Duluth Transit Authority Battery-Electric Bus Evaluation

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1 National Renewable Energy Laboratory
2 Center for Transportation and the Environment

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Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5400-83038
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Suggested Citation
Jeffers, Matthew, Leslie Eudy, Erik Bigelow, Greg Olberding, and Amy Posner. 2022. *Duluth Transit Authority Battery-Electric Bus Evaluation*. Golden, CO: National Renewable Energy Laboratory. NREL/ TP-5400-83038. https://www.nrel.gov/docs/fy22osti/83038.pdf.

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This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Transportation Federal Transit Administration and the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photo by Nancy Brown: Duluth Transit Authority.

Acknowledgments

This report could not have been possible without the cooperation of Duluth Transit Authority, manufacturer partners, and others. Transit agency staff provided data on the zero-emission and baseline buses, reviewed analyses and reports, and participated in meetings to discuss the agency's overall experience. Manufacturers provided selected data and feedback and reviewed reports. The U.S. Department of Transportation Federal Transit Administration and the U.S. Department of Energy Vehicle Technologies Office provided funding for the evaluation. Staff from the Center for Transportation and the Environment (included as co-authors) facilitated data collection, contributed their analysis and explanations to this report, and were instrumental in capturing Duluth Transit Authority's experience and impacts of the battery-electric bus deployment. The authors thank the following individuals for their support of the evaluation:

U.S. Department of Transportation Federal Transit Administration
Mary Leary
Terrell Williams

U.S. Department of Energy Vehicle Technologies Office
Dennis Smith
Mark Smith

Center for Transportation and the Environment
Erik Bigelow
Greg Olberding
Amy Posner

Duluth Transit Authority
Nancy Brown
Jim Caywood
Jeffrey Dahlgren
Rod Fournier
Aleda Johnson
Carla Montgomery
Mark Ness
Greg Yardley

Proterra
Mike Finnern

List of Acronyms and Abbreviations

BEB	battery-electric bus
CTE	Center for Transportation and the Environment
dge	diesel gallon equivalent
DTA	Duluth Transit Authority
ESS	energy storage system
FTA	Federal Transit Administration
HVAC	heating, ventilating, and air conditioning
MBRC	miles between roadcalls
mpdge	miles per diesel gallon equivalent
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
SOC	state of charge
ZEB	zero-emission bus

Executive Summary

In 2018, Duluth Transit Authority (DTA) began operating a fleet of seven battery-electric buses (BEBs) in its service area of Duluth, Minnesota. DTA is collaborating with the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. The focus of the evaluation is to compare performance and cost of the BEBs to that of conventional technology in similar service and track progress over time. DTA enlisted the help of the Center for Transportation and the Environment (CTE) to manage the project and provide technical services with the BEB fleet and infrastructure. This report contains a combination of analyses performed by NREL and by CTE.

The BEBs operating at DTA are 40-foot Proterra Catalyst buses with a 440-kWh energy storage system (ESS). NREL also collected a subset of data on a conventional fleet of 10 GILLIG diesel buses of similar age as the BEBs for the primary baseline comparison to the BEB fleet. DTA equips all its buses with fuel-fired auxiliary heaters to aid in keeping the interior of the bus warm during cold months. Both the diesel and electric bus fleets have auxiliary diesel-fired heaters. DTA installed eight 50-kW charging stations along two lanes of its indoor facility to charge the fleet of electric buses.

DTA first deployed its BEBs in late 2018. Early deployment issues in 2018–2019, followed by service interruptions caused by the COVID-19 pandemic in 2020, resulted in periodic delays in data collection for this evaluation. The intent of each NREL evaluation is to cover at least one full year of service of the advanced-technology buses. Because of the delays, the data periods are not consistent for each key performance element provided in the report. This evaluation generally covers the BEB operation from late 2018 through spring 2021.

Table ES-1 summarizes the results of the evaluation for the BEBs and diesel baseline buses. For the analysis, NREL collected data from several sources including DTA staff, CTE staff, ViriCiti data loggers, and the utility provider.

Table ES-1. Summary of DTA Evaluation Results

Data Item	BEB	Diesel
Number of buses	7	10
Total mileage in evaluation period	218,526	450,497
Average monthly mileage per bus	1,115	4,095
Average bus availability (85% is target)	51.8%	88.4%
Average charger availability	95.3%	—
Fuel economy, electric only (kWh/mile) [a]	2.32	—
Fuel economy, including diesel (kWh/mile) [b]	2.64	—
Fuel economy (mpdge) [c]	14.23	4.86
Energy/fuel cost ($/kWh electricity; $/gal diesel)	0.141	1.84
Energy/fuel cost ($/mi) [d]	0.47	0.44

[a] Electric-only fuel economy based on electricity from chargers
[b] Combined fuel economy based on charger electricity and diesel fuel for auxiliary heaters
[c] Miles per diesel gallon equivalent
[d] BEB cost includes diesel fuel for auxiliary heater

DTA planned to begin deploying the BEBs on shorter blocks to allow the operators and other staff to became more familiar with the BEB technology performance and capabilities. During the school year, the BEBs would be used primarily on the UMD Circulator Route 23—a 5.5-mile circulator connecting the University of Minnesota Duluth to downtown. The agency planned to expand service for the buses over time, with a goal of random dispatch to cover all routes. The agency initially used the BEBs only during the week because the weekend blocks were longer, and they were unsure of the BEB's ability to meet the driving range of those longer blocks.

Since the first few BEBs began entering service, the BEB fleet accumulated almost 225,000 combined miles as of April 2021. The BEBs averaged 1,115 monthly miles per bus. This is lower than the baseline diesel bus fleet average of 3,640 monthly miles per bus.

During the evaluation period, the BEBs were dispatched for morning service, returned to the depot, and then dispatched again for afternoon service. The diesel buses were dispatched only once per day. Daily availability for both fleets was determined based on each bus's readiness for service at morning pull-out. The overall average availability for the BEBs was 51.8%. The diesel fleet availability was 88.4%. Unavailability for the BEBs was most often due to general bus issues (29.7%), followed by electric drive system issues (9.1%). General bus issues included problems with the auxiliary heater, brakes, suspension, and doors. Electric drive system issues included problems with high-voltage batteries, traction motors, and inverters. CTE collected data on the individual charger availability beginning in May 2019 and extending through February 2021. DTA currently has eight chargers for its seven-BEB fleet, which were available 95.3% of the time.

On average, the BEB fleet is approximately three times as energy efficient as the diesel fleet. The BEB fleet fuel economy shows a strong seasonal correlation, with lower fuel economy and greater amount of diesel fuel used during colder months. During the warmer months, there is little or no difference between the electric-only and combined fuel economy (which includes electricity and diesel fuel), indicating little or no need for supplemental diesel heating. The combined fuel economy for the BEB fleet varies seasonally between approximately 10 mpdge and 20 mpdge. The diesel fleet fuel economy is much lower, averaging 4.9 mpdge, and does not demonstrate a pronounced seasonal variation like the BEB fleet.

The average electricity price of $0.141/kWh equates to a diesel-equivalent fuel price of $5.29 per diesel gallon equivalent. The average diesel price was $1.84/gal. The fuel efficiency of the BEB fleet offsets much of the impact of the higher equivalent fuel price for electricity, which is approximately three times the cost of diesel fuel. This results in a very similar average fuel cost per mile for the BEB fleet compared to the baseline diesel fleet. The added diesel fuel for heating increased the average BEB fuel costs only slightly, from $0.45/mile to $0.47/mile. The diesel fleet had an average fuel cost of $0.44/mile.

One of the primary reasons NREL and the Federal Transit Administration originally selected DTA as a top-priority zero-emission bus (ZEB) evaluation was due to the cold climate in Duluth, Minnesota. As part of its work for DTA, CTE analyzed the provided data to determine how the BEBs performed in the cold conditions. When evaluating BEB range, the data show a strong correlation of driving range to daily average ambient temperature, with a peak median driving range of approximately 160–165 miles around 55°F–60°F, and declining range with either increased or decreased temperature. In colder weather, the BEBs' diesel auxiliary heaters were used to greater extent for cabin heating. All vehicle components tended to require more energy per mile at colder temperatures. As the temperature decreased, the BEBs used a greater proportion of energy to power the air compressor and heating, ventilating, and air-conditioning (HVAC) inverter and a lesser proportion of energy to power the traction motor.

The reduced range in cold weather was primarily caused by two factors. The first is the additional energy required for heating and defrosting/defogging, which decreases the effective fuel economy of the BEBs, and the thermal energy is not able to be recaptured through regenerative braking. A secondary, compounding factor during days with snowy roads is that a safety feature of the BEBs temporarily deactivates regenerative braking when traction loss (wheel-slip) is detected. This reduces the amount of kinetic energy that can be recaptured through regenerative braking, further reducing the effective fuel economy and driving range of the buses on cold, snowy days.

NREL typically collects detailed maintenance work orders to conduct an analysis of maintenance costs by system for ZEB evaluations. Because the DTA BEBs were under warranty, all early maintenance work was handled by the manufacturer. By April 2019, DTA mechanics were handling most of the maintenance work; however, these records were not available for analysis. DTA encountered several technical issues with the buses and infrastructure, including:

Low-voltage batteries: DTA found that when the low-voltage batteries begin to lose charge, there are more fault codes in ancillary systems on the bus, including fault codes for the camera system or the cooling system. DTA policy is to remove the bus from service for fault codes, but when BEBs were removed due to fault codes, DTA was often unable to identify the problem. Charging the batteries would clear the fault codes, and DTA evaluates the code before automatically removing the bus from availability. DTA is on the original equipment manufacturer's (OEM's) schedule for an upgrade to the low-voltage battery system to prevent the batteries from deteriorating so quickly.

Extended downtime for repairs: Several issues led to BEBs experiencing excessive downtime, particularly during the COVID-19 pandemic. Staffing shortages at DTA delayed troubleshooting and repairs on the BEBs, often compounded by the lack of availability of OEM technicians. Moreover, global supply chain issues led to long lead times for necessary parts, causing issues to remain unresolved.

Chargers: DTA experienced a catastrophic failure of one of its chargers. The root cause was traced to a capacitor quality issue. The charger OEM (Tritium) replaced the damaged charger at DTA and replaced the capacitors on all other units with ones from a different manufacturer. To avoid future issues, Tritium has also added a software control that will shut down a charger if the relevant error code is triggered, requiring thorough inspection and repair before reactivation.

Interior heating: Despite the presence of auxiliary diesel heaters, DTA experienced issues sufficiently heating the cabin of the bus during winter weather, particularly around the driver compartment. Drivers would use the electric-powered defroster as a primary source of heat, leading to significant range reductions; however, even this was not enough to sufficiently heat the driver compartment. Proterra improved the cold weather package of the BEBs to address this issue by including heated driver seats, a convector to redirect diesel-generated heat to the driver compartment, and software upgrades for the heating system.

Corrosion: Both conventional buses and BEBs experience challenges with corrosion due to extreme winter conditions and exposure to corrosive agents such as road salt in the DTA service area. The DTA BEB fleet experienced multiple issues with corrosion on brakes and electrical connectors. Proterra installed splash guards and other covers to protect sections of the undercarriage to help reduce the problem.

As with all new technology development, lessons learned during this project can help other transit agencies successfully deploy BEB technology. Advanced-technology deployments typically experience unexpected challenges that need to be resolved. Many of DTA's challenges with the BEB fleet involved issues with their performance in cold temperatures and on snowy roads. DTA anticipated the possibility of some of these challenges and included the cold weather package in the specifications of the BEBs. Even with the additional ducting and auxiliary heater, the agency had to work with the OEM to adjust the system to meet requirements for keeping the driver and passengers warm during colder days.

For other transit agencies in cold climates, DTA stresses that understanding the service requirements and how weather conditions affect range is extremely important. Specific recommendations are:

- Analyze current routes for energy use and match the BEBs with routes that are within your specific BEB technology's capabilities.
- Understand that colder conditions will lower the range of the BEBs and plan winter deployments accordingly.
- Consider auxiliary heating to keep drivers and passengers comfortable and minimize the energy used by electric heaters in very cold weather.
- Be aware that snowy roads may reduce the BEBs' use of regenerative braking and result in increased energy use.

DTA reports that its drivers enjoy the BEBs and feel that the traction is better than the diesel buses. The agency has a good working relationship with its manufacturer and utility partners and has learned a lot about the technology and how it performs in the colder climate of Duluth. As one of the first deployments of its BEBs in a northern area, Proterra has made numerous design improvements to address cold weather challenges. These improvements have been incorporated into current and next-generation BEB designs.

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Introduction

The purpose of this report is to present the results from an evaluation of seven battery-electric buses (BEBs) in operation at Duluth Transit Authority (DTA) in comparison to a fleet of diesel baseline buses. DTA is collaborating with the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. The focus of the evaluation is to compare performance and cost of the BEBs to that of conventional technology in similar service and track progress over time.

NREL has evaluated advanced-technology transit buses for more than a decade. Recent evaluations focus on zero-emission buses (ZEBs)—both BEBs and fuel cell electric buses. The results of these evaluations are published with several objectives: document the performance results and lessons learned, present data and experience to aid agencies interested in ZEB deployments, and provide feedback to federal and state agencies that could inform research and development funding decisions.

NREL initiated this evaluation under funding from the Federal Transit Administration (FTA) as part of a continuous effort to evaluate the real-world cost and performance of ZEBs deployed in transit service. DTA experienced issues in getting the BEBs deployed after delivery, which resulted in a delay of the evaluation start. NREL's project through FTA ended prior to the completion of the evaluation. The U.S. Department of Energy's Vehicle Technologies Office agreed to fund the completion of the evaluation and report.

DTA enlisted the help of the Center for Transportation and the Environment (CTE) to manage the project and provide technical services with the BEB fleet and infrastructure. CTE has aided DTA with all aspects of the project, from modeling potential routes for BEB use in all types of weather conditions to data collection and analysis of the bus performance. This report contains a combination of analyses performed by NREL and by CTE.

Fleet Profile—DTA

DTA provides fixed-route transit service to Duluth, Minnesota, and surrounding communities of Superior (Wisconsin), Proctor, and Hermantown. The fixed-route fleet consists of 57 diesel, 6 diesel hybrid, and 7 battery-electric buses. DTA also provides paratransit service with a fleet of 12 vehicles, and 3 trolley buses are operated as a downtown shuttle service in summer months. Figure 1 shows the rows of conventional buses parked indoors at DTA's bus depot and Figure 2 shows a map of the DTA service area.

Figure 1. Indoor parking location at DTA's bus depot

Photo by M. Jeffers, NREL

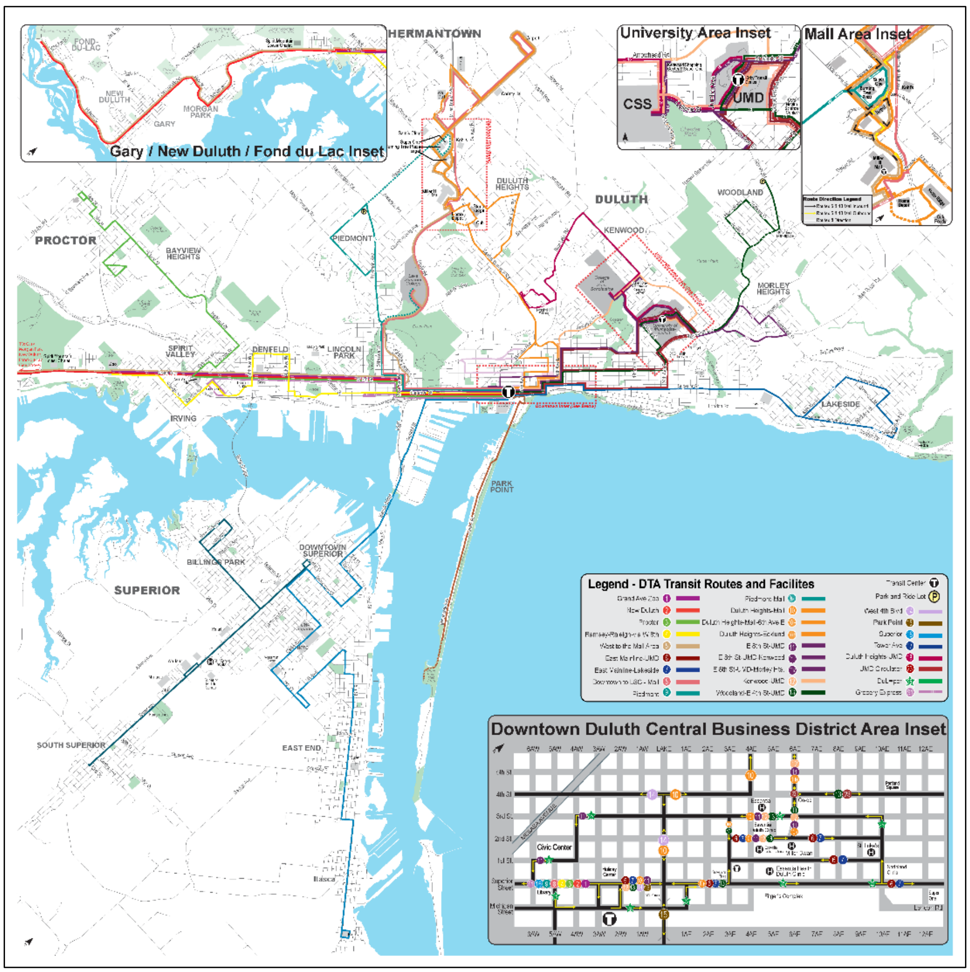

Figure 2. DTA system map

Image from DTA

Clean Vehicle Technologies at DTA

DTA began investigating clean technologies for its fleet in 2007 with the purchase of diesel hybrid buses. With the announcement of FTA's Low or No Emission Vehicle Deployment Program (Low-No Program) in 2014, the agency saw the opportunity to explore zero-emission buses for its fleet. The Low-No Program was established under the Moving Ahead for Progress in the 21st Century Act (MAP-21). The program provided capital funding for purchase of low-emission or zero-emission transit buses and supporting equipment. The program's purpose was to "deploy the cleanest and most energy efficient U.S.-made transit buses that have been largely proven in testing and demonstrations but are not yet widely deployed in transit fleets."[1] DTA was one of 10 awards in the initial round of the program. DTA's goals for the deployment included operating a pilot fleet of BEBs and associated charging infrastructure in a cold climate to determine how well the technology would work for the agency. The agency understood the potential challenge of keeping the interior of the bus warm during the winter months and opted for a cold weather package from the bus manufacturer that included a fuel-fired heater.

DTA first began operating its BEBs in late 2018. Early deployment issues, followed by service interruptions caused by the COVID-19 pandemic, resulted in periodic delays in data collection for this project. The intent of each NREL evaluation is to cover at least one full year of service of the advanced-technology buses. Because of the delays, the data periods are not consistent for each key performance element provided in the report. DTA believes that delays in the data collection period provides for a better analysis because it allowed time for the agency to learn about operating the BEBs, as discussed in the Technical Issues and Resolutions section.

DTA contracted with a third-party provider, ViriCiti LLC, for a comprehensive telematics system on the buses that communicates real-time information on the status of the buses and their operations, as well as charger data, directly to DTA staff. The ViriCiti telematics system was also installed on 10 model year 2020 diesel buses. DTA believes that an independent third-party telematics system was necessary for objectively obtaining and retaining data on the buses so it could fairly and consistently represent the performance of both types of vehicles during the evaluation period. They plan to continue using the ViriCiti system on as many buses as economically feasible.

Bus Technology Descriptions

The BEBs operating at DTA are 40-foot Proterra Catalyst buses with a 440-kWh energy storage system (ESS). The BEB fleet was the primary focus of this data collection and analysis effort. NREL also collected a subset of data on a conventional fleet of 10 GILLIG diesel buses of similar age as the BEBs for the primary baseline comparison to the BEB fleet. Table 1 provides selected specifications for each bus type. Figure 3 is a photo of one of the BEBs. A baseline diesel bus is pictured in Figure 4. DTA equips all its buses with fuel-fired auxiliary heaters to aid in keeping the interior warm during the cold months. Both fleets have auxiliary diesel-fired heaters.

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[1] U.S. Department of Transportation Federal Transit Administration. "FY13 Discretionary Funding Opportunity: Low or No Emission Vehicle Deployment Program (LoNo) Program." *Federal Register* 79, no. 6 (January 9, 2014): 1668–1672. https://www.gpo.gov/fdsys/pkg/FR-2014-01-09/pdf/2014-00134.pdf.

Table 1. System Descriptions for the BEBs and Diesel Buses

Vehicle System	BEB	Diesel
Number of buses in evaluation	7	10
Bus manufacturer	Proterra	GILLIG
Bus year and model	2018 Catalyst	2018 standard low-floor diesel
Length (ft)	40	40
Gross vehicle weight rating (lbs)	42,000	39,600
Electric drive motor or engine	220 kW (peak) permanent magnet drive motor, 295 horsepower	Cummins I-9 engine, 280 horsepower
Accessories	Electric	Mechanical
Energy storage or fuel capacity	440 kWh nominal (354 kWh usable)	100 gallons diesel
Charging equipment	8 depot chargers, 50 kW	—
Bus purchase cost	$981,000	$460,000

Figure 3. DTA battery-electric bus

Photo from DTA

Figure 4. DTA diesel bus

Photo from DTA

Charging Infrastructure

DTA installed eight charging stations to service the fleet at a cost of $40,000 per charger. These chargers are rated at 50 kW each and are installed along two bus lanes in its indoor parking facility. Figure 5 is a photo of one of the chargers, manufactured by Tritium for Proterra. The charging system installation, which cost $290,000, included a new transformer, electric panel boxes, meters, conduit, and wiring. The system installation also included a 250-kW backup generator for resiliency during emergencies when power might be interrupted. The agency worked closely with its utility partner and reports that they were supportive of the BEB deployment. During the electrical infrastructure upgrade, the agency planned for the ability to charge up to 20 BEBs for potential future expansion of the BEB fleet. The buses are typically charged each night—maintenance staff are responsible for plugging them in when the buses return to the depot. Eight chargers give DTA a spare unit to service the fleet of seven BEBs.

Figure 5. Electric vehicle supply equipment at DTA parking garage

Photo by M. Jeffers, NREL

In-Service Operations Evaluation Results

DTA received the first two BEBs in September 2018. CTE conducted acceptance testing of these buses to verify that they met DTA's contractual requirements and operational expectations. DTA originally placed the BEBs into service on November 19, 2018; however, the buses were periodically removed from service for operational evaluations, including the effective range and insufficient interior heating. DTA worked with Proterra to address these issues (explained further in the section on Technical Issues and Resolutions). DTA's 2018 GILLIG buses (used as a baseline for this evaluation) arrived in August and September 2018 and went into service shortly thereafter.

NREL follows a standard evaluation protocol, outlined in previous reports, that establishes the start—or clean point—of the evaluation period.[2] Normally, the evaluation period is a consistent date range for all aspects of the analysis and covers at least one year of operation. The COVID-19 pandemic resulted in reduced bus service and delays in data collection midway through the evaluation. Because of these delays and other startup issues, the data collection periods varied for different portions of the analysis based on the data received. This evaluation generally covers the BEB operation from late 2018 through spring 2021; Table 2 outlines the specific data collection periods by each data type.

Early in the BEB deployment, DTA staff began closely tracking the BEB operation and recording a variety of information daily, such as route/block assignments, operator assignments, bus availability, time in/out of depot, state of charge (SOC) at start/end, miles traveled, diesel fuel consumed (for fuel-fired heater), roadcalls, and other related operational notes. DTA recorded similar information for the selected conventional buses used as the baseline fleet. Most of NREL's analysis was drawn from this data source. However, the additional effort required by DTA staff for this detailed data collection was not sustainable after the pandemic started, so these records cover December 2018 through February 2020. Additionally, the BEBs were outfitted with ViriCiti data loggers to record daily operation. DTA provided NREL access to daily summaries from this data source. Lastly, monthly utility bills from DTA's electric utility, Minnesota Power, were used to analyze charging profiles and electricity costs.

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[2] Leslie Eudy and Matthew Jeffers. 2018. *Zero-Emission Bus Evaluation Results: King County Metro Battery Electric Buses*. Washington, D.C.: Federal Transit Administration. FTA Report No. 0118. https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/115086/zero-emission-bus-evaluation-results-king-county-metro-battery-electric-buses-fta-report-no-0118.pdf.

Table 2. Summary of Data Collection Periods

Data Type	BEB Fleet Data Period	Diesel Fleet Data Period
Bus availability	December 2018–February 2020	April 2019–February 2020
Bus use	January 2019–April 2021	April 2019–February 2020
Fuel economy	January 2019–April 2021	April 2019–February 2020
Electricity costs	January 2019–April 2021	—
Diesel fuel costs	January 2019–April 2021	January 2019–April 2021
Charging power	September 2018–November 2020	—
Roadcalls	April 2019–February 2020	April 2019–February 2020
Cold weather analysis	October 2018–February 2022	—

Route Assignments

DTA planned to start the BEBs on shorter blocks while the operators and other staff became more familiar with the BEB technology performance and capabilities. During the school year, the BEBs would be used primarily on the UMD Circulator Route 23—a 5.5-mile circulator connecting the University of Minnesota Duluth to downtown. Figure 6 is a map showing Route 23.[3] The agency planned to expand service for the buses over time, with a goal of random dispatch to cover all routes. This could be a challenge for the BEBs because of DTA's practice of interlining buses between routes. Interlining is a practice where a driver's work assignment starts on one route, then changes to one or more additional routes before the end of the shift. Because of this practice, a driver might cover more miles during a shift (or block of work) than would be required for multiple rounds of a single route. Limited weekend staff results in longer blocks of work. The agency initially used the BEBs only during the week because the weekend blocks were longer, and they were unsure of the BEB's ability to meet those longer ranges.

During the COVID-19 pandemic (beginning in mid-March 2020), DTA reduced all service to Saturday levels. The BEBs were temporarily removed from service due to range concerns. The BEB fleet did not operate at all during May 2020.

[3] Duluth Transit Authority. "Routes & Schedules." http://www.duluthtransit.com/timetable/current/23.

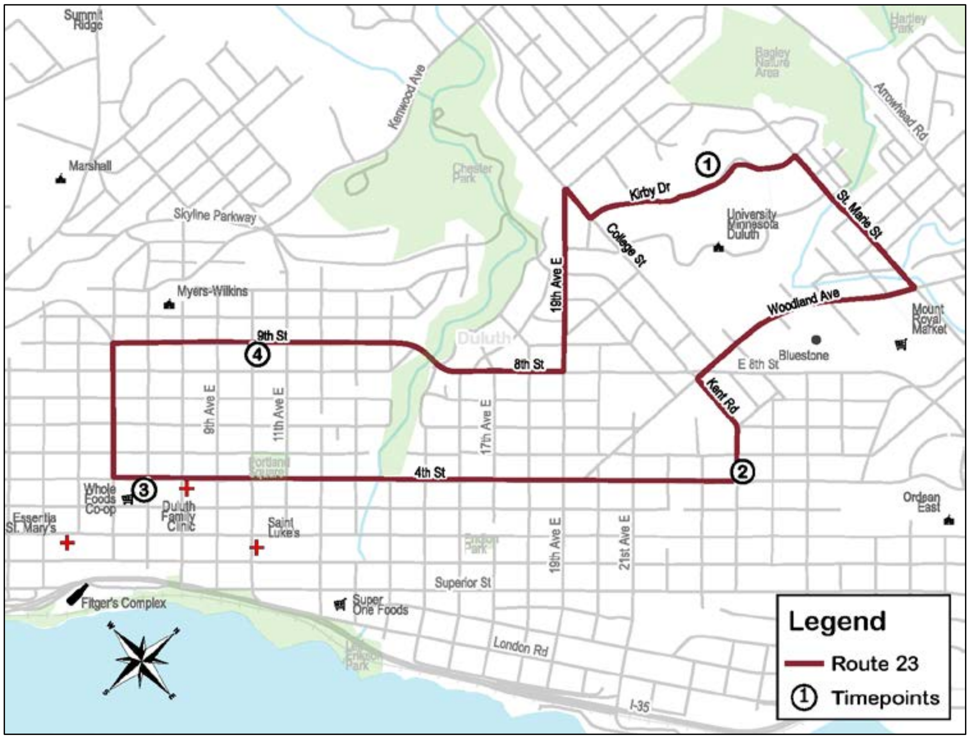


Figure 6. Route 23 service map

Image from DTA

Bus Use

Figure 7 tracks the accumulated mileage of the BEBs since they were received and placed into service. Since the first few BEBs began entering service, the BEB fleet accumulated almost 225,000 combined miles as of April 2021. The dip in mileage from March through June 2020 corresponds with the service interruption due to the COVID-19 pandemic. Figure 8 provides the monthly miles separated by individual bus.

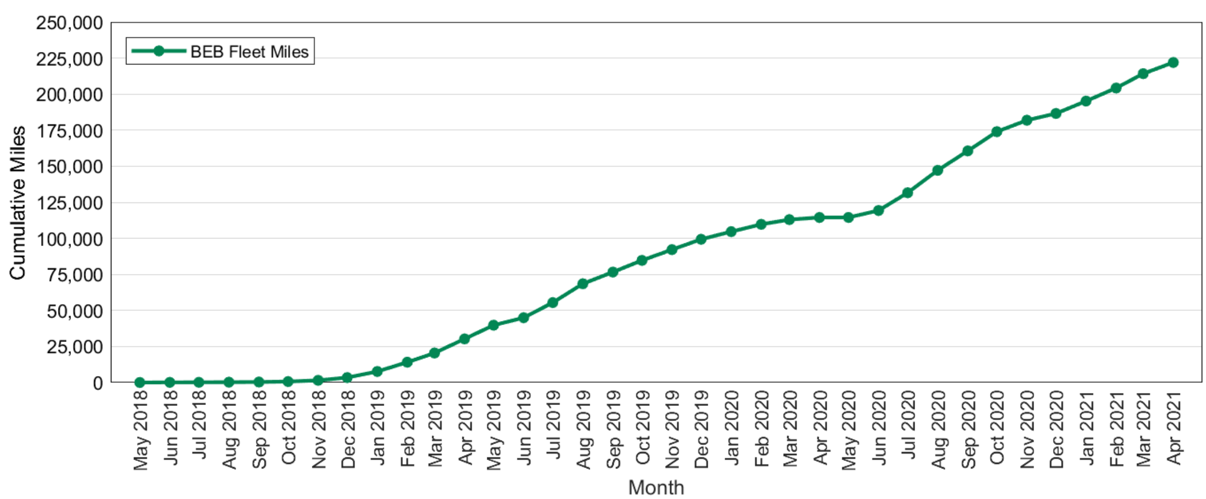


Figure 7. Cumulative miles for the BEB fleet

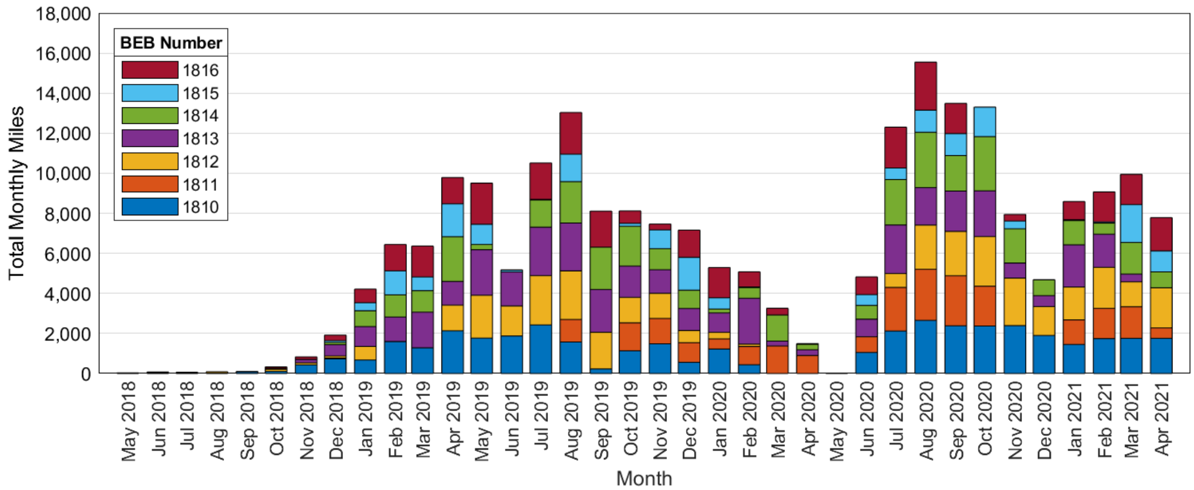


Figure 8. Total monthly miles for each BEB

Table 3 provides the evaluation period mileage for each bus and the average monthly mileage by bus type, which is also displayed in Figure 9. The BEBs averaged 1,115 monthly miles per bus. This is lower than the baseline diesel bus fleet average of 4,095 monthly miles per bus.

Table 3. Average Monthly Miles

Bus	Total Miles	Bus Months	Average Monthly Miles
1810	39,987	28	1,428
1811	23,289	28	832
1812	34,235	28	1,223
1813	38,645	28	1,380
1814	34,095	28	1,218
1815	17,991	28	643
1816	30,284	28	1,082
BEB Fleet	**218,526**	**196**	**1,115**
Data period: January 2019–April 2021			

Bus	Total Miles	Bus Months	Average Monthly Miles
1800	47,276	11	4,298
1801	45,952	11	4,177
1802	48,901	11	4,446
1803	46,757	11	4,251
1804	44,248	11	4,023
1805	48,445	11	4,404
1806	46,142	11	4,195
1807	45,356	11	4,123
1808	45,811	11	4,165
1809	31,609	11	2,874
Diesel Fleet	**450,497**	**110**	**4,095**
Data period: April 2019–February 2020			

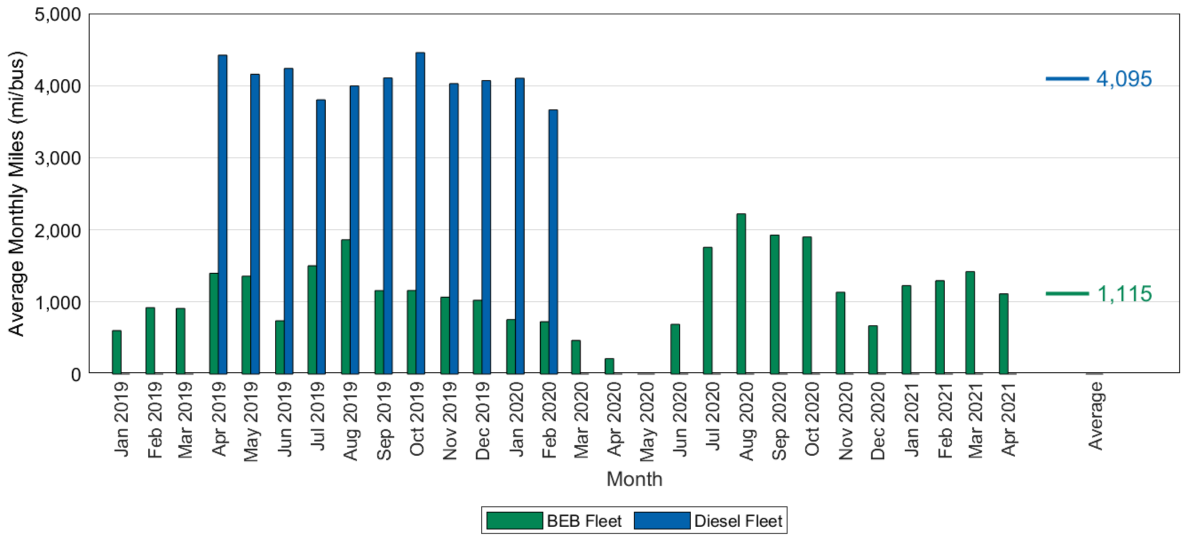


Figure 9. Average monthly miles for BEB and diesel fleets

Bus Availability

Availability, which is a measure of reliability, is presented as the percentage of days the buses are available for use out of days that the buses are planned for passenger service. Buses available for service may have been used in passenger service, training, or for special events, or they may have been available but just not used. Buses unavailable for service may have had issues with the propulsion system (electric drive, energy storage system) or general bus maintenance, or were undergoing scheduled maintenance. Accidents are removed from the data—the bus is considered "not planned" during the repair time.

The availability analysis covers 15 months of data collected for the BEB fleet (December 2018–February 2020) and 11 months of data for the diesel fleet (April 2019–February 2020). Initially, planned service for DTA was 7 days per week for both the BEB and diesel bus fleet. During 2020, DTA reduced service for the BEBs to weekdays only. During the evaluation period, the BEBs were dispatched for morning service and again for afternoon service, returning to the bus depot to charge between the two shifts. The daily availability for the BEBs was tracked based on their readiness for morning pull-out. Each bus was therefore counted as available if it was planned for service and ready for service at morning pull-out. The diesel buses were dispatched only once per day, so they were also counted as available if they were planned for service and ready for morning pull-out. The overall average availability for the BEBs was 51.8%. The diesel fleet availability was 88.4%. Table 4 provides the average availability for each bus and the overall fleet totals.

Table 4. Availability for the BEB and Diesel Fleets

Bus	Planned Days	Available Days	Availability (%)
1810	312	177	56.7%
1811	296	157	53.0%
1812	299	139	46.5%
1813	311	231	74.3%
1814	307	147	47.9%
1815	300	94	31.3%
1816	292	152	52.1%
BEB Fleet	**2,117**	**1,097**	**51.8%**
Data period: December 2018–February 2020			

Bus	Planned Days	Available Days	Availability (%)
1800	294	270	91.8%
1801	289	265	91.7%
1802	299	278	93.0%
1803	291	267	91.8%
1804	294	260	88.4%
1805	293	277	94.5%
1806	296	262	88.5%
1807	287	260	90.6%
1808	295	260	88.1%
1809	268	171	63.8%
Diesel Fleet	**2,906**	**2,570**	**88.4%**
Data period: April 2019–February 2020			

The stacked area charts in Figure 10 and Figure 11 show each bus's contribution to the monthly availability of its fleet, with the top line representing the overall monthly availability of the fleet. The BEBs show lower overall availability as well as higher month-to-month variability, which may indicate more issues with the new technology or more time spent diagnosing and repairing issues with which the maintenance staff are less familiar. In some cases, parts availability issues resulted in a BEB being unavailable for longer than expected. In other cases, fleet policy delayed the BEBs from being placed back into service. DTA doesn't allow a bus to be operated if a warning light is on. In the early deployment, BEBs were pulled from service as soon as a light came on. In many cases, the cause was not serious however it resulted in lost service and lowered availability. As DTA staff became more familiar, issues like these were addressed quickly. By contrast, the conventional diesel buses show higher and more consistent overall availability on a fleet level and individual bus level. The per-bus availability ranges from 31.3% to 74.3% for the BEBs and from 63.8% to 94.5% for the diesel buses during their respective data periods.

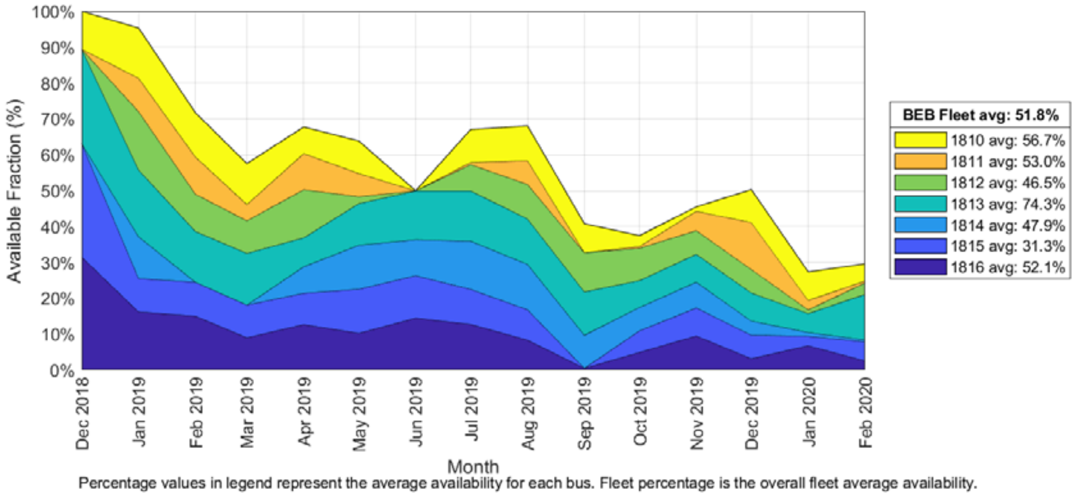


Figure 10. Monthly availability for the BEB fleet

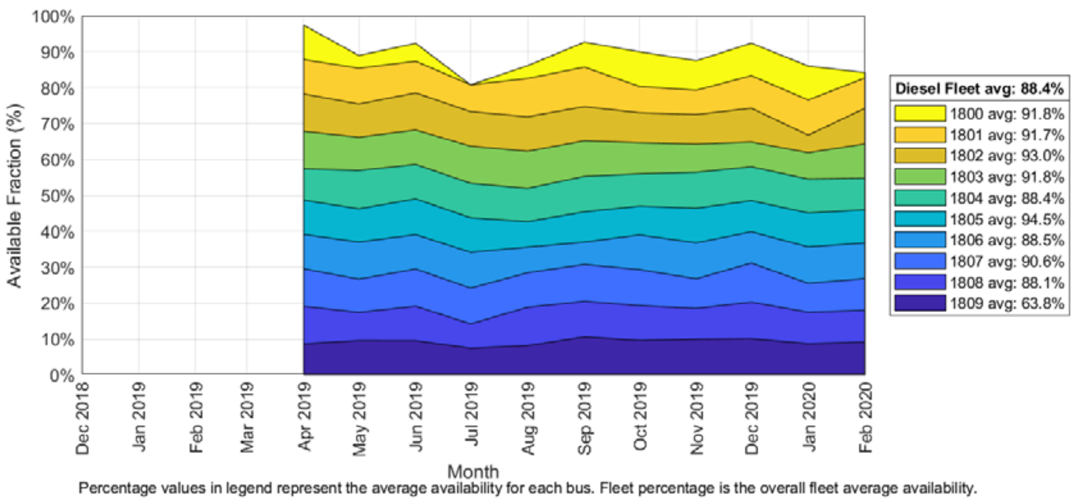


Figure 11. Monthly availability for the diesel fleet

Figure 12 tracks the monthly average availability for the BEB and diesel fleets as line series along the top of the chart. The stacked columns in the figure show the number of days that the BEBs were unavailable, organized into six categories. The unavailable categories are transmission, charging issues (including bus-side and charger-side issues), ESS, electric drive, preventive maintenance (PM), and general bus maintenance. The general bus maintenance category covers everything that does not fall into one of the other categories.

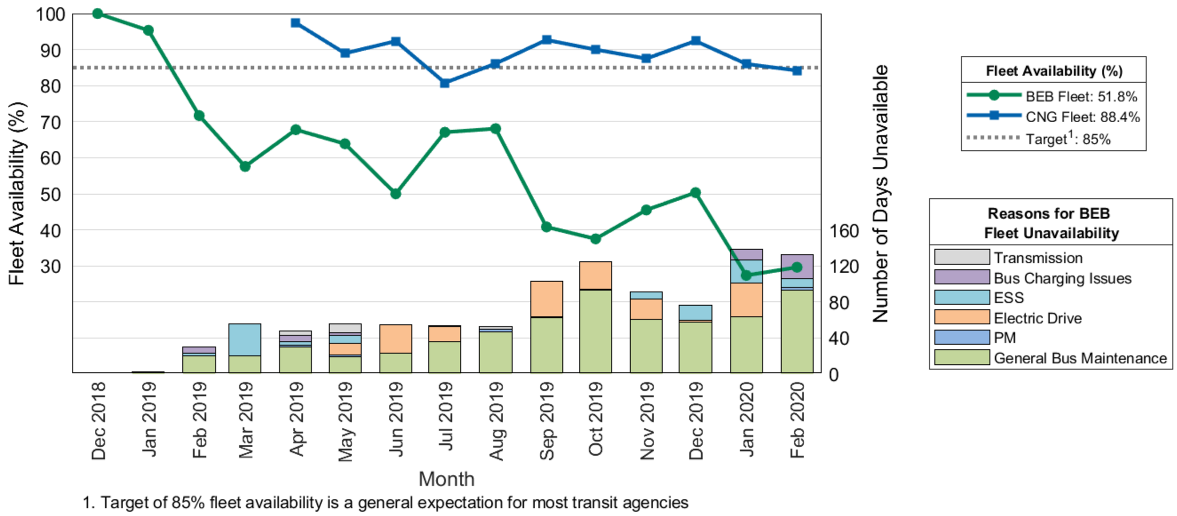


Figure 12. Monthly availability and reasons for unavailability for the BEB fleet

The pie charts in Figure 13 display the overall percentage of available days for the BEB and diesel fleets, the percentage of days each fleet was unavailable for service, and the reasons for unavailability. The electric drive, ESS, and charging issues categories apply only to the BEB fleet, and the engine category applies only to the diesel fleet. These pie charts represent overall fleet availability during the respective data collection periods listed above. Table 5 corresponds to Figure 13 and provides a breakdown of the number of days and availability percentages for each category.

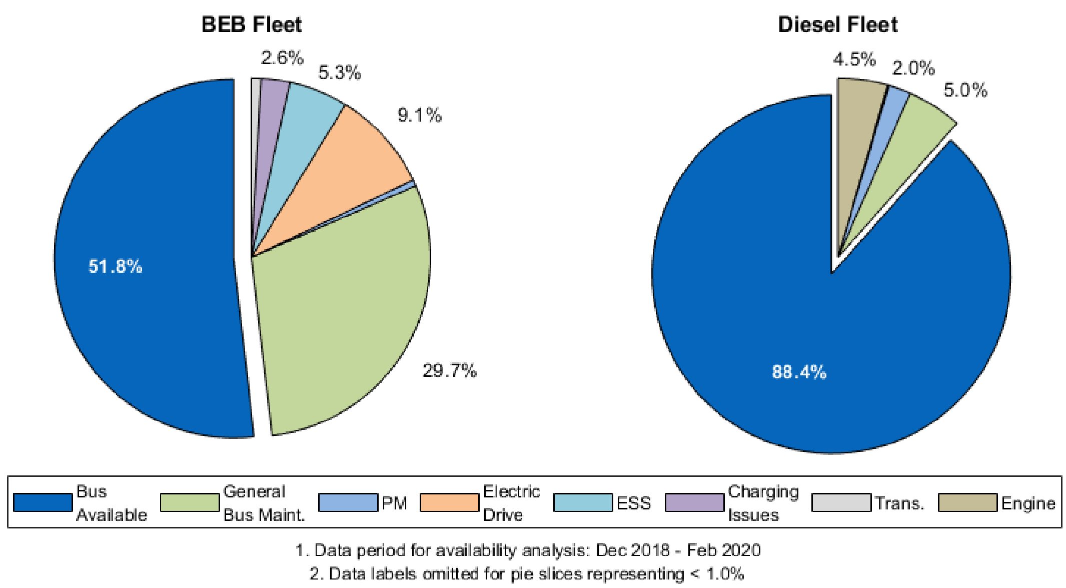


Figure 13. Overall availability for the BEB and diesel fleets

Table 5. Summary of Availability and Unavailability by Category

Category	BEB (days)	BEB (%)	Diesel (days)	Diesel (%)
Days planned	2,117	—	2,906	—
Days available	**1,097**	**51.8**	**2,570**	**88.4**
Days unavailable	1,020	48.2	336	11.6
General bus maintenance	629	29.7	144	5.0
Preventive maintenance	12	0.6	58	2.0
Electric drive	193	9.1	—	—
ESS	113	5.3	—	—
Charging issues	55	2.6	—	—
Transmission	18	0.9	4	0.1
Engine	—	—	130	4.5

Unavailability for the BEBs was most often due to general bus issues (29.7%), followed by electric drive issues (9.1%). Bus issues included problems with the auxiliary heater, brakes, suspension, and doors. Electric drive issues included problems with high-voltage batteries, traction motor, and inverters. Major issues are described in the Technical Issues and Resolutions section.

Charger Availability

DTA installed eight charging units to power its fleet of seven BEBs. CTE collected data on the individual charger availability beginning in May 2019 and extending through February 2021. The data were not available during the months of April, May, and June 2020 when the BEB fleet was temporarily out of service due to the COVID-19 pandemic. Figure 14 shows the monthly average availability of the chargers. Overall, the chargers were available 95.3% of the time. On a daily basis, the lowest availability for the chargers was 62.5%, but the average was rarely below 87.5%.

In the months following the end of NREL's evaluation period, DTA reported that they experienced an increasing number of technical issues with the chargers, combined with delays in troubleshooting and repairing the issues, which severely impacted the availability of the chargers. The charger availability deteriorated to the point where only one charger was available for several weeks, which prevented DTA from operating the BEB fleet. DTA continues to work with the charger manufacturer to resolve these issues.

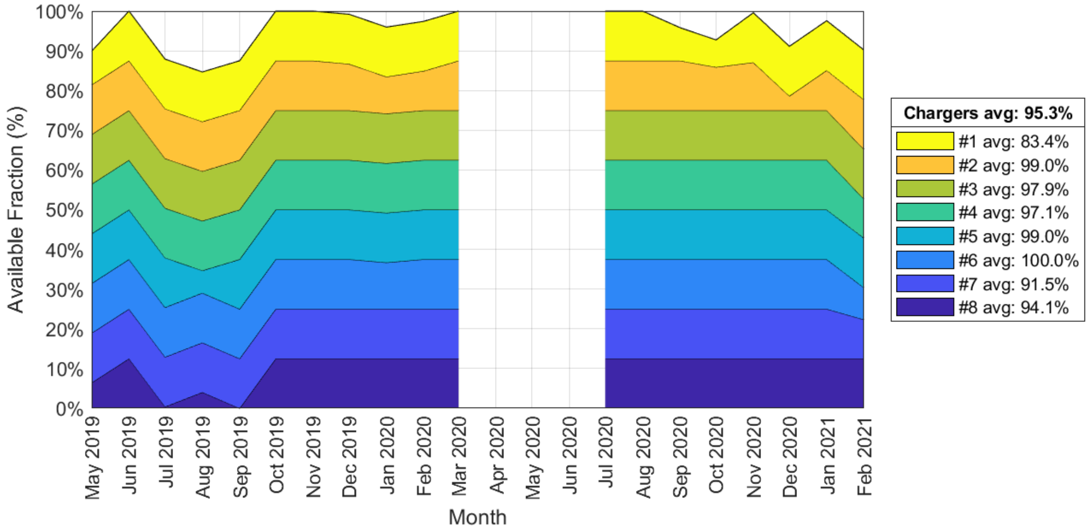


Figure 14. Monthly availability for chargers

Fuel Economy, Energy Use, and Cost

NREL collected mileage and energy consumption data for the BEBs and baseline diesel buses to evaluate the efficiency, or fuel economy, of each fleet. Electrical energy consumption data for the BEBs were obtained from ViriCiti data loggers. In addition to electrical resistance heating, the BEBs are equipped with auxiliary diesel fuel-fired heaters to ensure adequate heating of the passenger compartment during cold weather. This is similar to conventional buses operating in colder climates, which typically have supplementary auxiliary heaters for the passenger compartment. All DTA buses are equipped with auxiliary heaters—those on the diesel buses draw fuel from the existing diesel tank, and the BEBs have a diesel tank installed as part of the cold weather package. Diesel fuel records were provided by DTA for the diesel bus fleet as well as the diesel heaters in the BEBs. The data period for the BEB fuel economy analysis is January 2019 through April 2021 (28 months). The data period for the diesel fleet is April 2019 through February 2020 (11 months).

Table 6 lists the per-bus mileage, energy consumption, and fuel economy for the BEBs and diesel buses, along with the fleet totals and fleet-average efficiencies. For the BEBs, the electrical efficiency is calculated using only the electrical energy from the high-voltage bus batteries; the combined fuel efficiency includes electrical energy from the batteries as well as energy from the diesel fuel used for passenger heating. Electricity consumption in kilowatt-hours (kWh) was converted to diesel gallon equivalent (dge), and vice versa, based on the per-unit energy content of each fuel.[4] The conversion factor used was 37.64 kWh/dge.

[4] Alternative Fuels Data Center. "Fuel Properties Comparison." https://afdc.energy.gov/fuels/properties.

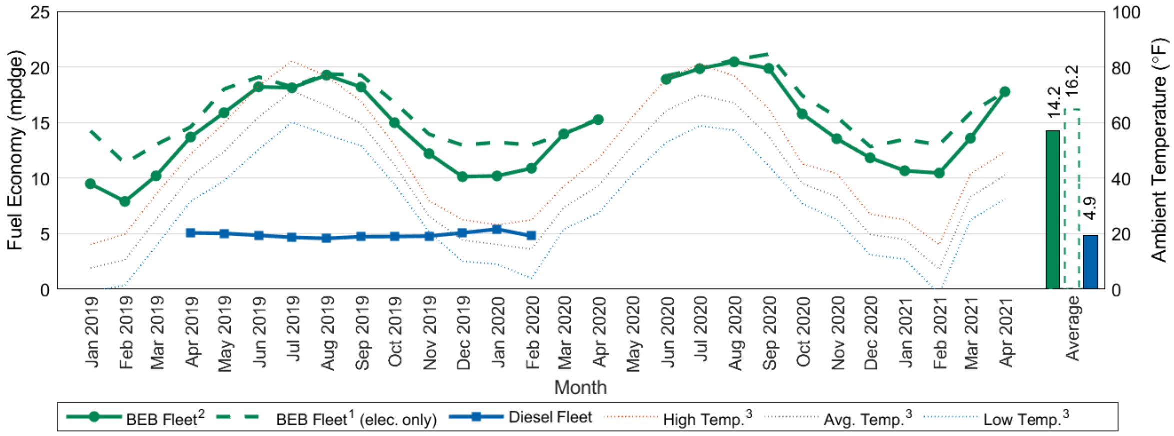
Table 6. Mileage, Fuel Use, and Fuel Economy

Bus	Mileage (fuel base)	Electricity Consumption (kWh)	Electrical Efficiency (kWh/mi)	Diesel Fuel Consumption (dge)	Combined Fuel Efficiency (kWh/mi)	Equivalent Fuel Economy (mpdge)
1810	39,987	92,658	2.32	288.5	2.59	14.54
1811	23,289	54,227	2.33	231.3	2.70	13.93
1812	34,235	74,364	2.17	309.5	2.51	14.98
1813	38,645	89,614	2.32	332.6	2.64	14.24
1814	34,095	81,361	2.39	255.9	2.67	14.10
1815	17,991	44,417	2.47	188.1	2.86	13.15
1816	30,284	71,324	2.36	249.6	2.67	14.12
BEB Fleet	**218,526**	**507,966**	**2.32**	**1,855.4**	**2.64**	**14.23**
1800	42,156	—	—	8,786	—	4.80
1801	42,166	—	—	8,443	—	4.99
1802	42,911	—	—	9,063	—	4.73
1803	41,829	—	—	8,512	—	4.91
1804	39,528	—	—	8,320	—	4.75
1805	44,288	—	—	8,813	—	5.03
1806	41,487	—	—	8,589	—	4.83
1807	39,582	—	—	8,238	—	4.80
1808	39,881	—	—	8,116	—	4.91
1809	26,566	—	—	5,460	—	4.87
Diesel Fleet	**400,393**	—	—	**82,341**	—	**4.86**

Figure 15 shows the monthly average fuel economy in miles per diesel gallon equivalent (mpdge) for the BEB and diesel bus fleets. For the BEB fleet, trends are shown for the electric-only fuel economy (dashed green line) and for the combined fuel economy (electricity and diesel fuel energy, solid green line). Monthly average ambient temperatures recorded at Duluth International Airport[5] are also plotted in Figure 15 to highlight seasonal variation of fuel economy. The plotted temperatures include the daily high, daily low, and daily average temperatures. The BEB fleet fuel economy shows a strong seasonal correlation, with lower fuel economy and greater amount of diesel fuel used during colder months. During the warmer months, there is little or no difference between the electric-only and combined fuel economy, indicating little or no need for supplemental diesel heating. The combined fuel economy for the BEB fleet varies seasonally between approximately 10 mpdge and 20 mpdge. The diesel fleet fuel economy is much lower, averaging 4.9 mpdge, and does not demonstrate a pronounced seasonal variation like the BEB fleet. The energy efficiency benefit of the BEB fleet over the

[5] National Oceanic and Atmospheric Administration, National Centers for Environmental Information. "Climate Data Online." https://www.ncdc.noaa.gov/cdo-web/.

diesel fleet varies throughout the year from approximately two to four times. On average, the BEB fleet is approximately three times as energy efficient as the diesel fleet.



1. BEB equivalent fuel economy for electrical energy only; kWh converted to diesel gallon equivalent (dge): 37.64 kWh/dge
2. BEB equivalent fuel economy including diesel fuel from auxiliary heater
3. Monthly average of daily temperatures at Duluth International Airport; data acquired from: *https://www.ncdc.noaa.gov/*

Figure 15. Monthly fuel economy for the BEB and diesel fleets

Figure 16 provides some insight into the electrical energy consumption for the BEB fleet. The green columns on the left show the total monthly energy provided by the chargers to the bus fleet. The stacked blue columns show the total energy consumed by auxiliary loads while the bus is turned on but not moving (energy consumed idling, light blue), the total energy consumed while the vehicle is moving down the road (energy consumed driving, dark blue), and the total energy consumed while driving that is recovered through regenerative braking (energy regenerated driving, blue outline). Regenerative braking is the process by which kinetic energy of a moving bus is converted back to electrical energy by the electric motor(s) and stored in the batteries when the bus is slowing down. The white columns with blue outline indicate how much energy would be consumed—and would need to be replenished via charging—if regenerative braking was not available. For this reason, the energy charged columns in green are only slightly higher than the top of the dark blue columns, the difference accounting for small energy losses during charging. The figure also illustrates how important regenerative braking is for the overall efficiency of the bus. On average, the BEBs recuperate 21.6% of the expended energy through regenerative braking.

Because of Duluth's topography, the DTA BEBs have a high regeneration rate on routes that traverse the hills. Routes that are within the lower boundaries of Duluth and those that are between Duluth and Superior, Wisconsin, are relatively flat and do not have as high a regeneration performance as the hilly routes extending outside the city.

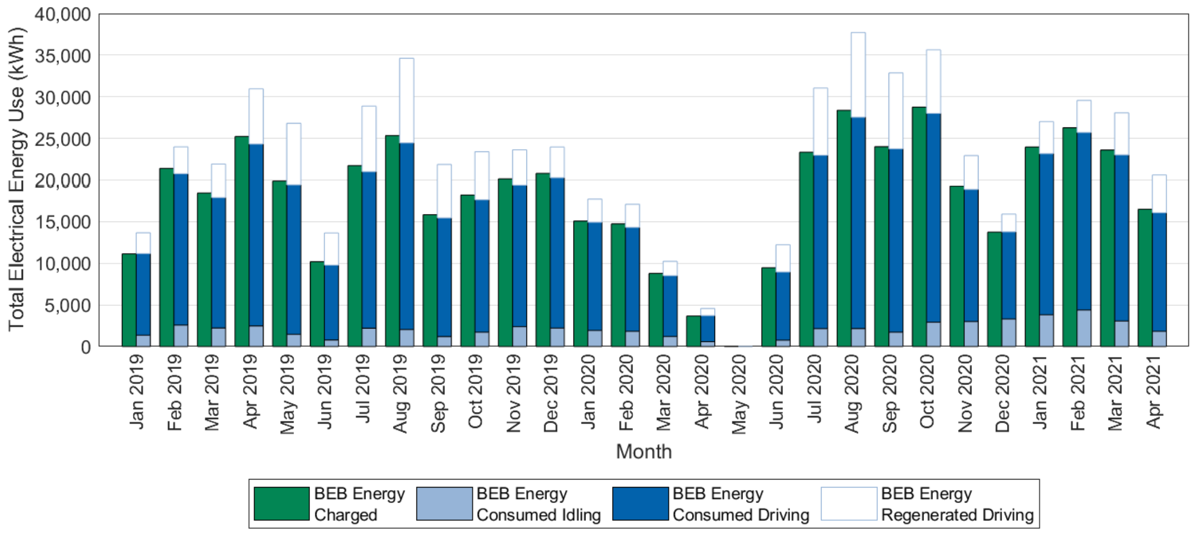


Figure 16. Monthly electrical energy consumption and regenerated energy for the BEB fleet

BEB Charging

During the evaluation period, the typical daily routine for the BEBs was to run peak service with separate morning and afternoon operation, each followed by bus charging at the depot. After completing morning peak service, the buses would return to the depot and park in a designated parking spot with a plug-in charger. The BEBs would be plugged in to charge throughout the middle part of the day, until needed for afternoon peak service. Similarly, upon returning from afternoon service, the BEBs would be plugged in again to charge overnight.

The charging profile of the BEB fleet, as measured by the electricity meter at the depot, is displayed in Figure 17. This chart uses translucent columns to show the combined charging power for all BEB chargers, reported in 15-minute intervals, throughout each day. Each daily charging profile is overlaid on the previous day, and all the days stack up in the chart to reveal the typical charging profile of the fleet during the data collection period. There are two primary charging periods: (1) midday charging, beginning around 9 a.m. and extending until approximately 3 p.m., and (2) evening charging, from approximately 6 p.m. to 11 p.m., with some buses continuing to charge until early the next morning. Both charging periods have staggered starting and ending times, as BEBs return to the depot at different times and require different durations of charging depending on their daily operation and energy consumption. During both periods, total charging power has at times exceeded 250 kW, which represents six or seven buses charging at the same time. The chart also shows trend lines indicating median charging levels at each time interval for weekday and weekend service. The weekday trend line shows a median charging power up to 100 kW, peaking between 11 a.m. and noon and again between 7 p.m. and 8 p.m. This power level represents two buses charging at the same time. The weekend trend line indicates no BEB charging on the weekend.

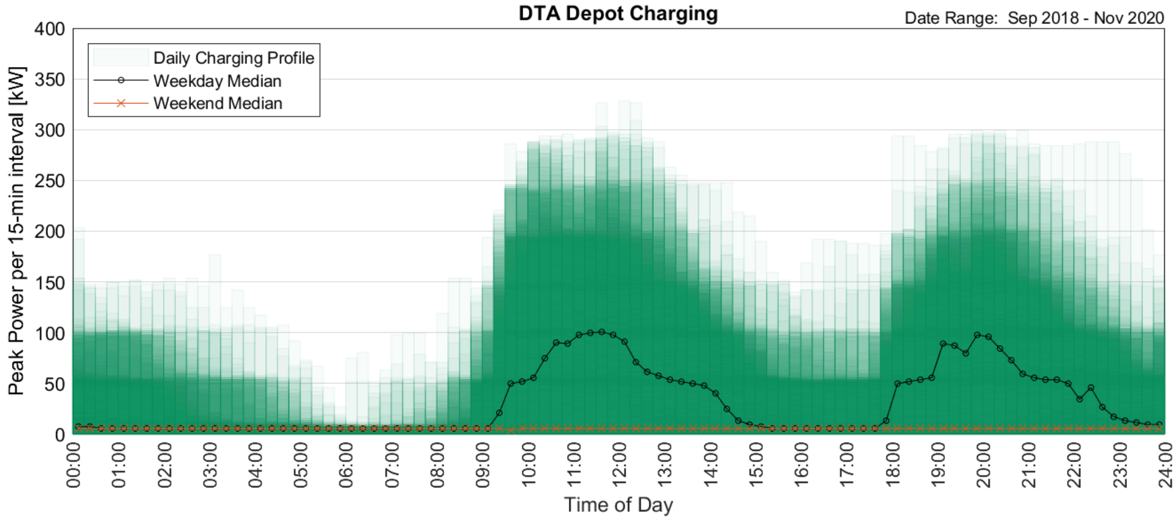


Figure 17. Fleet charging profile for depot charging

Figure 18 is a swarm plot of starting SOC and ending SOC values for each time the BEBs were dispatched into service during the data period of November 2018 to February 2020. The SOC values are organized by calendar month, and the chart includes monthly averages to indicate seasonal variation. The SOC start value is the battery charge level when the BEB leaves the depot to start service and is typically very near 100%. The SOC end value represents the amount of energy remaining when the BEB returns to the depot at the end of service. Based on DTA's operation of the BEBs, the ending values each represent a half day of transit service. Even within the same calendar month, there is wide variability in the ending SOC of the BEBs, highlighting the variability in scheduled route lengths, daily service requirements, passengers, traffic conditions, etc. In some cases, the ending SOC is as low as 20%–30%, but most often it remains above 40% during cold months and above 50% or 60% during warm months. This suggests the BEBs could sometimes be dispatched on longer routes, although the lower 20% of the SOC range should be avoided whenever possible to minimize battery degradation and operational risk. Derating of the BEB traction power may occur when a very low SOC (5%–7%) is reached. The monthly average minimum SOC varies seasonally between approximately 55% and 65%.

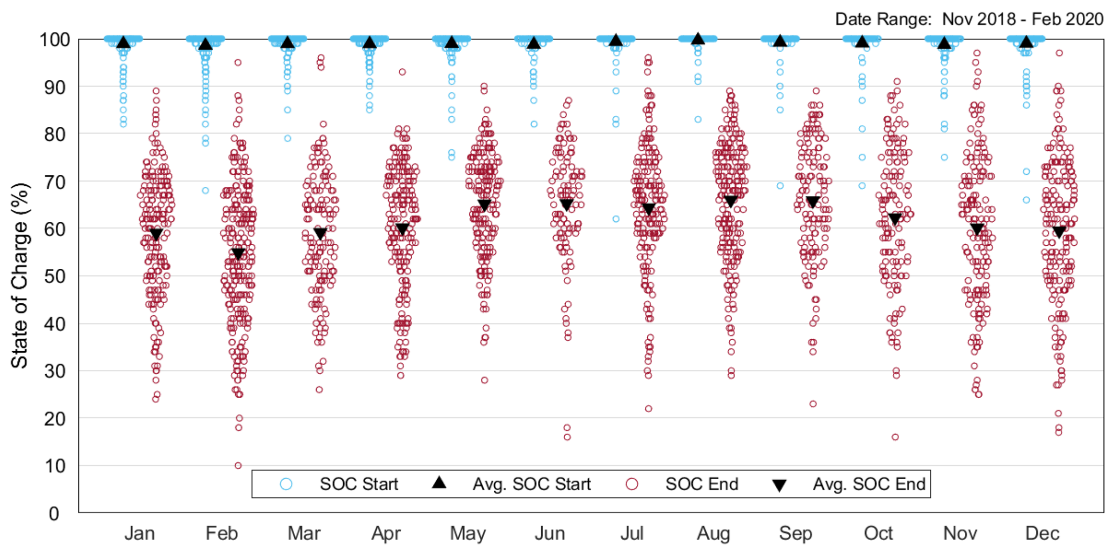


Figure 18. Swarm plot of trip start SOC and trip end SOC for the BEB fleet with monthly averages

Fuel Costs

DTA purchases electric power from its electric utility, Minnesota Power. A separate utility meter was installed with the BEB charging infrastructure to provide electricity to the chargers and measure the total energy consumption delivered. During the data collection period of January 2019–April 2021, the electric rate schedule for this meter changed from General Service Demand 25D to Commercial EV 29D. Both rate schedules include energy consumption charges and demand charges, as seen in Figure 19. This chart shows the charging costs for each monthly billing period and the contribution of each category of costs on a per-unit energy basis, including all monthly taxes and fees. The top of each column indicates the monthly total cost per kilowatt-hour for electricity to charge the BEB fleet. Energy consumption charges—a cost per unit of energy delivered ($/kWh)—were very consistent during the data collection period, at $0.076/kWh during most of the General Service Demand 25D rate and then at $0.060/kWh during most of the Commercial EV 29D rate. This is considered a low base rate for electricity charges and does not vary based on time of use. Demand charges are based on the power level, in kilowatts, that are demanded of the electricity service by the charging equipment. These costs are more variable and depend largely on how many buses are being charged simultaneously and the power level allowed by the charging equipment. The total monthly costs for demand charges have been converted to a per-kilowatt-hour basis and included in the chart to show the demand contribution to each monthly utility bill. For most months during the General Service Demand 25D rate, the demand charges accounted for approximately 40% of the total electricity costs. The demand fraction was capped below 30% of the total electricity costs during the Commercial EV 29D rate. As the most variable component of the electricity costs and the only one that is impacted by charging behavior, demand charges are the category that DTA could try to minimize with the use of scheduled or managed charging controls to reduce charging costs. The taxes, fees, and credits category (which was likewise converted to a per-kilowatt-hour basis for comparison) represents the fixed costs and includes all the credits, surcharges, adjustments, taxes, and fees that are included in the utility bills. This category of costs is normally a very small fraction of the bill, but it appears in the chart as a much larger fraction for months with very low energy consumption, such as May 2020 and June 2020. The average unit cost for electricity was $0.141/kWh.

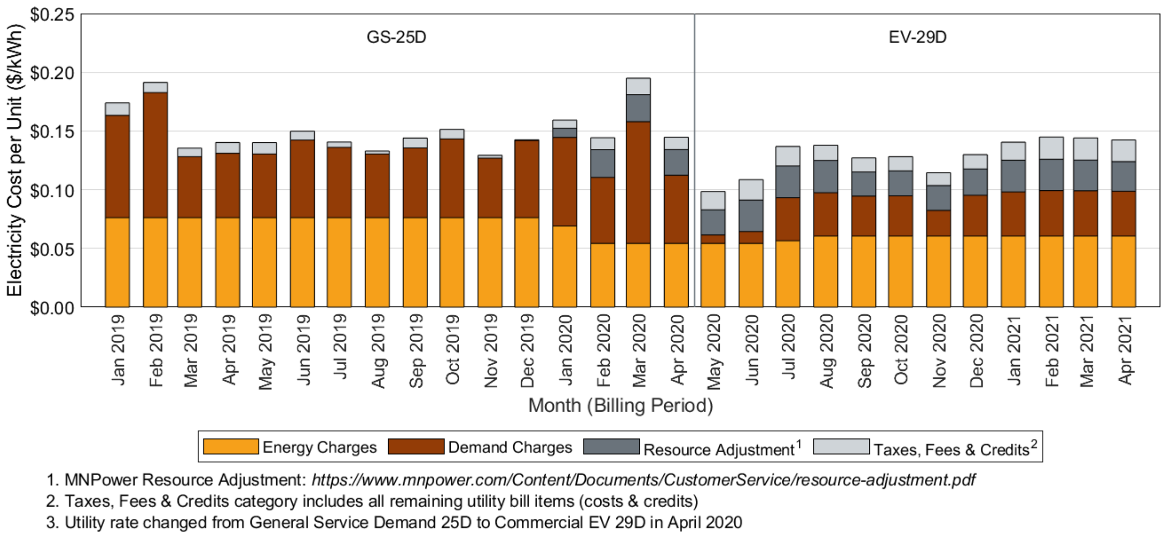


Figure 19. Electric utility component costs for depot charging

The average monthly price per unit for the two fuels is compared in Figure 20, shown in equivalent units and adjusted to correspond to the calendar month. The average electricity price of $0.141/kWh equates to a diesel-equivalent price of $5.29/dge, approximately 2.9 times the average diesel price of $1.84/gal.

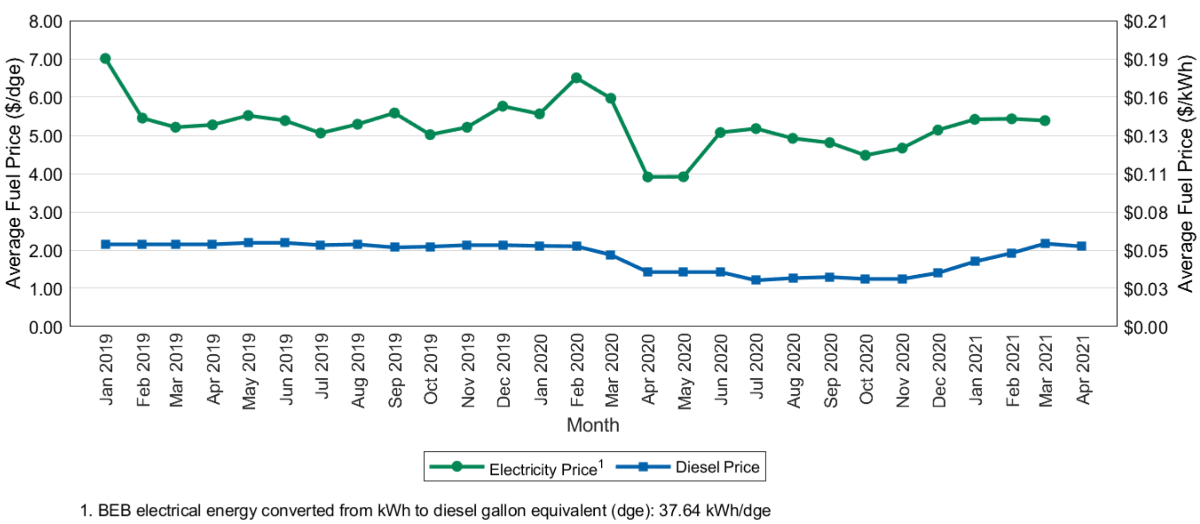


Figure 20. Equivalent monthly average fuel price for the BEB and diesel fleets

Combining the fuel economy of each fleet with the unit price for their respective fuels produces the monthly fuel cost per mile, as shown in Figure 21. The BEB fleet is approximately three times as fuel efficient as the diesel fleet, which offsets much of the impact of the higher fuel price (electricity cost is 2.9 times the cost of diesel fuel per dge). This results in a very similar average fuel cost per mile for the BEB fleet compared to the baseline diesel fleet. The BEB fuel-cost-per-mile trends are shown for electricity costs only (green dashed line) and for total fuel costs (electricity and diesel costs, solid green line). The added diesel fuel increased the BEB fuel costs only slightly, from $0.45/mile to $0.47/mile, on average. The diesel fleet had an average fuel cost of $0.44/mile.

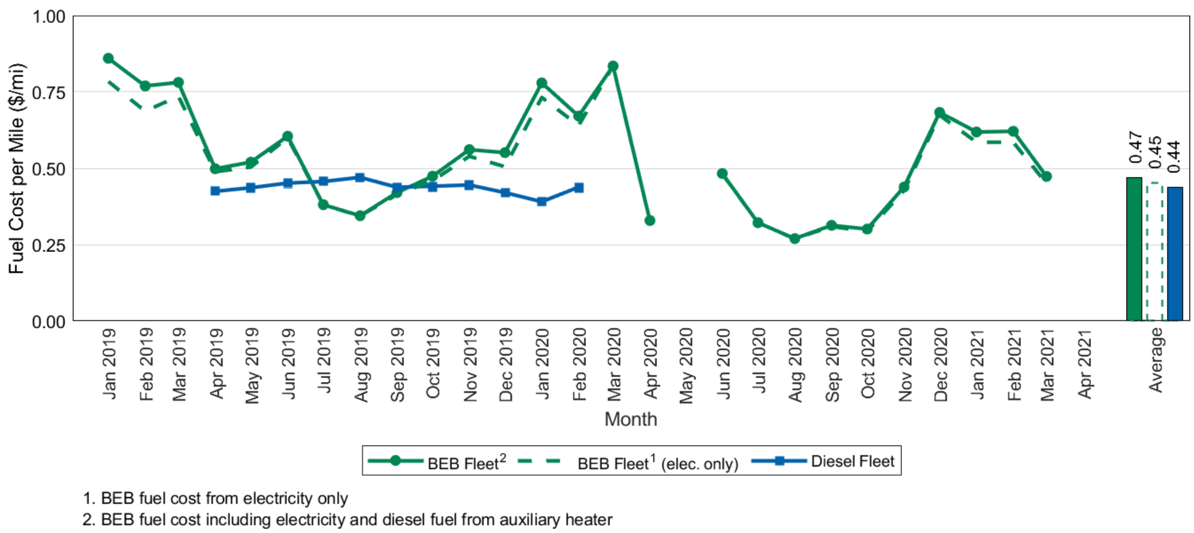


Figure 21. Monthly average fuel cost per mile for the BEB and diesel fleets

Winter Performance Analysis

One of the primary reasons NREL and FTA originally selected DTA as a top-priority ZEB evaluation was due to the cold climate in Duluth, Minnesota. There are outstanding questions regarding the operation, cost, and performance of BEBs in regions of the United States that experience cold and wintry weather, and the transit industry is very interested in the results of early deployments. As part of its work for DTA, CTE analyzed the available data to determine how the BEBs performed depending on the temperature and road conditions. This section outlines the results from the CTE analysis. Temperature data were obtained from the National Oceanic and Atmospheric Administration (NOAA), and efficiency data were collected through the ViriCiti data loggers.

Cold temperatures are known to have a detrimental effect on batteries; however, the real-world performance data for transit application are not readily available. CTE participated in an earlier study to analyze the performance of zero-emission buses in varying temperatures.[6,7] From the second report:

[6] Mark Henning, Andrew Thomas, and Alison Smyth. 2019. *An Analysis of the Association between Changes in Ambient Temperature, Fuel Economy, and Vehicle Range for Battery Electric and Fuel Cell Electric Buses*. Washington, D.C.: Federal Transit Administration. https://cte.tv/wp-content/uploads/2019/12/Four-Season-Analysis.pdf.

[7] Mark Henning, Andrew Thomas, and Alison Smyth. 2020. *Update of Investigation into Changes in Fuel Economy and Vehicle Range Related to Change in Ambient Temperature for Battery Electric and Fuel Cell Electric Buses*. Washington, D.C.: Federal Transit Administration. http://www.midwesthydrogen.org/site/assets/files/1413/four_seasons_update_final_rhfcc_12-2020.pdf.

> The results of the updated analysis showed that for temperature drops from 50-60° to 22-32° Fahrenheit, battery electric buses lost around 23.8% efficiency… [translating into a loss in range of 21%].
>
> …The inclusion of factors such as vehicle length, curb weight, and battery size in a statistical model for vehicle fuel efficiency allowed the Study Team to better understand the effect of change in ambient temperature on zero-emission buses.
>
> …Below 65° F in particular, ZEB fuel efficiency, and by extension range, seems more sensitive to temperature variation compared to fossil-fuel based vehicles, resulting in relatively higher fuel consumption as temperatures drop. This can be explained, in part, by the far greater amount of waste heat that fossil vehicles generate for propulsion compared to BEBs and FCEBs, which can be recycled and used for heating the passenger cabin. The magnitude of the increase in fuel consumption for both ZEB types, however, was smaller for this study update compared to that found in the 2019 Report. This could be due in whole or in part to the inclusion of additional control variables in our current statistical model that also explain variation in vehicle fuel efficiency. It could also be due to improvements over time in how agencies and their drivers operate the vehicles so as to minimize fuel consumption.

The study included early DTA data, as well as data from other BEB and fuel cell electric bus fleets. The analysis included here updates those data with the most recent data from the DTA BEB fleet.

Temperature Effects

The primary concern with BEB operation in cold weather is regarding the reduced capacity and performance of the high-voltage battery system, compounded by the additional heating loads, which leads to reduced effective driving range. It is well known that driving range is adversely affected in cold weather, and without adequate quantification, the uncertainty will continue to fuel range anxiety and hinder the broader deployment of BEBs.

Figure 22 shows the relationship between anticipated driving range of the BEBs and ambient temperature, based on DTA bus operation between January 2019 and December 2021. The anticipated range in the figure represents the estimated driving distance to reach 20% remaining battery SOC. For each instance, the anticipated driving range was calculated from the actual miles traveled and the change in SOC during bus operation in the ambient temperatures shown. The solid black trendline shows the moving median calculated at each temperature, ±2°F. The data show a strong correlation of driving range to ambient temperature, with a peak median driving range of approximately 160–165 miles around 55°F–60°F, and declining range with either increased or decreased temperature. For a temperature increase of 30°F, the range decreases approximately 20%; for a temperature decrease of 30°F, the range decreases approximately 33%. In colder weather, the BEBs’ diesel auxiliary heaters were used to greater extent for cabin heating, so the trendline for anticipated driving range begins to flatten for operation in very cold temperatures.

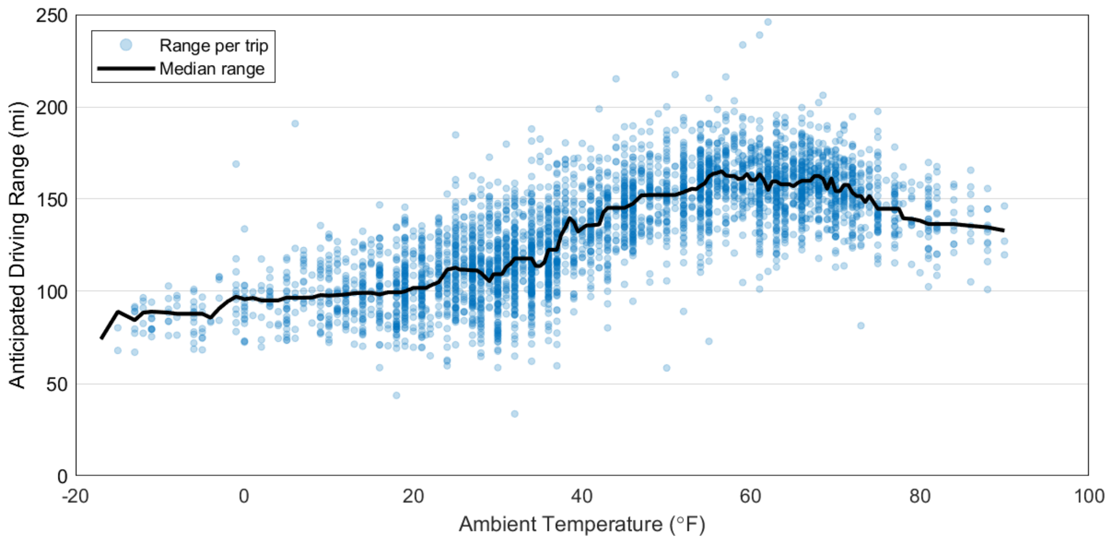


Figure 22. Anticipated driving range vs. ambient temperature for the BEB fleet

Figure 23 provides the energy efficiency by component (kWh/mile) and daily average temperature from October 2020 through February 2022. The average daily temperature is separated into four ranges—frigid (below 20°F), cold (20°F–32°F), cool (33°F–50°F), and warm (greater than 50°F). All components tended to require more energy per mile at colder temperatures. As the temperature decreased, the BEBs used a greater proportion of energy to power the air compressor and heating, ventilating, and air-conditioning (HVAC) inverter and a lesser proportion of energy to power the traction motor. Components such as the power steering and cooling pump showed little difference in energy required for the different temperature ranges.

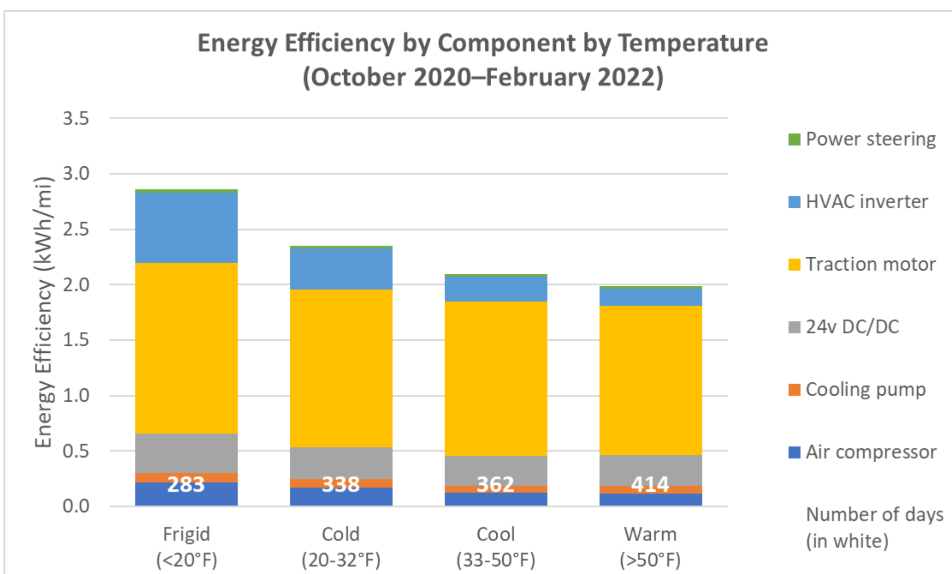


Figure 23. Energy efficiency by component for various temperatures ranges

For the same date range (October 2020–February 2022), BEB availability and reasons for unavailability were also organized by temperature range (Figure 24). As temperatures decreased, the relative fraction of issues related to the electric drive system decreased, while the fraction of ESS (battery) issues and general bus issues both increased.

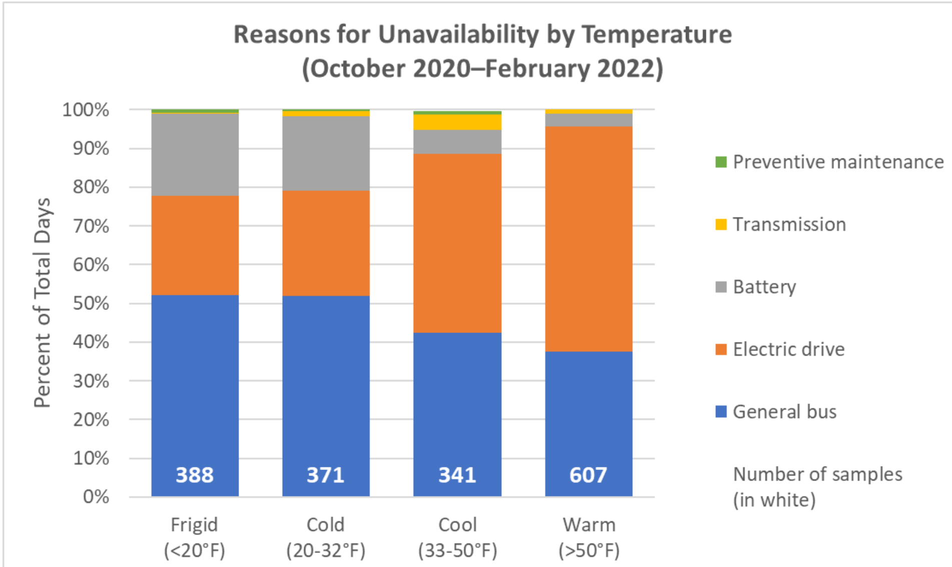


Figure 24. Reasons for unavailability for various temperature ranges

Effects of Road Conditions and Snow

A secondary concern that emerged during this evaluation for BEBs operating in cold locations with snowy weather is slippery road conditions and the impact on the efficiency of regenerative braking. Figure 25 shows a seasonal correlation between snowfall in Duluth—when the roads were more often covered in snow—and decreased energy recovery from regenerative braking. This result is because the regenerative braking is temporarily disabled when traction loss (wheel-slip) is detected, limiting its efficiency benefit on snowy roads. It's important to note that this behavior of the electric powertrain is a safety feature intended by the BEB manufacturer. Some energy efficiency is sacrificed to ensure safe and consistent handling of the vehicle. Nevertheless, it impacts the operation of these BEBs in a snowy environment. DTA experienced issues with its hybrid buses during snowy conditions where the wheels would lock up; however, these diesel hybrid buses have a shut-off switch on the instrument panel that allows the bus operator to disengage the regenerative braking during similar snow events. Because the drivers were uncomfortable with the situation, DTA does not typically dispatch the hybrid buses during snowstorms.

Another factor contributing to the reduced energy recovery during winter is the increased fraction of energy used for cabin heating and defrosting/defogging, which cannot be recaptured with regenerative braking like the energy used for propulsion.

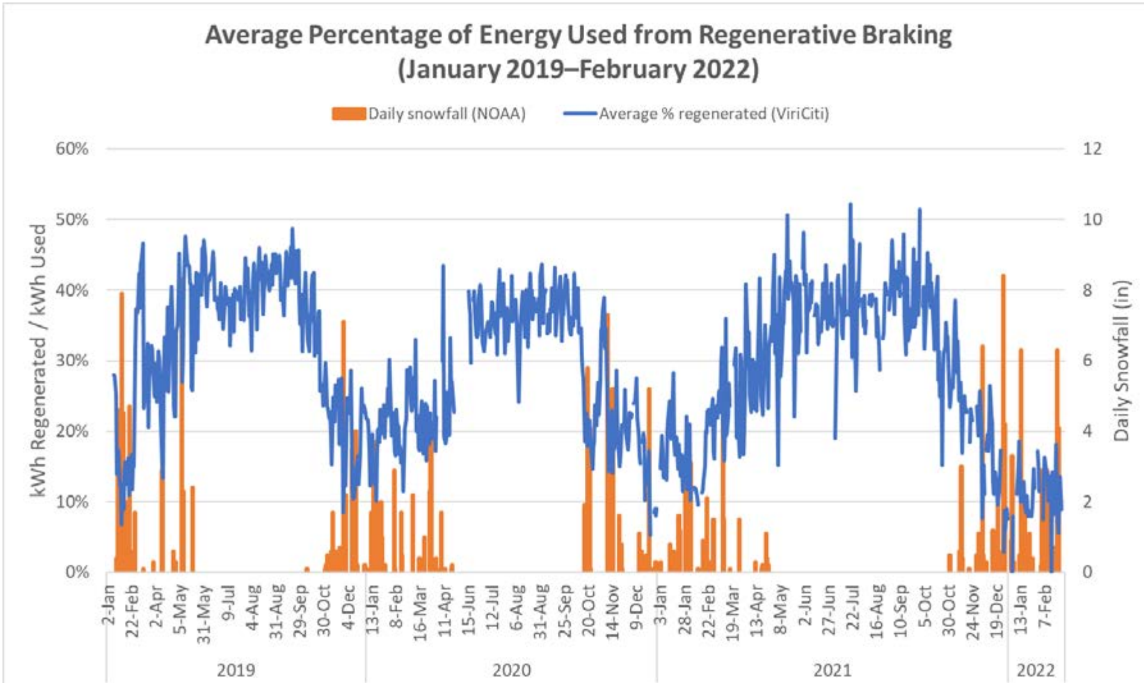


Figure 25. Seasonal correlation between increased snowfall and reduced energy regenerated

Roadcall Analysis

A roadcall, or revenue vehicle system failure (as named in the National Transit Database[8]), is defined as a failure of an in-service bus that causes the bus to be replaced en route or causes a significant delay in schedule. If the problem with the bus can be resolved 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 en route, such as interlocks (doors, air system), engines, or things that are deemed to be safety issues if operation of the bus continues. They do not include roadcalls for problems with radios, fareboxes, or destination signs.

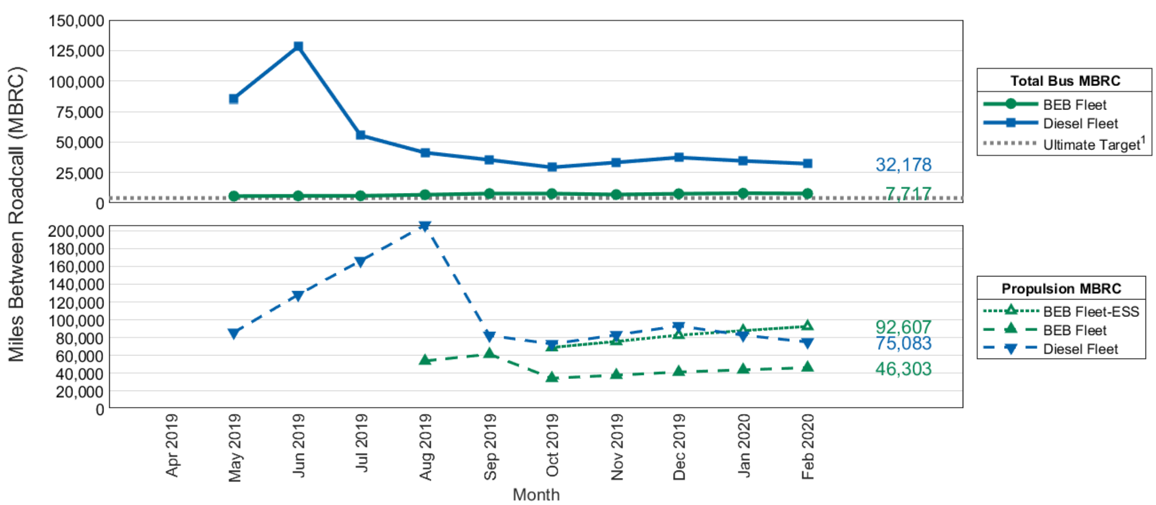
The transit industry measures reliability as mean distance between failures, also documented as miles between roadcalls (MBRC). Table 7 provides the MBRC for the BEBs and diesel buses categorized by bus roadcalls, propulsion-related roadcalls, and ESS-related roadcalls. Propulsion-related roadcalls include all roadcalls due to propulsion-related systems, including the battery system (or engine for a conventional bus), electric drive, fuel, exhaust, air intake, cooling, non-lighting electrical, and transmission systems. The ESS-related roadcalls and ESS-related MBRC are included only for the BEBs. This roadcall analysis includes data accumulated from April 2019 through February 2020.

[8] U.S. Department of Transportation Federal Transit Administration. "The National Transit Database." www.transit.dot.gov/ntd.

Table 7. Roadcalls and MBRC

	BEB Fleet	Diesel Fleet
Data collection period	April 2019–February 2020	April 2019–February 2020
Months	11	11
Total fleet miles	92,607	450,497
Bus-related roadcalls	12	14
Bus-related MBRC	7,717	32,178
Propulsion-related roadcalls	2	6
Propulsion-related MBRC	46,303	75,083
ESS-related roadcalls	1	—
ESS-related MBRC	92,607	—

Figure 26 presents the cumulative MBRC by category for the BEBs and diesel baseline buses. The upper plot tracks the overall MBRC for the two bus fleets; the lower plot tracks the MBRC for propulsion-only roadcalls for both fleets and ESS-related roadcalls for the BEBs. The U.S. Department of Energy and FTA have not established performance targets specific to BEBs, but the MBRC targets established for fuel cell electric buses[9] were based on typical conventional buses, and the targets could be considered appropriate for any advanced technology. The ultimate target for bus MBRC (4,000 miles) is included in the upper plot of Figure 26 as a black dotted line for reference. The overall MBRC for the BEBs (7,717 miles) is much lower than the incumbent diesel technology (32,178 miles), but the cumulative trend for BEBs was consistently above 5,000 miles and increasing slowly over this data collection period. The DTA BEBs have achieved a propulsion-related MBRC of 46,303 miles compared to 75,083 miles for the diesel buses. Understanding the true trends for this type of reliability metric requires a long period of continuous and complete data collection.



1. Ultimate Target adopted from: FCTO Program Record #12012, Sept. 2012, *http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf*

Figure 26. Cumulative bus MBRC and propulsion-related MBRC

[9] U.S. Department of Energy. 2012. “Fuel Cell Bus Targets.” Fuel Cell Technologies Program Record # 12012. www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf.

Emissions Savings

The emissions analysis outlined in this section was conducted by CTE as part of its BEB analysis for DTA. Table 8 provides a list of the tailpipe emissions avoided by use of the BEB fleet based on an estimated reduction of more than 55,000 gallons of diesel fuel, from the start of service through December 2021. Table 9 summarizes the total greenhouse gas emissions reductions for the BEB fleet. Considering both the emissions from the grid to charge the buses and from diesel-fired heaters, DTA has saved more than 357,000 lbs of greenhouse gas emissions by using the BEBs. This is equivalent to the carbon removed from the air by 4,161 tree seedlings over a 10-year period.

Table 8. Tailpipe Emissions Reduced (November 2018–December 2021)

Metric	Savings	Unit
Diesel fuel avoided	55,754	gal
Greenhouse gases	1,279,559	lbs
CO_2	1,247,779	lbs
CO	424	lbs
Nitrogen oxides (NO_x)	24,420	grams
Volatile organic compounds (VOCs)	2,286	grams
PM2.5	1,004	grams
PM10	1,115	grams

Table 9. Greenhouse Gas Emissions Reductions for the BEB Fleet

Metric	Greenhouse Gases (lbs)
Diesel emissions avoided [a]	1,279,559
Grid emissions for charging electricity [b]	874,160
Diesel heater emissions	47,655
Overall savings	357,744

[a] Based on observed miles per gallon from March 2019–February 2020

[b] Based on the carbon intensity of the Minnesota electric grid, per the U.S. Energy Information Administration (https://www.eia.gov/electricity/state/minnesota/index.php)

Technical Issues and Resolutions

NREL typically collects detailed maintenance work orders to conduct an analysis of costs by system for ZEB evaluations. Because the DTA BEBs were under warranty, all early maintenance work was handled by the manufacturer. NREL does not include warranty work in the cost calculations because that is covered by the capital cost of the buses. By April 2019, DTA mechanics were handling most of the maintenance work; however, these records were not available for analysis. This section describes some of the technical issues encountered by DTA, along with the solutions required to address the issues. The general issues with the project are described first, followed by issues specific to winter and snowy road conditions.

General Issues

In the early days of the BEB deployment, DTA staff admit to a steep learning curve on understanding the various telematics messages on the BEBs that are not typically found on a diesel bus. One example might be unfamiliarity with the concept of "self-healing" advisory indicators in the bus telematics system. Self-healing is a process where a bus may indicate an issue using a code that is later rectified as the bus is operated. For example, during cold weather, a dash advisory would flash that the transmission was shifting slower than normal. Although it was nearly indiscernible to the bus operator, the BEB telematics would notify the bus and DTA of an anomaly. When the indicator light flashed, DTA's policy was to take the bus out of service to evaluate it. As DTA became more familiar with the operation of the BEBs, they learned that as the bus warms up, the transmission returns to normal operation and the advisory indicator "self-heals" and clears itself.

The BEBs have a much more sophisticated telematics reporting system than traditional diesel buses, and thus BEBs appear to have more issues with internal systems than diesel buses because there are no comparable metrics in the diesel buses. As DTA continues to evaluate the BEBs, the unique BEB indicators are monitored in real time. DTA no longer removes the BEBs from service for some indicators that convey non-operational issues, such as a camera surveillance system issue that poses no safety risk to the bus or the riders.

Early in the deployment, there were other factors that caused the DTA BEBs to be removed from service for short periods of time, in addition to the advisory indicators. DTA evaluated different types of steering wheels, door controllers, etc., and removed the buses from service to install the equipment. BEBs were also removed from service to retrain drivers on the particulars of operating a BEB on Duluth's hills. Diesel buses roll backwards when sitting on an incline, which can be mitigated by holding a foot on the brake and quickly transitioning to the accelerator pedal, or "feathering" the accelerator to keep the bus from rolling back if the wait is only a few seconds. The BEBs must be operated differently; braking and accelerating simultaneously causes the bus to pause, resulting in a longer-than-normal rollback. Upon DTA's request, the original equipment manufacturer (OEM) quickly reprogrammed the BEBs to a zero-rollback function, which is now standard on all new vehicles. Early in the deployment, DTA removed the BEBs from service for a week until the reprogramming was complete and all drivers were trained on operating a BEB on an incline.

Axle weight: The original specification of the buses included an axle that was undersized, with a weight rating that was less than the weight of a fully loaded bus. This undersized axle would limit the number of standees and result in fewer passengers allowed on the buses. The solution required new axles to be manufactured for retrofit on the buses. DTA had already received the first two buses when this issue was discovered. The retrofit of the first two buses was handled at a local shop, and DTA opted to delay delivery of the remaining BEBs until the axle changes could be made.

Low-voltage batteries: DTA has experienced several issues with low-voltage batteries on the BEB fleet. The batteries would go dead within weeks of being charged. Early in the DTA deployment, advisory indicators for auxiliary systems on the buses, such as a camera system or the electronic control module (ECM), were occurring at a much higher rate on the BEBs than on the diesel buses. Because of the indicator, DTA removed the BEB from service to investigate the cause and was often unable to identify an issue. DTA technicians were eventually able to correlate the increased number of advisory indicators in auxiliary bus systems to a low state of charge in the low-voltage battery system. As they began charging up the low-voltage batteries as part of their maintenance routine, the advisory indicators substantially decreased. Nonetheless, the low-voltage batteries are replaced more often than on the diesel buses. Proterra recognized the problem and has been on a campaign to retrofit their older buses with protectors to prevent the low-voltage batteries from draining so quickly.

Extended downtime for repairs: Downtime for BEBs that needed troubleshooting and repair was compounded by several factors. First, DTA experienced problems with parts availability and supply chain issues for several repairs on the BEBs, partly due to the COVID-19 pandemic. In some cases, parts being shipped from overseas were delayed. These problems caused some BEB issues to go unresolved for long periods of time. The issues also affected the diesel buses, causing delays up to one year in some cases.

DTA staff triages bus repairs as frequently as necessary to ensure that enough buses are available to meet DTA service requirements. BEB and diesel bus repairs are prioritized based on a number of factors, including whether the issue had already been diagnosed or could likely be diagnosed quickly, the complexity of the repair, whether or not parts are available for the repair, or capability of available staff to perform the repairs. Because DTA was an early adopter, the BEB manufacturer's troubleshooting manual was not as detailed as it is now, causing some delays in repairs as staff conducted additional research. Some BEB repairs were delayed until the BEB manufacturer's engineers evaluated the root cause of an issue and established a best practice for the repair.

As DTA technicians continue to repair the buses and the BEB technical staff has observed causes and outcomes, the learning curve has flattened substantially, and delays for troubleshooting and repairs have decreased proportionately. This learning curve is not unique to the BEB manufacturers; DTA has worked through this process with multiple manufacturers through the years and will continue to share observations and data with all BEB manufacturers to continue to spur growth and acceptance of the technology.

Downtime due to service needs: Although it is difficult to detect in the aggregate bus data, some diesel buses are limited in service similar to the BEB buses. DTA's 35-foot diesel buses cannot serve high-passenger-load routes and are allocated to off-peak hours and days when they can meet the service demands. Older diesel buses and BEBs are not deployed on runs that go late into the night or on weekends. Newer buses are deployed on those runs to minimize the risk of a bus breaking down when there are fewer maintenance personnel available to respond to calls for assistance. Because the BEBs only make up 10% of the DTA's fleet, the appearance that they were not as available is distorted by these factors that were not measured on specific segments of the diesel fleet.

Chargers: DTA experienced a catastrophic failure of one of its chargers. The root cause was traced to a capacitor quality issue—the capacitor overheated, resulting in off-gassing of hydrocarbons including propane. The sealed charger cabinet allowed a buildup of propane that reached the flammability limit. A spark ignited the gas, which over pressurized the sealed enclosure and caused a failure of a fastener on the cover and partial expulsion of the plastic outer door. The charger OEM (Tritium) replaced the unit at DTA. Tritium replaced the capacitors on all units with ones from a different manufacturer. During the investigation, Tritium discovered the charger had a specific error code about 12 to 18 hours before the failure. To avoid future issues, Tritium has added a software update that will shut down a charger if that code is triggered. After shutdown, the charger can only be reactivated by a technician after it has been thoroughly inspected for potential issues. To avoid issues at other locations, Tritium has replaced all capacitors and instituted the software solution in all its chargers.

In the months following the end of the BEB evaluation, DTA continues to experience other cascading maintenance issues with the chargers that are unrelated to the capacitors. Two chargers have been replaced by the manufacturer, but they do not seem to be able to meet the heavy use of a transit system. DTA's chargers are exhibiting frequent failures, in part due to the lack of parts and inability of the manufacturer to diagnose issues remotely. DTA has been forced to periodically park the BEB fleet due to the unavailability of chargers and continues to seek resolution to the ongoing reliability issues with these chargers.

Issues Specific to Winter Performance and Snowy Road Conditions

Regenerative braking issues: Slick, snowy roads present a challenge for buses with regenerative braking. A safety feature on electric drive buses deactivates the regenerative braking when the traction control system engages due to wheel-slip. The regenerative braking is reactivated once the bus comes to a complete stop. This drivetrain behavior results in lower energy efficiency for the buses during snowy weather, which effectively reduces the driving range. However, the regenerative braking is an asset for DTA due to Duluth's topography, as it improves range and performance during favorable weather.

Interior heating: Anticipating potential issues with heating the interior of the buses, DTA opted for a cold weather package for the BEBs, which included a diesel-fired auxiliary heater, pump, and convector fans to help keep drivers and passengers warm during the colder months. The agency also wanted to minimize range reductions from using the electrically driven heater as a primary heat source. Early into the deployment, the buses were experiencing range issues during cold weather and the drivers complained about their area being too cold. To keep the driver compartment warm, drivers would often operate the defroster constantly throughout the day, which, being powered by electricity, had a considerable effect on the bus's energy efficiency and effectively reduced operating range. Proterra made several upgrades to address these issues. They reprogrammed the software controlling the heat to use the diesel heaters as the primary source of heat and set the electric heaters as secondary (original programming had the electric heaters as primary, supplementing with the diesel heaters). To improve the driver area heating, Proterra added heated seats and an additional convector to route warm air from the auxiliary heater to the driver's area. Lastly, they resolved an issue with the defroster. The original design had the electric heater providing heat to the defroster. However, the available heat was not sufficient during the coldest days and lowered the efficiency of the buses. Proterra changed the software to use the auxiliary heater to handle defrost. These changes resolved most of the operator's cold weather complaints.

Corrosion: DTA experienced multiple issues with corrosion on the buses (brakes, electrical connectors) due to frequent cold and snowy conditions and exposure to corrosive agents such as road salt. Proterra installed splash guards and other covers to protect sections of the undercarriage and help alleviate the problem.

Power steering pump: The DTA BEB deployment also highlighted other issues unique to a cold weather environment. DTA experienced high-pitched squealing from the power steering pump during extreme cold weather (−30°F). It performed properly, but DTA would not deploy the BEBs in the cold because the loud noise caused concern from the passengers. DTA discovered that because there is minimal waste heat generated on the BEB compared to a combustion engine, the power steering fluid and fluid lines remained cold and made more noise when the pump was engaged. The OEM resolved the issue by installing a larger power steering fluid tank and hoses on the BEBs to handle the more viscous fluid in cold weather. Consequently, there were days when the BEBs could have otherwise been placed into service but were held out due to DTA policy rather than a true unavailability of the buses. Public perception of the safety of the buses is crucial to their long-term success, and DTA did not want riders to lose confidence in the ability of the BEBs in cold weather.

Summary of DTA Experience

As with all new technology development, lessons learned during this project could help other agencies considering BEB technology. One of NREL's goals for advanced-technology vehicle evaluation is to document the experience of early adopter transit agencies and share critical lessons learned with the rest of the industry to increase the successful deployment of these vehicles elsewhere in similar service. In addition, highlighting remaining challenges can help support technology improvements in next-generation ZEBs.

Advanced-technology demonstrations typically experience unexpected challenges and issues that need to be resolved. Most of DTA's challenges with the BEB fleet involved issues with their performance in cold temperatures and on snowy roads. DTA anticipated the possibility of some of these issues and included the cold weather package in the specifications of the BEBs. Even with the additional HVAC ducting and auxiliary heater, the agency had to work with the OEM to adjust the system to meet requirements for keeping the driver and passengers warm during colder days.

For other transit agencies in cold climates, DTA stresses that understanding the service requirements and how weather conditions affect range is extremely important. Specific recommendations are:

- Analyze current routes for energy use and match the BEBs with routes that are within your specific technology's capabilities.
- Determine well in advance whether on-route or depot charging makes more sense for your agency's operations, to avoid complications during the bid process.
- Understand that colder conditions will lower the range of the BEBs and plan winter route assignments accordingly.
- Be aware that snowy roads will reduce the BEBs' use of regenerative braking and result in increased energy use.
- Consider auxiliary heating to keep drivers and passengers comfortable and minimize the energy used by electric heaters in very cold weather.

DTA reports that access to performance data on the BEBs was vital to their understanding of how the buses operated in the service and aided in the learning curve for implementing a new technology into the fleet. The agency recommends using a third-party data logger and collection system to track bus performance. DTA found the data tracking so valuable that it opted to install the systems on ten of its diesel buses.

Gradual degradation in battery capacity is normal for lithium-based batteries. Over the span of years of operation, a layer in the electrode/electrolyte interface grows in the battery, resulting in electrical isolation and in turn causing the usable capacity of the battery to decrease. DTA purchased a warranty on its batteries from Proterra, covering the battery packs down to 80% of the initial usable capacity. Throughout the deployment, CTE has monitored battery state of health to ensure the buses have retained enough battery capacity to meet service needs and remain above that 80% threshold. CTE and DTA worked with Proterra to ensure an appropriate methodology for performing these estimates. In October 2021, Proterra reduced the restricted portions of DTA's BEB batteries, effectively increasing the usable capacity.

DTA experienced a steep learning curve for maintenance of the BEBs. Proterra handled all maintenance and repair in the early stages when the buses were still under warranty. Over time, the maintenance staff have taken over all diagnostics and repair for the BEBs with occasional assistance from the OEM as needed. DTA reports that, by the fall of 2021, the maintenance staff were self-sufficient with the buses. Repair for the BEBs takes about the same time as the diesel buses.

DTA also worked closely with its electric utility, Minnesota Power, to bolster the financial efficacy of the BEB pilot program. Minnesota Power introduced a Commercial EV electricity rate in March 2020, which capped demand charges at 30% of the total bill and led to a lower electricity cost per mile for the DTA BEBs.

DTA reports that its drivers like the BEBs and feel that the traction is better than the diesel buses. The agency has a good working relationship with its manufacturer and utility partners and has learned a lot about the technology and how it performs in the colder climate of Duluth. As one of the first deployments of its BEBs in a northern area, Proterra has made numerous design improvements to address cold weather challenges. These improvements have been incorporated into current and next-generation BEB designs.

What's Next for DTA

DTA is committed to continuing their work with bus manufacturers to improve low- and no-emission vehicle technology to meet the needs of transit agencies operating in cold weather climates. DTA's long-term plan is to have 25% of the bus fleet transition to low- or no-emission vehicles no later than 2030, and to accelerate that transition thereafter. The transition may not rely exclusively on battery electric buses, but also other technologies that meet the objective of reducing DTA's carbon footprint and greenhouse gas emissions to the lowest possible level while maintaining service requirements.

DTA is also committed to serving as a resource for other agencies and industries to spur further adoption of low- and no-emission fleet vehicles in all types of climates and operating profiles. Their work to help other agencies overcome perceived barriers and take advantage of opportunities that low- and no-emission vehicles offer has reassured fleet operators all over the U.S. that the technology is viable and a worthwhile venture.

Glossary

Term	Definition
Availability	The number of days or shifts the buses are actually available, compared to the days or shifts that the buses are planned for operation, expressed as percentage availability.
Clean point	For each evaluation, NREL works with the project partners to determine a starting point—or clean point—for the data analysis period. The clean point is chosen to avoid some of the early and expected operations problems with a new vehicle going into service, such as early maintenance campaigns. In some cases, reaching the clean point may require 3–6 months of operation before the evaluation can start. This applies to new technology buses as well as conventional buses.
Miles between roadcalls (MBRC)	A measure of reliability calculated by dividing the number of miles traveled by the total number of roadcalls, also known as mean distance between failures. MBRC results in the report are categorized as follows: • Bus MBRC: Includes all chargeable roadcalls. Includes propulsion-related issues as well as problems with bus-related systems such as brakes, suspension, steering, windows, doors, and tires. • Propulsion-related MBRC: Includes roadcalls that are attributed to the propulsion system. Propulsion-related roadcalls can be caused by issues with the transmission, batteries, and electric drive. • ESS-related MBRC: Includes roadcalls attributed to the ESS only (specific to BEBs).
Revenue service	The time when a vehicle is available to the general public with an expectation of carrying fare-paying passengers. Vehicles operated in a fare-free service are also considered revenue service.
Roadcall	A failure of an in-service bus that causes the bus to be replaced en route or causes a significant delay in schedule. The analysis includes chargeable roadcalls that affect the operation of the bus or may cause a safety hazard. Nonchargeable roadcalls can be passenger incidents that require the bus to be cleaned before going back into service, or problems with an accessory, such as a farebox or radio.

Appendix A. DTA Fleet Summary Statistics

Table A-1. DTA—Fleet Operations and Economics

	BEB	Diesel
Number of buses	7	10
Data period start [a]	January 2019	April 2019
Data period end [a]	April 2021	February 2020
Number of months in data period [a]	28	11
Total distance in data period (mi)	218,526	450,497
Average monthly distance per bus (mi)	1,115	4,095
Bus availability (85% is target)	51.8%	88.4%
Charger availability	95.3%	—
Total distance, fuel base (mi)	218,526	400,393
Fuel economy, electric only (kWh/mi)	2.32	—
Fuel economy, including diesel (kWh/mi)	2.64	—
Fuel economy (mpdge)	14.23	4.86
Energy/fuel cost ($/kWh electricity; $/gal diesel)	0.141	1.84
Energy/fuel cost ($/mi)	0.47	0.44
Miles between roadcall (MBRC) – bus	7,717	32,178
MBRC – propulsion system only	46,303	75,083
MBRC – ESS only	92,607	—

[a] Data period start and end dates are not identical for all analysis metrics, depending on data availability

Table A-2. DTA—Fleet Operations and Economics (SI units)

	BEB	Diesel
Number of buses	7	10
Data period start [a]	January 2019	April 2019
Data period end [a]	April 2021	February 2020
Number of months in data period [a]	28	11
Total distance in data period (km)	351,674	644,354
Average monthly distance per bus (km)	1,794	5,858
Bus availability (85% is target)	51.8%	88.4%
Charger availability	95.3%	—
Total distance, fuel base (km)	351,674	644,352
Fuel economy, electric only (kWh/km)	1.44	—
Fuel economy, including diesel (kWh/km)	1.64	—
Fuel economy (L/100 km)	16.53	48.37
Energy/fuel cost ($/kWh electricity; $/L diesel)	0.141	1.14
Energy/fuel cost ($/km)	0.29	0.27
Kilometers between roadcall – bus	12,419	51,784
Kilometers between roadcall – propulsion system only	74,515	120,831
Kilometers between roadcall – ESS only	149,032	—

[a] Data period start and end dates are not identical for all analysis metrics, depending on data availability

Appendix B. Characterization of Conventional Bus Operation

Prior to the delivery of the battery-electric buses to DTA, NREL was interested in characterizing the typical operation of DTA's existing fleet of conventional transit buses. To this end, NREL installed data loggers on a subset of conventional buses to record their normal service on a variety of routes as they were randomly dispatched into service.

A total of seven buses were instrumented—five diesel buses and two diesel hybrids. Figure B-1 shows an example of the ISAAC data loggers that were connected to each bus's controller area network (CAN) to record 1-Hz data of the bus operation every time the vehicle was keyed on. The primary operating parameters collected by the loggers include odometer, vehicle speed, Global Positioning System (GPS) coordinates, engine speed, and diesel fuel rate.

Figure B-1. ISAAC data logger used for preliminary data collection

Photo by M. Jeffers, NREL

The data collection period for the data loggers covered 42 calendar days, from April 4 through May 15, 2018. A total of 250 vehicle days of operation were collected during that time, and at least 29 days of operation were collected for each of the seven instrumented buses. The calendar plot in Figure B-2 displays the total vehicle miles traveled by the instrumented sub-fleet during the data collection period. One or more buses were operated nearly every day of the period, and operation was captured for every day of the week, with Sunday having the lightest service requirements. Figure B-3 shows a map of the routes traveled by the instrumented buses, which collectively covered the vast majority of DTA's service territory and totaled nearly 30,000 miles of operation.

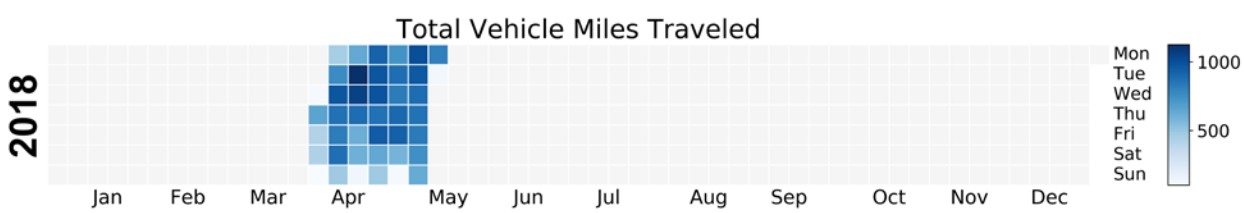


Figure B-2. Calendar plot of daily vehicle miles traveled during preliminary data collection

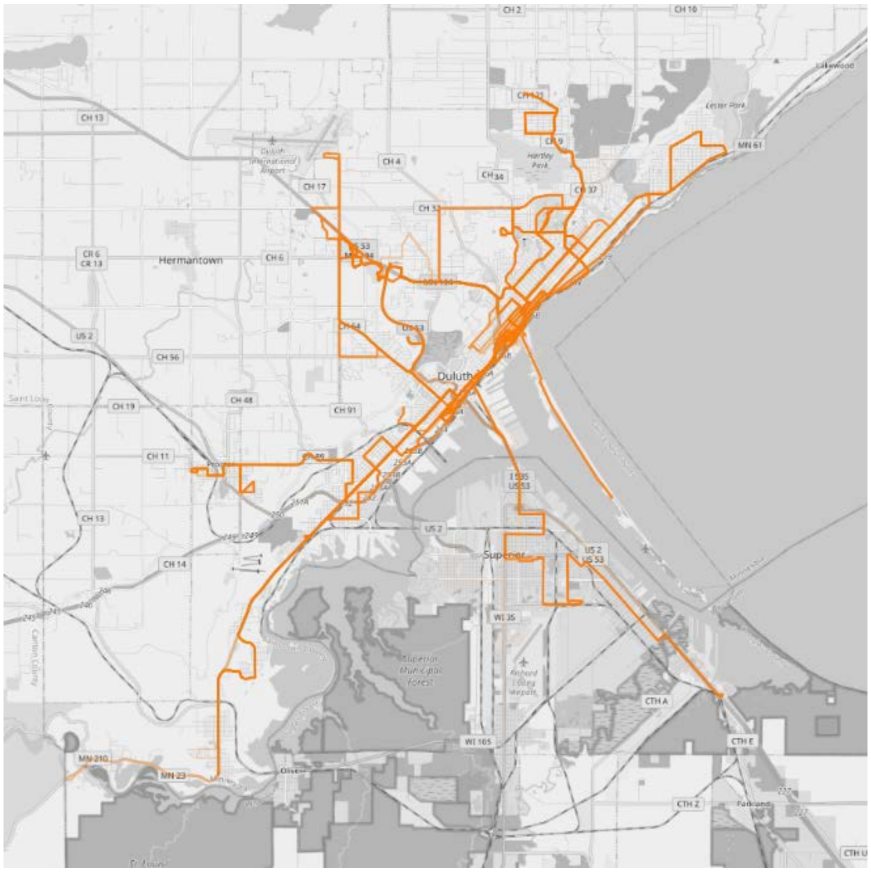


Figure B-3. Map of DTA bus routes traveled during preliminary data collection

Table B-1 provides a summary of operating statistics for the instrumented sub-fleet. Most buses traveled more than 240 miles during their longest day, although the average daily distances for the buses were all between 99–133 miles.

The two diesel hybrid buses (labeled 127H and 128H) tended to have shorter operating days, in terms of daily distance and hours of operation, and they also demonstrated a higher fraction of daily driving time—with correspondingly lower fraction of idle time—than the standard diesel buses. These statistics are largely dictated by the scheduled routes for the hybrid buses, but the reduced idle fraction also highlights the benefit of the hybrid powertrain.

Table B-1. DTA Conventional Bus Operating Statistics

Vehicle ID	Vehicle Days	Max. Daily Distance [mi]	Avg. Daily Distance [mi]	Max. Operating Hours [h]	Avg. Operating Hours [h]	Avg. Driving Speed [mph]	Avg. Fuel Economy [mpg]	Avg. Driving Time Fraction [%]	Avg. Idle Time Fraction [%]
127H	30	207.5	99.4	14.8	7.6	19.0	6.30	70.7	29.3
128H	29	173.8	103.1	12.2	7.7	18.2	6.38	75.0	25.0
152	38	244.7	113.8	20.1	9.3	19.2	5.36	65.7	34.3
154	38	244.4	124.3	19.9	10.0	19.5	5.31	65.1	34.9
155	40	242.0	132.8	19.5	10.6	19.6	5.58	65.4	34.6
156	38	242.1	125.3	19.6	10.2	19.3	5.64	65.0	35.0
158	37	243.9	125.8	19.8	10.0	19.7	5.53	65.5	34.5
Fleet	**250**	**244.7**	**119.0**	**20.1**	**9.5**	**19.3**	**5.64**	**66.8**	**33.2**

The following figures show distributions of numerous drive cycle metrics for the sub-fleet of instrumented buses, which are used to help characterize typical bus operation for DTA. Based on the collected data, DTA's buses normally operate between 7–14 hours per day; however, some days require up to 20 hours of operation. Daily distance varies between 90–210 miles per day, with a notable peak just below 100 miles. Approximately 5% of the days require just over 240 miles of driving.

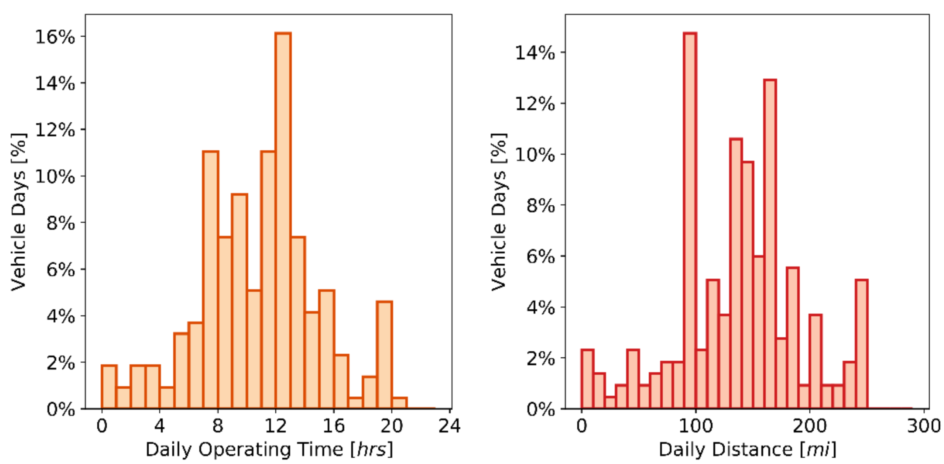


Figure 27. Distribution of daily operating hours and daily distance

Average overall speeds for the buses range from 10–15 mph, whereas average driving speeds (excluding stopped time) were typically closer to 20 mph. The buses normally make 2–4 stops per mile, and the mean stop duration is very often less than 1 minute.

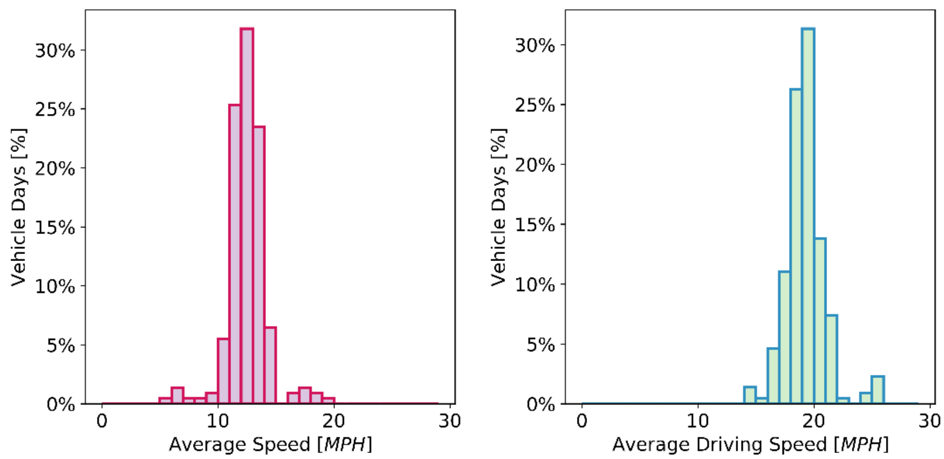


Figure B-5. Distribution of daily average speed (overall) and daily average driving speed

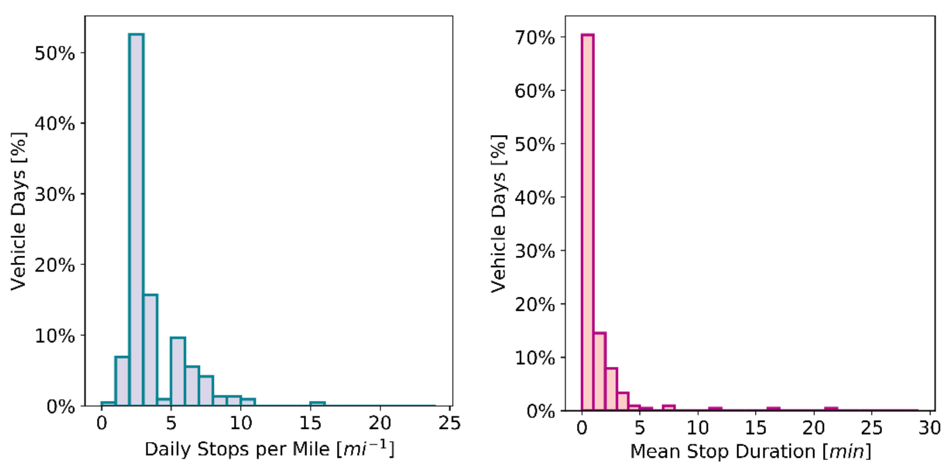


Figure B-6. Distribution of daily stops per mile and mean stop duration

Daily diesel fuel consumption for the conventional buses can vary widely based on scheduled route, driving conditions, ambient weather conditions, and other factors. The distribution in Figure B-7 shows the conventional buses consuming between 14–34 gallons per day for most days during this data collection period. For more than half of the recorded days, 16%–18% of the fuel was consumed while idling (vehicle stopped with the engine on). The plots in Figure B-8 show the difference in fuel consumption and idle fuel fraction between the standard diesel and hybrid diesel buses, and the plots in Figure B-9 show the fuel economy results. The hybrids demonstrated notably higher fuel economy—averaging 6.34 mpg—than the standard diesel buses, which averaged 5.48 mpg.

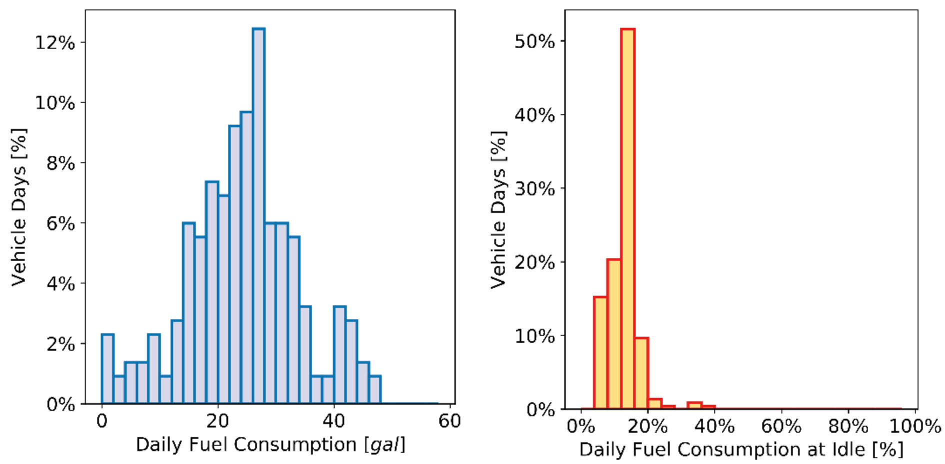


Figure B-7. Distribution of daily fuel consumption and fraction of idle fuel consumption

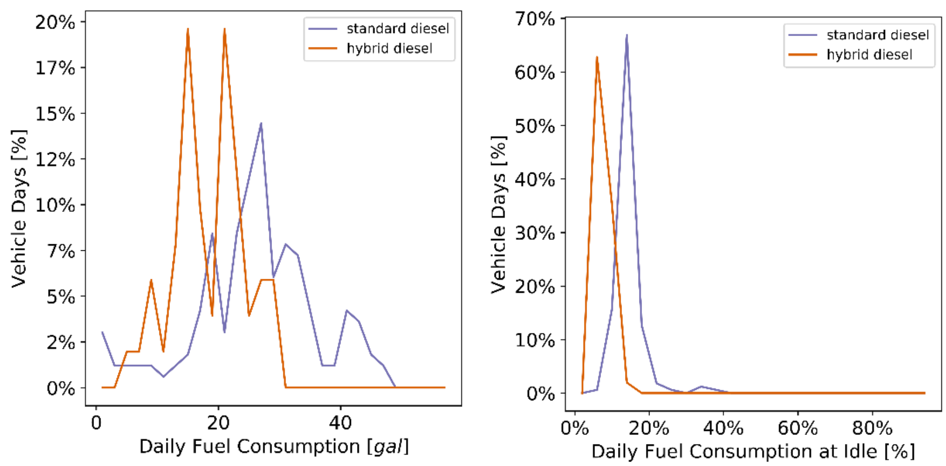


Figure B-8. Distribution of daily fuel consumption and fraction of idle fuel consumption, standard diesel vs. hybrid diesel

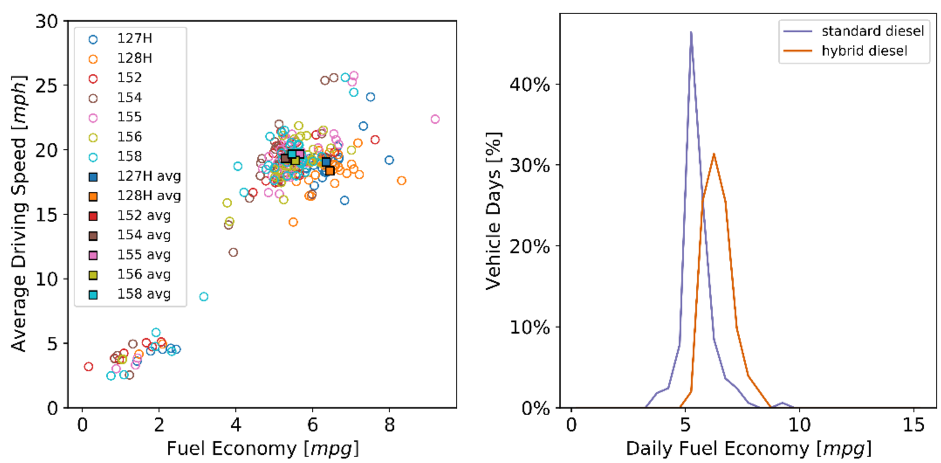


Figure B-9. Average driving speed vs. fuel economy and distribution of fuel economy, standard diesel vs. hybrid diesel

Detailed vehicle speed distributions are provided in Figure B-10, which show the fraction of total operating time (top left) and the fraction of moving time (top right) spent at each vehicle speed. The lower two plots show the fraction of total operating time and fraction of moving time on a cumulative basis. Due to the stop-and-go nature of transit operation, approximately 40% of the cumulative time for the fleet was spent at zero speed (lower left). Nearly 90% of the time was spent at speeds of 30 mph or less, and the buses rarely exceeded 50 mph.

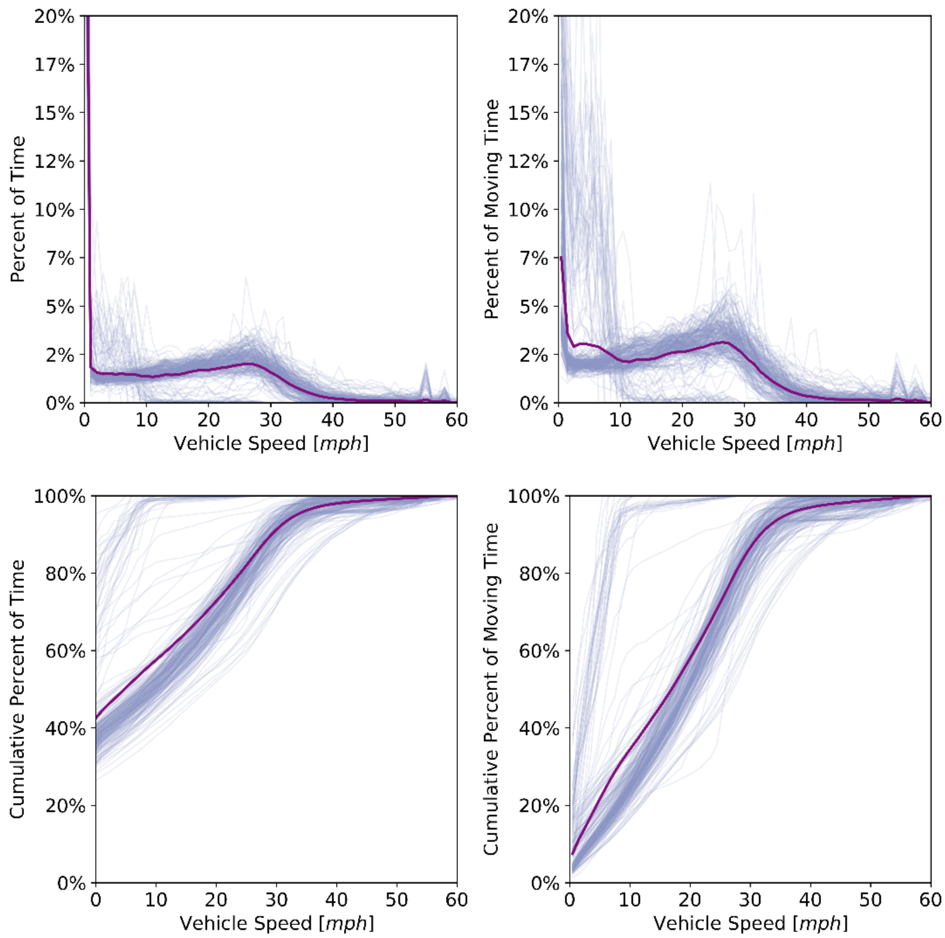


Figure B-10. Vehicle speed distributions