include the energy cost of the buses—fuel for the diesel buses and electricity for the battery buses. Figure 6 shows the monthly per-mile costs for the two bus fleets. The stacked bars separate the costs for fuel and maintenance. Although the battery buses have much better equivalent fuel economy, the electricity costs (at $0.79/mi) are twice as much, on a per-mile basis, as the diesel fuel costs (at $0.37/mi). During the evaluation period the average diesel price was $1.86/gal while the average electricity price was $0.23/kWh ($8.75/dge). Utility rates are the same for on-route charging and in-depot charging, but the rates vary seasonally. Base rates for electricity consumption are approximately $0.25/kWh for summer months (May through October) and $0.19/kWh for winter months (November through April). County Connection is not subject to electricity demand charges on the current rate schedule.

Table 3. Maintenance Costs by System

System	Battery		Diesel	
	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)
Cab, body, and accessories	0.11	*34*	0.14	*32*
Propulsion-related	0.08	*24*	0.12	*29*
PM inspections	0.07	*23*	0.07	*17*
Brakes	0.02	*5*	0.05	*12*
Frame, steering, and suspension	0.02	*5*	0.01	*2*
HVAC	0.01	*3*	0.02	*4*
Lighting	0.02	*5*	0.01	*1*
General air system repairs	0.00	*1*	0.01	*2*
Axles, wheels, and drive shaft	0.00	*0*	0.00	*0*
Tires	0.00	*0*	0.00	*0*
Total	***0.31***	*100*	***0.42***	*100*

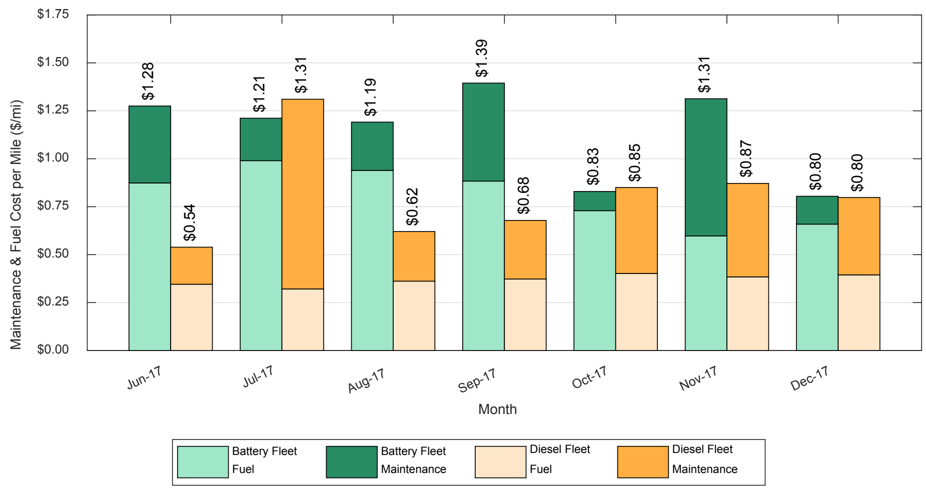

Figure 6. Monthly average maintenance and fuel cost per mile for the battery and diesel fleets

The monthly per-mile maintenance costs shown in Figure 6 include scheduled and unscheduled maintenance. During the data period, the overall average maintenance cost was $0.31/mi for the battery bus fleet compared to $0.42/mi for the diesel buses. The battery buses are under warranty and much of the maintenance work is handled by the manufacturer.

Future Analysis

County Connection will continue operating the four battery electric buses, and NREL plans to continue evaluating the in-service performance of the buses through one full year of operation. Future analyses will take a closer look at the utility costs, energy consumption and charging efficiency for the battery fleet. The full evaluation will also include detailed maintenance costs for all buses in the evaluation and a fleet-wise summary of the maintenance costs by vehicle system.

U.S. Department of Transportation
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Zero-Emission Transit Bus Evaluations

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