CALIFORNIA ENERGY COMMISSION

California Energy Commission

Clean Transportation Program

FINAL PROJECT REPORT

Los Angeles Department of Transportation and BYD Electric Bus Demonstration

Performance, Maintenance, and Energy Use Summary Report

Prepared for: California Energy Commission

Prepared by: CALSTART

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PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program, formerly known as the Alternative and Renewable Fuel and Vehicle Technology Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued Solicitation Number PON-14-605 to fund medium- and heavy-duty vehicle advanced technology demonstration projects that will lead to commercialization, reduce greenhouse gas emissions, and reduce petroleum use. In response to PON-14-605, the recipient submitted an application, which was proposed for funding in the CEC's notice of proposed awards March 24, 2015, and the agreement was executed as ARV-15-003 on August 01, 2015.

ABSTRACT

With funding from the CEC, CALSTART partnered with the Los Angeles Department of Transportation and BYD Motors to deploy and demonstrate four battery electric transit buses in revenue service in downtown Los Angeles, California. This study collected over twelve months of data from October 2017 to November 2018, and examined the buses on measures of performance, maintenance, as well as cost of ownership and operation. It also compared these measures between the electric buses and Los Angeles Department of Transportation's compressed natural gas buses. This study found that the four electric buses outperformed the compressed natural gas buses in efficiency, operating costs (including fuel costs and maintenance costs), emissions, and fuel consumption. Also, while the cost of the electric buses was higher than the compressed natural gas buses, Los Angeles Department of Transportation's four electric buses had operating costs that were about one-third of the compresse natural gas buses. This was partly due to two reasons: Los Angeles Department of Transportation's favorable overnight depot charging at low base rates with no demand charges, and a maintenance warranty placed on the electric buses by BYD. With these operating cost savings, Los Angeles Department of Transportation can expect a simple payback period on the premium of the electric bus price in about 10 years, and less than eight years at BYD's current, lower price for the same bus, both within the typical service life of a transit bus of 12 years. With respect to maintenance, while the electric buses outperformed the compressed natural gas buses in terms of cost, one of the buses did experience two recurring issues that put it out of service for a significant amount of time: a faulty charger cooling system and a damaged battery pack cover causing water damage to the battery. Additionally, the buses were under warranty by BYD, lowering the actual maintenance costs incurred by Los Angeles Department of Transportation. Importantly, this study was limited to the operations of only four electric buses. Los Angeles Department of Transportation and other transit fleets should take scale into consideration as electrifying a larger number of buses will likely change capital and operating costs and will present challenges to other facets of fleet operations including scheduling, charging optimization, electricity demand, and maintenance.

Keywords: bus, BYD, CALSTART, California Energy Commission, electric, fleet, fuels, LADOT, Los Angeles, transit, transportation, zero-emission

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EXECUTIVE SUMMARY

This report presents the findings from an evaluation of four battery electric transit buses operated in revenue service for the Los Angeles Department of Transportation. Los Angeles Department of Transportation, committed to transitioning its fleet to all electric vehicles by 2030, demonstrated four BYD transit buses on two urban routes in Los Angeles, California from March 2017 through April 2019. Los Angeles Department of Transportation purchased the buses through a grant provided by the CEC. The grant also funded this study on the four electric buses compared to Los Angeles Department of Transportation's compressed natural gas buses. The goal of this project was to demonstrate battery electric bus technology, evaluate their use on Los Angeles Department of Transportation routes, and share the knowledge with the industry. To do so, CALSTART evaluated the buses on performance, operating costs, reliability and availability, and maintenance. This report does not include any analysis on the costs (capital or maintenance) associated with charging infrastructure.

BYD manufactured the four electric buses used in this study. All of them were 35 feet long with a nominal driving range of 145 miles and a top driving speed of 62.1 miles per hour. To charge the buses, Los Angeles Department of Transportation installed four vehicle chargers at their depot on East Washington Boulevard in downtown Los Angeles. CALSTART collected and analyzed data from two sources: ViriCiti data loggers and manually recorded data provided by Los Angeles Department of Transportation. While the demonstration lasted from March 2017 through April 2019, not all four buses started service in March 2017. Bus 17301 started on March 01, 2017; 17302 started on April 26, 2017; and, 17303 and 17304 started on September 01, 2017. Additionally, the first date for which ViriCiti data became available was October 21, 2017. As CALSTART's began analysis on November 16, 2018, the researchers collected and analyzed over twelve months of data ranging from October 21, 2017 to November 15, 2018.

Los Angeles Department of Transportation operated the buses on two routes: the DASH A Downtown Route, an all-urban route serving part of Downtown Los Angeles, and the DASH Observatory Route, which has a 750-foot change in elevation. CALSTART compared bus performance between the two routes to determine what effect the altitude change had on performance.

Overall, the study found that the electric buses outperformed the compressed natural gas buses in multiple ways but raised some concerns in terms of maintenance and reliability. First, the electric buses had an overall efficiency of 1.81 kilowatt-hours (kWh)/mile based on energy consumed by the vehicle, and 2.00 kWh/mile based on energy measured at the charger. By comparison, compressed natural gas buses showed an efficiency of 0.47 gasoline gallon equivalent per mile, equivalent to 15.56 kWh/mile, which is over eight times worse than that of the electric buses.

The electric buses also had operating costs (including electricity plus maintenance costs) that were about one-third of compressed natural gas bus operating costs. At an average charging cost of $0.23/mile and an average maintenance cost of $0.23/mile, the electric buses had a total operating cost of $0.46/mile. The compressed natural gas buses had an average fueling cost of $0.83/mile and an average maintenance cost of $0.44/mile, totaling $1.27/mile. Los

Angeles Department of Transportation can attribute the rather low electricity costs to their ability to charge overnight at the depot during Los Angeles Department of Water and Power's (LADWP) base rate hours, which imposed no demand charges. Likewise, the relatively low maintenance cost per mile can be attributed, in part, to a warranty that BYD placed on the buses, covering some of the recurring maintenance costs. Los Angeles Department of Transportation's favorable charging and maintenance position should be considered by other fleets interested in adopting electric transit bus technology, as it may change from one transit property to the next.

In addition to efficiency and operating cost improvements, use of the electric buses provide significant reductions in emissions and fuel. CALSTART contracted with Engine, Fuel, and Emissions Engineering, Inc. to conduct portable emissions testing on one of Los Angeles Department of Transportation's CNG buses during simulated service. The results indicated that replacing one compressed natural gas bus with an electric bus would reduce the annual emissions of carbon dioxide (CO_2) by 97,300 kilograms, equivalent to taking about 22 typical passenger vehicles off the road. Including other tested criteria emissions – carbon monoxide, nitrogen oxides, total hydrocarbon emissions, and particulate matter – the total amount of emissions reduced per bus per year is 97,800 kilograms.

The electric buses also showed an estimated net fuel cost savings of $18,280 per bus per year. At the projected annual fuel consumption and an average cost of compressed natural gas per gasoline gallon equivalent, Los Angeles Department of Transportation was estimated to spend $24,870 on compressed natural gas per bus per year, while the annual cost of electricity to charge an electric bus was calculated at $6,590, equaling $18,280 in savings.

While CALSTART found evidence of maintenance savings for the electric buses compared to the compressed natural gas buses, it should be taken with reservations for two reasons. First, the buses in this study are relatively new, model year 2017. While the maintenance data herein provides good information for short term maintenance costs, longer term studies should be conducted to fully assess electric bus maintenance. Second, BYD placed a warranty on all four of the electric buses and covered the costs of many repairs, lowering the actual maintenance cost incurred by Los Angeles Department of Transportation.[1]

Several maintenance issues occurred throughout the demonstration, but two issues happened recurrently. First, Los Angeles Department of Transportation experienced ongoing issues with the onboard charging system of one bus (17302), first occurring in September 2017. Upon inspection, BYD discovered that the cooling system surrounding the onboard charging components was damaged. Separately, Bus 17302 experienced charging issues again in March

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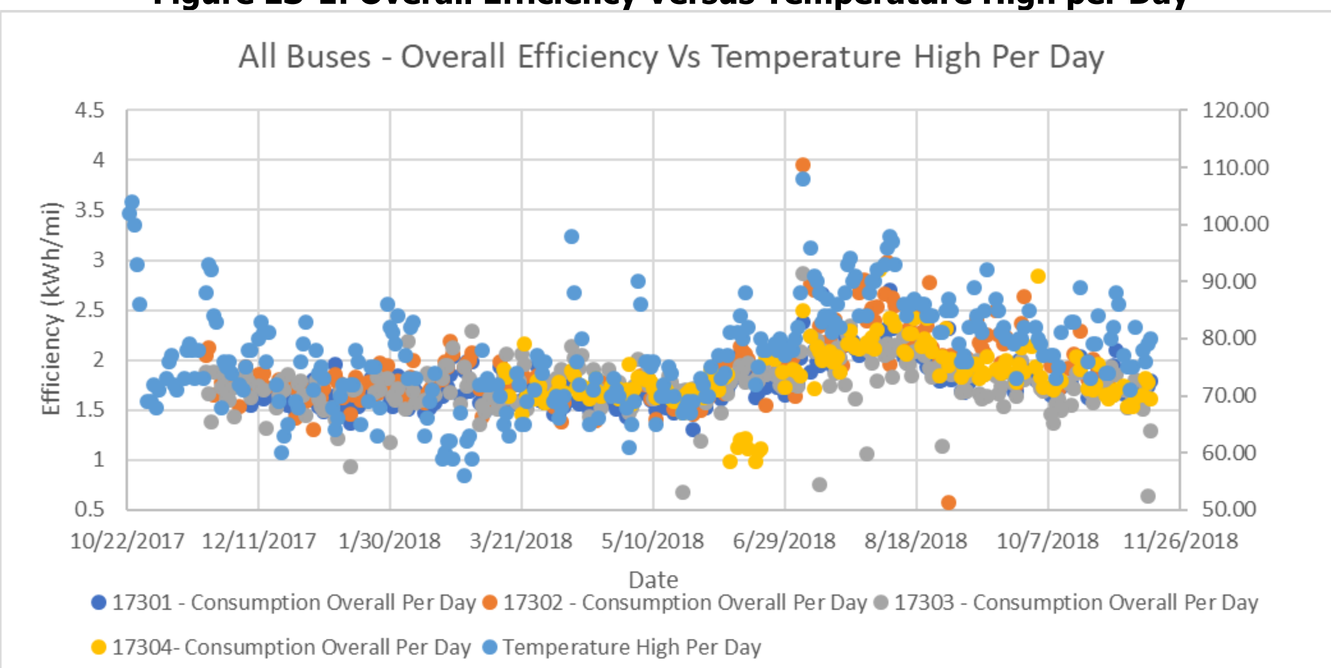
1 BYD's general warranty spans the first two years of operation at 100,000 miles bumper to bumper. The warranty covers all aspects of the bus except cosmetic damage or damage caused by accident. It does not cover the cost of repair on tires, windows, mirrors, or other damage caused by passengers or operators, nor does it cover the facility-side charging infrastructure for the buses. All propulsion related systems on the bus are covered by a 5-year, 350,000-mile warranty. Finally, the battery is covered by a 12-year warranty with a promise to maintain at least 70 percent capacity.

and April 2018. This time, it was due to water leakage in the battery caused by a cracked battery pack cover. While the issue was corrected and repaired, it occurred again in January and February 2019. The issue was repaired again and has been monitored since.

Next, the initial purchase price of the electric buses is significantly higher than that of the compressed natural gas buses. The electric buses in this study cost $778,000 each, and since then the price has dropped to $720,000. By comparison, the compressed natural gas buses cost $525,133 each. Despite the higher price, the estimated savings in operating costs gives Los Angeles Department of Transportation a simple payback period of about 10 years on the premium coming with an electric bus purchase. At the $720,000 price tag, it drops to just under 8 years. Use of the Hybrid and Zero-Emission Truck and Bus Voucher Incentives provided by the State of California would bring down the estimated payback period to just over 3 years.

Beyond cost results, this study also found evidence of a correlation between temperature change and vehicle efficiency. Figure ES-1 shows overall efficiency for each of the electric buses plotted alongside the temperature high per day. As temperature rises from May to October 2018 so does the kWh/mi value for efficiency. Note that higher efficiency values signal worse efficiency measurements. This trend is likely due to the use of the air conditioning system during hot summer months, diverting energy away from the driveline and worsening efficiency. A sensitivity analysis to determine the marginal effect of temperature change on efficiency would be a valuable next step in understanding this trend.

Figure ES-1: Overall Efficiency Versus Temperature High per Day



Source: Data from ViriCiti and Los Angeles Department of Transportation, analysis by CALSTART

Regarding electric bus performance on the DASH A Downtown route compared to the DASH Observatory route, the study found only slight differences in efficiency, energy use, distance, and regeneration. The buses had an average efficiency of 1.81 kWh/mi on the DASH A

Downtown route and 1.76 kWh/mi on the DASH Observatory route, a route characterized by a 750-foot change in elevation. The buses also consumed slightly more energy per day on the DASH Observatory route, and they regenerated more energy on this route, likely due to both the longer distance traveled per day on that route as well as the change in elevation.

In terms of reliability, the electric buses were out of service more than the compressed natural gas buses. From January 01, 2017, to March 31, 2019, compressed natural gas bus 17305 was out of service 19 days and compressed natural gas bus 17306 was out of service 21 days, for an average of 20 days. By comparison, the electric buses were out of service an average of 27 days over shorter time spans. Table ES-1 shows the number of days that each electric bus was out of service during the demonstration.

Table ES-1: Electric Bus Reliability Results

Electric Bus Number	Date That the Bus Started Service	Days Out of Service Through March 31, 2019
17301	March 01, 2017	24
17302	April 26, 2017	42
17303	September 01, 2017	18
17304	September 01, 2017	24
Average Across All Electric Buses		**27**

Source: Data from Los Angeles Department of Transportation, Analysis by CALSTART

While this study found that the electric buses, which Los Angeles Department of Transportation demonstrated, performed favorably, it is important to remember that it is limited to the operation of only four buses. Los Angeles Department of Transportation should take scale into consideration for any plans of electric bus fleet expansion. The addition of electric buses will present more challenges for Los Angeles Department of Transportation with respect to capital and operating costs, route scheduling, charging optimization, electricity demand, and maintenance.

Other transit fleets interested in adopting electric transit bus technology should consider the following limitations of this study. First, this study was performed in Los Angeles, California which has a moderate climate year-round. As hot and cold temperatures can impact vehicle performance, it is important to keep geography and climate in mind. Next, this study was conducted in downtown Los Angeles, an urban setting. More rural or suburban locations may impact vehicle performance and use differently. Next, more research on electric bus maintenance costs would be valuable. This study showed promising results for the BYD buses studied, and longer-term studies would help transit properties better prepare for maintaining this recent technology. Finally, other fleets should consider their local utility's electricity rate design. Los Angeles Department of Transportation benefitted from low-cost, overnight charging at base rates with no demand charges. Depending on the local utility's rate structure, other transit properties may have additional challenges in paying for the electricity to charge their buses.

In summary, this study found that the four electric buses demonstrated in revenue service with Los Angeles Department of Transportation performed better than the compressed natural gas buses in terms of efficiency, emissions, fuel consumption, and operating costs. While maintenance savings were evident, they should be taken with reservations due to the warranty on the buses and due to the recent model year of the buses. Additionally, Los Angeles Department of Transportation should consider how these results may change if it decides to scale-up its electric bus fleet. Finally, other transit agencies will benefit from the analysis provided in this report, as Los Angeles Department of Transportation's experience provides a useful case study on the operation of this advanced technology.

CHAPTER 1: Introduction

1.1 LADOT's Current Fleet and Electrification Goals

The Los Angeles Department of Transportation (LADOT) provides public transit services in the City of Los Angeles, California, as well as some areas adjacent to the city. It operates the second-largest fleet in Los Angeles County, consisting of over 350 vehicles and serving over 21 million passengers per year. LADOT currently operates a 100 percent clean-fueled fleet with vehicles powered by compressed natural gas (CNG) and liquid propane gas.[2] Their vehicles operate on three types of routes. Section 2.2 of this report describes them as DASH, Commuter Express, and CityRide routes.[3]

On November 8, 2017, LADOT committed to transition its entire fleet to electric vehicles by the year 2030 or earlier. Approved unanimously by the Los Angeles City Council, this commitment not only set a goal to transition the fleet to 100 percent zero-emission vehicles, but also to grow jobs, to prioritize disadvantaged communities, to integrate renewable energy for powering the vehicles, and to manufacture vehicles as locally as possible.[4]

In 2016 and prior to LADOT's zero-emission commitment, CALSTART partnered with LADOT and battery electric bus manufacturer BYD Motors to deploy and demonstrate four battery electric transit buses on LADOT's DASH A Downtown route.

1.2 BYD's History and Status as an Electric Vehicle Manufacturer

BYD started as a battery manufacturer but has recently grown its business as a battery electric vehicle manufacturer. LADOT chose BYD as the manufacturer and provider of the four battery electric transit buses to be deployed and demonstrated by LADOT in this project. A global company with headquarters for its North America office in Los Angeles, CA and a manufacturing facility in nearby Lancaster, BYD met LADOT's goal of manufacturing electric vehicles as locally as possible.

1.3 Project Purpose and Goals

CALSTART, LADOT, and BYD teamed up with funding from the CEC to deploy and demonstrate four electric buses. For more than a year, the buses operated in service on LADOT's Dash A Downtown route to test that the technology is capable of meeting LADOT's needs in a cost-effective manner. Meanwhile, CALSTART, using data loggers from ViriCiti, monitored the performance of these buses in real time to compare them with baseline CNG buses. Per CEC Agreement Number ARV-15-003 the goal of this project was to demonstrate battery electric

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2 Los Angeles Department of Transportation. (2018). *LADOT Annual Report: Fiscal Year 2017 – 2018*. Los Angeles, CA: LADOT

3 See The Los Angeles Department of Transit Website https://www.ladottransit.com

4 City of Los Angeles. (2017, November 09). *City Council File Number 17-0739*. Retrieved December 12, 2018, from http://clkrep.lacity.org/onlinedocs/2017/17-0739_CA_11-09-2017.pdf

bus technology and publish its performance for the knowledge and benefit of other transit districts. More specific objectives of the agreement were as follows:

- Build four new zero-emission BYD battery-electric buses;
- Conduct a 12-month field demonstration of the buses in disadvantaged communities in Los Angeles; and,
- Demonstrate reduced greenhouse gas emissions and fuel costs.

In addition to collecting and analyzing performance data for the electric buses, CALSTART also held an event titled "Voice of the Customer Commercialization" to further meet the goal of educating transit districts on battery electric transit bus technology and its benefits. Section 1.4: Voice of the Customer Commercialization Event explains the event and its outcomes.

1.4 Voice of the Customer Commercialization Event

To determine fleets' understanding of battery electric transit bus technology, educate them on the technology and its benefits, and to capture feedback from fleets on the opportunities and challenges in adopting such technology, CALSTART held a Voice of the Customer Commercialization Event on January 18, 2017 at the Los Angeles International Airport. CALSTART invited fleets from the 88 cities within Los Angeles County that operate routes similar to LADOT's DASH routes. At the event, attendees listened to speakers from CALSTART, Los Angeles World Airports, Los Angeles Department of Water & Power, Los Angeles Department of Transportation, and BYD. Attendees also had the opportunity to take part in a ride and drive of electric transit buses. Finally, attendees were asked to participate in roundtable discussions on the topic of adopting battery electric transit bus technology.

Upon completion of the Voice of the Customer Commercialization event, fleets seemed to have left the event with a better understanding of the benefits and challenges of operating electric transit buses. Fleets in attendance reported understanding that electric buses have potential to reduce fuel costs and maintenance costs. They also reported becoming more aware of the additional costs of electric charging infrastructure and how that may pose challenges in adopting the technology.

The Voice of the Customer Commercialization event also presented an opportunity for regulators to share various funding opportunities for purchasing these vehicles. Most transit agencies represented at the event reported that they would be interested in purchasing electric buses within the next five years; increasing awareness of available funding programs may have an impact on increasing the volume of electric transit buses produced in California.

More findings from the Voice of the Customer Commercialization event, including roundtable discussion takeaways, as well as pre-event and post-event survey results are available in APPENDIX D: Voice of Customer Commercialization Activities Report.

CHAPTER 2:
Project Specifics

2.1 Vehicle Selection

During the demonstration, LADOT operated four BYD 35-foot, battery electric transit buses. These buses were numbered 17301, 17302, 17303, and 17304 in LADOT's fleet. The electric buses were compared to two CNG-powered El Dorado E-Z Rider II buses of the same model year as the electric buses (2017), numbered 17305 and 17306. The specifications for the electric buses appear in Table 1. Additionally, photos of both the electric bus and the CNG bus it was compared to appear below in Figure 1 and Figure 2.

Table 1: BYD Battery Electric Transit Bus Specifications

Dimensions	
Length	35.8 feet
Width	102 inches
Height	140 inches
Wheelbase	222.7 inches
Curb Weight	28,660 pounds
Gross Vehicle Weight	41,877 pounds
Seats	32+1
Performance	
Top Speed	62.1 miles per hour
Max Gradeability	≥ 18%
Range	≥ 145 miles
Turning Radius	42.7 feet
Approach/Departure Angle	9 / 9 degrees
Chassis	
Front Axle	ZF low floor beam axle RL75A
Rear Axle	BYD in-wheel drive axle
Suspension	Air suspension (with electronically controlled air suspension)
Brakes	Front & rear brakes, ABS, Regenerative braking
Tires	305/70 R 22.5
Powertrain	
Motor Type	AC Synchronous
Continuous Power	100 kW x 2
Max Torque	550 Nm x 2
Battery Type	Iron-Phosphate
Battery Capacity	270 kWh
Charging Capacity	80 kW
Charging Time	3-4 hours

Source: BYD

Figure 1: Photo of the BYD Electric Bus

Source: Los Angeles Department of Transportation

Figure 2: Photo of the El Dorado CNG Bus

Source: CALSTART

2.2 Route Selection

LADOT operates buses on three types of routes: DASH, Commuter Express, and CITYRIDE. DASH routes provide travel within a specific neighborhood as opposed to between neighborhoods; LADOT operates 27 different DASH Routes. Commuter Express routes provide travel between neighborhoods, making a limited number of stops to shorten travel times. LADOT operates 14 different Commuter Express lines. CITYRIDE is a transportation assistance program, providing travel services disabled riders and for riders age 65 and over. This program is more flexible than the other two, offering both a taxi and a dial-a-ride service.

All four electric buses operated on two DASH routes during the demonstration: the DASH A Downtown Route and the DASH Observatory Route. Most of the time, the electric buses operated on the DASH A Downtown Route. This route serves City West, connecting to the 7th Street Metro Center Red, Purple, Blue, and Expo Lines, and then continuing up Figueroa Street to 1st Street serving the Civic Center, Little Tokyo, the Gold Line, and the Arts District. See Figure 3 for a map of the route shown in blue.

Figure 3: DASH A Downtown Route

Source: LADOT

DASH A operates Monday through Friday with no service on Saturdays, Sundays or the following holidays: New Year's Day, Memorial Day, Independence Day, Labor Day, Thanksgiving Day, and Christmas Day. It operates every 7 minutes from 6:00 AM to 6:30 PM. This route deploys nine vehicles to serve it on a daily basis. For more information, Table 2 shows a summary of daily route statistics for buses travelling the DASH A Downtown route.

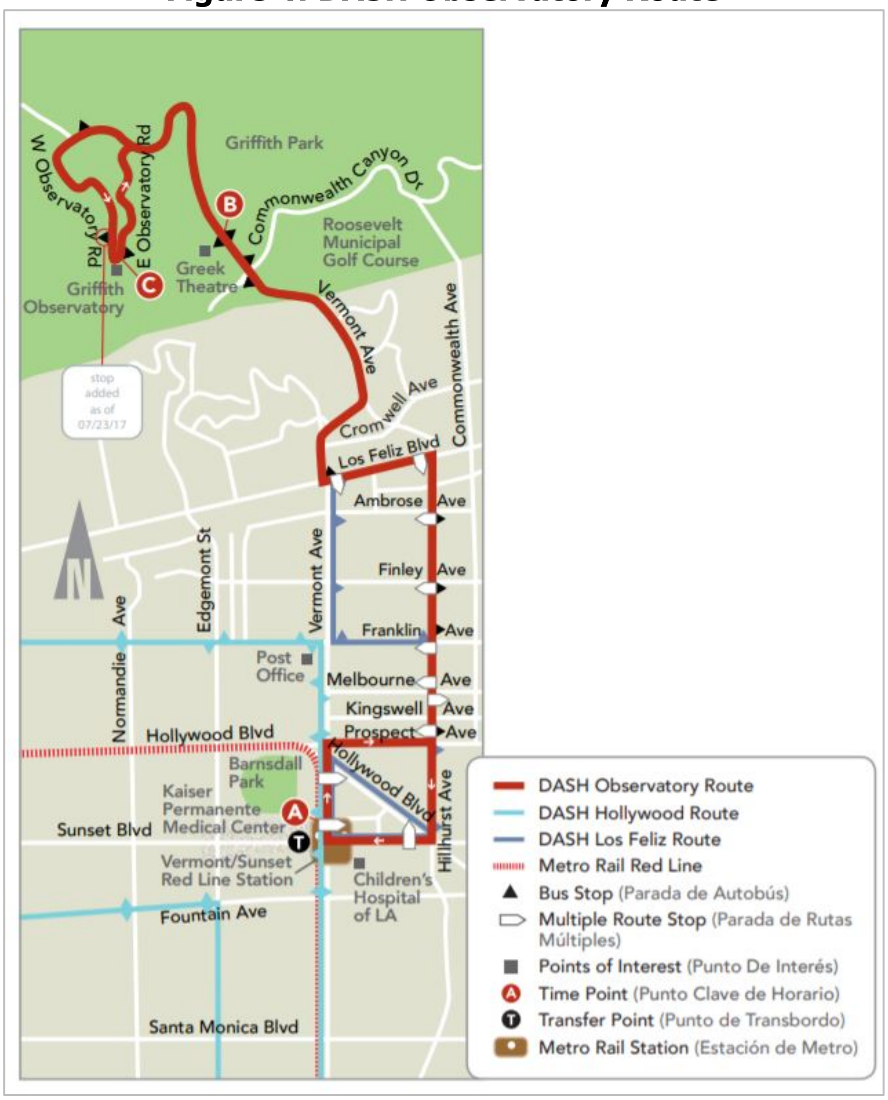
Table 2: Daily Statistics for DASH A Route

Daily Route Statistics	
Revenue Miles	691.2 miles
Total Miles	741 miles
Miles per Bus	76.8 miles
Revenue Hours	113.9 hours
Total Hours	117.1 hours
Hours per Bus	12.7 hours
Number of Trips	108

Source: LADOT

On select weekends, the four electric buses serves the DASH Observatory Route. While LADOT operates buses on this route every day of the year, the electric buses in this study only cover it on weekends. On weekends, this route operates every 20 minutes from 10:00 AM to 10:30 PM. See Figure 4 for a map of the DASH Observatory Route.

Figure 4: DASH Observatory Route



Source: LADOT

This route serves Sunset Boulevard and Vermont Avenue, before traveling up Hillhurst Avenue toward and around Griffith Park and Griffith Observatory. The route presents an uphill climb as the bus travels toward Griffith Observatory, and then downhill travel as it returns toward Sunset and Vermont. The elevation difference is about 750 feet.[5] While the elevation change sets this route apart from the DASH A Downtown route, it is similar in distance at about 7 miles to complete one loop. Table 3 shows a summary of daily route statistics for buses travelling the DASH Observatory route.

Table 3: Daily Statistics for DASH Observatory Route (Saturdays and Sundays Only)

Daily Route Statistics (Saturdays and Sundays Only)	
Revenue Miles	188.10
Total Miles	228.00
Miles per Bus	76.00
Revenue Hours	39.50
Total Hours	42.98
Hours per Bus	14.33
Number of Trips	80.00

Source: LADOT

Due to delays in vehicle deployment, the four electric buses started servicing these two routes on different dates. Table 4 shows the months for which each bus started service for LADOT.

Table 4: Vehicle Deployment Months for Each Electric Bus

Vehicle Deployment and Service Start Months for Each Electric Bus	
Bus Number	**Service Start Month**
17301	March 2017
17302	April 2017
17303	September 2017
17304	September 2017

Source: LADOT

2.3 ViriCiti Data Logger Equipment and Online Portal Details

Data loggers from ViriCiti were installed on each battery electric bus to record performance data throughout the demonstration. The data logger, known as the DataHub, recorded data directly from the onboard controller area network bus (Figure 5).

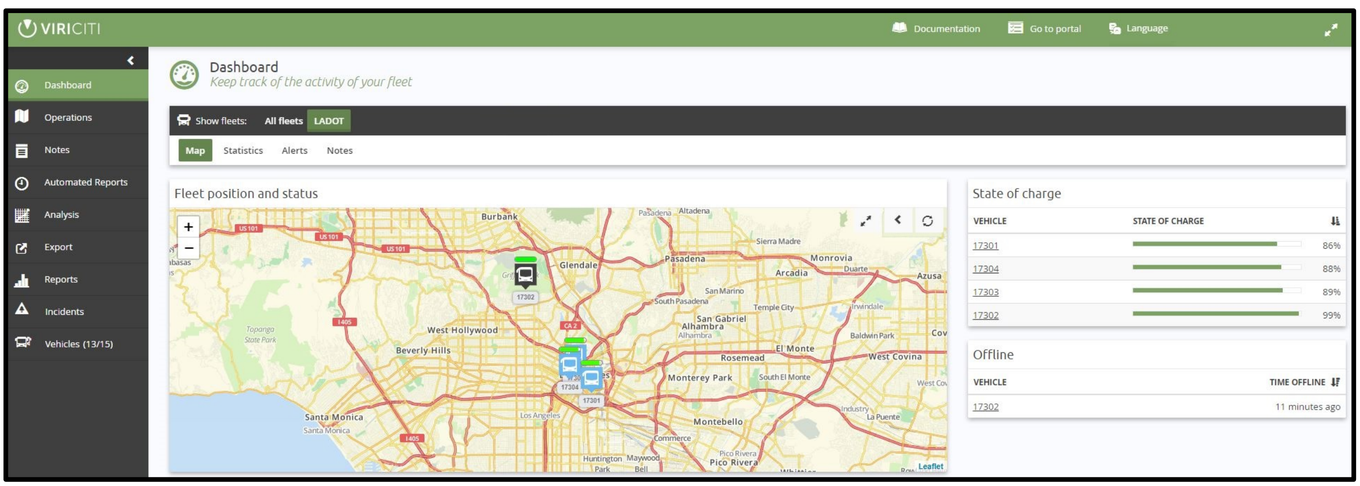
5 According to the United States Geological Survey, the elevation at Griffith Observatory is 1135.25 feet and the elevation at the Vermont/Sunset Metro stop is 385.25 feet. See: Webpage Featuring Location of Griffith Observatory https://viewer.nationalmap.gov/theme/elevation/##bottom

Figure 5: ViriCiti DataHub

Source: ViriCiti

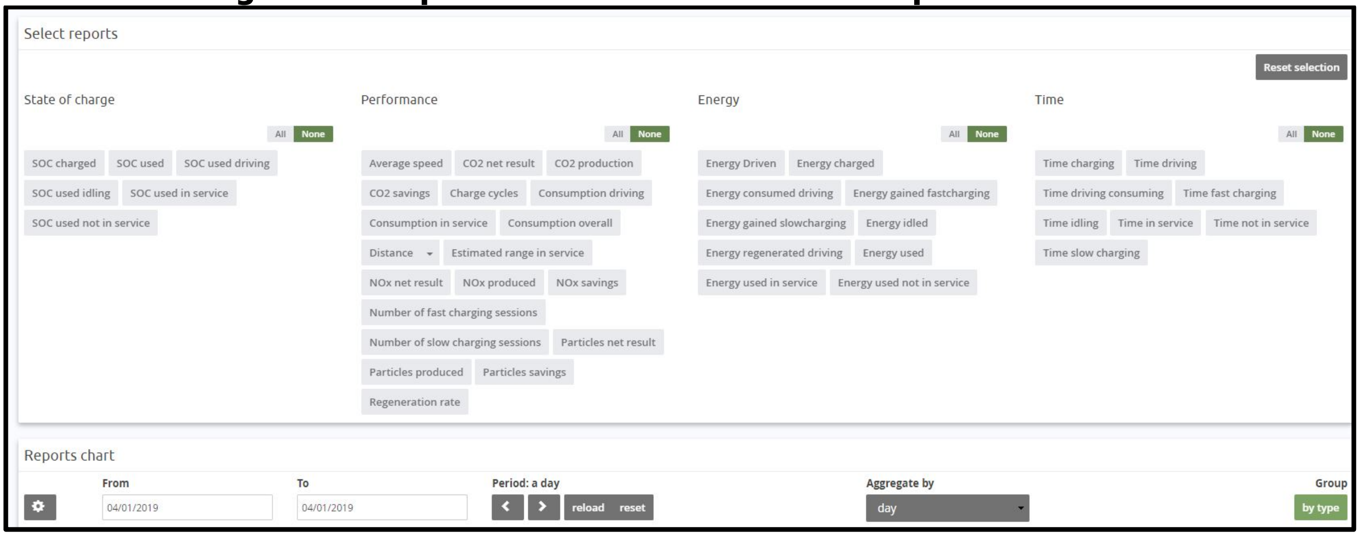
The DataHub, small and compact at 6.5" X 4.5" X 2" and weighing about one pound, collects signals from the vehicle's controller area network bus and location data from global positioning system signals in real time, second by second. The DataHub is equipped with an 800-megahertz processor, one gigabyte of random access memory, and eight gigabytes on-board memory. All data collected by the DataHub is transmitted via Wi-Fi or a global system for mobile communications network, when necessary, to ViriCiti's servers, and the transfer is protected by a 2048-bit encryption. Once transmitted to ViriCiti's servers, all data is made accessible on ViriCiti's online portal, a platform that allows for data analysis and reporting. Figure 6 and Figure 7 and show snapshots of ViriCiti's online portal.

Figure 6: Snapshot of the ViriCiti Online Portal Dashboard



Source: ViriCiti

Figure 7: Snapshot of the ViriCiti Portal - Reports Function



Source: ViriCiti

The online portal makes vehicle data readily available to fleet managers and other users via customizable dashboards, charts, and exports. The dashboard depicted in Figure 6 shows where all the tracked buses are in real time along with their state-of-charge. Portal users may also click the Statistics button to see summary statistics of fleet performance, including energy consumption, efficiency, and distance. Users may also click the Alerts button to see any pending alerts regarding the buses.

CALSTART used, primarily, the Reports function to export data on the electric buses. As shown in Figure 7, the Reports function makes parameters available for export to a comma-seperated value file over any time period and for any time frequency desired. With this function, one simply selects the bus(es) they wish to view, then selects the parameters they wish to analyze, a date range, and how frequently one wishes the data to be aggregated (by day, by hour, by month, by year, etc.). Once all the selections are made, one downloads the data to a comma-seperated value file for further analysis.

2.4 Electric Bus Charging

The buses use four BYD alternating-current, wall-mounted, vehicle charging boxes which were installed at LADOT's bus depot on East Washington Boulevard in downtown Los Angeles, CA. The charger specifications are shown in Table 5 and photos of them can be seen in Figure 8.

Table 5: Charging Box Specifications

Charging Box Specifications	
Input Voltage	3-Phase 480 Voltage Alternating Current
Output Voltage	3-Phase 480 Voltage Alternating Current
Input Current	Max 96 Alternating
Output Current	Max 48 Alternatingx2
Rated Output Power	80 kW
Frequency	60 Hertz
Degree of Protection	IP55
Total Weight	30 kg

Source: BYD

Figure 8: LADOT Depot Chargers

Source: CALSTART

CHAPTER 3:
Data Collection

3.1 Overview

For the duration of the demonstration, CALSTART collected data on each of the four electric buses and two baseline CNG buses in terms of bus performance and maintenance. Using the ViriCiti data loggers and manual logs prepared by LADOT, CALSTART collected daily data and used that data to analyze the performance of the electric buses.

3.2 Electric Bus Performance Data

CALSTART collected data on electric bus performance through two sources: ViriCiti data loggers and manual logs prepared by LADOT. ViriCiti data captured results from the vehicles themselves while LADOT's data captured results on energy usage as the vehicle interfaced with their facilities. Chapter 4 will show how these parameters were processed and used to analyze the electric buses. Every parameter collected and shown in this section consists of raw data provided by the source with no modification or processing by CALSTART.

Table **6** and Table 7 show the breakdown of every parameter collected and the source of each. To see samples of this data from the source, see Appendex E: Raw Data Samples.

Table 6: Electric Bus Performance Data from ViriCiti

ViriCiti Parameter Name	Parameter Alias	Parameter Unit	Parameter Description
Consumption overall	Overall efficiency	kWh/mile	Efficiency of energy consumed while the vehicle is turned on
Consumption driving	Efficiency while driving	kWh/mile	Efficiency of energy consumed while the vehicle is driving only
Consumption in service	Efficiency while in service	kWh/mile	Efficiency of energy consumed while the vehicle is in service
Average speed	-	Miles per hour	Average speed per day
Energy consumed driving	Energy consumed driving (excluding recovered energy)	kWh	Energy consumed while driving, excluding recovered energy
Energy driven	Energy consumed driving (including recovered energy)	kWh	Energy consumed while driving, including recovered energy
Energy idled	-	kWh	Energy consumed while standing still
Energy used in service	-	kWh	Energy used while the vehicle is in service
Energy used not in service	-	kWh	Energy used while the vehicle is not in service
Energy used	-	kWh	Total energy used while the vehicle is switched on
Distance	-	miles	The distance the vehicle has driven in a day, in miles
Energy charged	-	kWh	The amount of energy charged in a day
Energy regenerated driving	-	kWh	The amount of energy regenerated by regenerative braking
State of Charge used	-	%	The amount of energy used while the vehicle was turned on expressed as a percent of the total battery capacity
Regeneration rate	-	%	The amount of energy regenerated expressed in percent of the total amount of energy used while driving

Source: Data from ViriCiti, analysis by CALSTART

Table 7: Electric Bus Performance Data from LADOT

LADOT Parameter Name	Parameter Unit	Parameter Description
Date	MM/DD/YYYY	The date for which data is recorded
Start miles	miles	The number of miles on the odometer when the bus is started each day
End miles	miles	The number of miles on the odometer when the bus stops operating at the end of each day
Total miles	miles	End miles minus start miles
State of charge start	%	The state of charge in percent of total battery capacity as shown on the charger when the bus is started each day
State of charge end	%	The state of charge in percent of total battery capacity as shown on the charger when the bus is plugged into the charger at the end of operation each day
kWh used	kWh	The total amount of energy used while the bus was in operation per day, from the time it was unplugged from the charger to the time it is plugged back into the charger
kWh per mile	kWh/mi	kWh used divided by total miles
kWh charged	kWh	The total amount of energy charged by the bus per day
Temperature high of the day	Fahrenheit	The high temperature per day, in Fahrenheit
Start time	HH:MM	The time that the bus starts operating each day
End time	HH:MM	The time that the bus stops operating each day
Revenue start time	HH:MM	The time that the bus starts revenue service each day
Revenue end time	HH:MM	The time that the bus stops revenue service each day
Revenue total hours	hours	The total amount of hours that the bus is in revenue service each day
Total hours	hours	The total amount of hours that the bus is operating each day
kW rate	$US	The cost of one kilo-watt of electricity as reported by utility bills for LADOT per day
Operation rate	$US	The contracted rate for operating the vehicle

Source: Data from LADOT, analysis by CALSTART

To avoid confusion, CALSTART assigned some ViriCiti parameters aliases (see

Table **6**) which will be referred to throughout this report. This was done because ViriCiti's parameter nomenclature confuses the terms "consumption" and "efficiency". For example, ViriCiti refers to overall vehicle efficiency (kWh/mi) with the name "Consumption overall", which could be confused with energy consumption per unit of time instead of the rate of kWh per mile to which it actually refers. Throughout the remainder of this report, any parameter with an alias will be referred to by its alias, and any parameter without an alias will be referred to by its source parameter name.

3.3 CNG Bus Performance Data

CALSTART collected data on CNG bus performance via manual logs that LADOT provided. As with the electric bus data, the CNG bus parameters collected reflect only raw data that has not been processed or altered in any way by CALSTART. Table 8 shows the breakdown of data collected on CNG bus performance. To see a sample of this data from the source, view APPENDIX E: Raw Data Samples.

Table 8: CNG Bus Performance Data from LADOT

Vehicle Type	Source Parameter Name	Parameter Unit	Parameter Description
CNG	Mileage	Miles	Cumulative number of miles traveled by each bus
CNG	Miles between	Miles	The total number of miles traveled in between dates when the bus was driven (daily mileage)
CNG	Gallons of fuel	GGE	The total amount of fuel consumed on dates when the bus was driven

Source: Data from LADOT, analysis by CALSTART

3.4 Maintenance Data

In addition to performance data, CALSTART also obtained maintenance data for all the electric buses as well as two conventional CNG buses. LADOT provided all maintenance data by sending CALSTART full paper copies of all maintenance logs, preventative and un-planned, for each bus. As in

Table **6** through Table 8, the maintenance data consists of data provided by LADOT with no modification or processing by CALSTART. Table 9 shows what parameters were included in the maintenance logs for both Preventative Maintenance Inspection (PMI) and un-planned work orders. To see a sample of this data from the source, view APPENDIX E: Raw Data Samples.

Table 9: Maintenance Data for Electric and CNG Buses from LADOT

Parameter Name	Parameter Unit	Parameter Description
PMI & Work Order -Date started	MM/DD/YYYY	The date that maintenance starts
PMI & work order -Date completed	MM/DD/YYYY	The date that maintenance ends
PMI & work order -Labor costs	$US	Total labor costs (labor hours times labor rate)
PMI & work order -Parts costs	$US	Total parts costs
PMI & work order -Tires costs	$US	Tire costs
PMI & work order -Warranty costs	$US	Total warranty costs
PMI & work order -Outside costs	$US	Total outside costs
PMI & work order -Shop costs	$US	Total shop costs
PMI & work order -Tax costs	$US	Total tax costs
PMI & work order -Misc. costs	$US	Total miscellaneous costs
PMI & work order -Sublet parts costs	$US	Total sublet parts costs
PMI & work order -Sublet labor costs	$US	Total sublet labor costs
PMI & work order -Total maintenance costs	$US	Total maintenance costs; the sum of all prior costs

Source: Data from LADOT, analysis by CALSTART

CHAPTER 4: Data Processing and Preparation for Analysis

4.1 Electric Bus Performance Data

4.1.1 Preparing ViriCiti Data

To analyze data coming from ViriCiti, CALSTART used the Report function of ViriCiti's online portal to download daily data for the parameters listed in

Table **6**. When data was exported from ViriCiti's online portal, a date range from January 01, 2017 to November 15, 2018 was chosen. However, due to delays in installing ViriCiti data loggers on each bus as well as delays in deploying buses 17303 and 17304,[6] ViriCiti did not have data available for any of the buses until October 21, 2017. Also, the first date for which data was available varied by bus. Table 10 shows the dates on which ViriCiti data was first available for each bus.

Table 10: ViriCiti Data Availability by Bus

ViriCiti Data Availability by Bus	
Electric Bus Number	**Dates on Which ViriCiti Data Was First Available**
17301	December 08, 2017
17302	November 13, 2017
17303	October 21, 2017
17304	March 14, 2018

Source: Data from ViriCiti, analysis by CALSTART

Thus, the data analyzed in this report ranges from October 21, 2017 to November 15, 2018,[7] including over twelve months of data for all the buses, cumulatively.

To start analyzing the data, CALSTART first ran summary statistics for every parameter on each electric bus to determine the maximum, minimum, average, and median values. Next, scatterplots of every parameter were created as a way to visually inspect the data for outliers. Upon visual inspection, upper and lower bounds were determined, with data outside those bounds considered outliers. Outlier values were considered either unlikely to occur for a transit bus operating in service or impossible, such as state of charge used values above 100 percent. These bounds were determined for all electric buses simultaneously. Table 11 shows a list of these bounds for each parameter along with a justification for each bound. To see scatterplots of data over time for each parameter before and after the outliers were removed, see APPENDIX B: Outliers – Before and After Removal from the Data: .

Table 11: ViriCiti Data Outlier Bounds for All Electric Buses

Parameter (unit)	Lower Bound	Upper Bound	Justification for Bounds	% Omitted
Average Speed (miles per hourph)	0	20	Unlikely based on urban transit route and trend in speed values	0.02%
Distance (miles)	7	200	7 miles to complete 1 loop on DASH A Downtown Route; 200 miles is unlikely based on route length and average distance	6.03%
Efficiency while Driving (kWh/mi)	0.5	3.5	Efficiency unlikely outside these bounds based on other electric	0.17%

6 Bus 17303 was delivered to LADOT in July 2017 and Bus 17304 was delivered to LADOT in August 2017. Both started revenue service in September 2017.
7 November 15, 2018 was chosen as the end date as the data was downloaded on November 16, 2018, but data was collected until the end of the project on April 30, 2018.

Parameter (unit)	Lower Bound	Upper Bound	Justification for Bounds	% Omitted
			bus studies [8, 9, 10, 11]	
Overall Efficiency (kWh/mi)	0.5	3.5	Efficiency unlikely outside these bounds based on other electric bus studies [8, 9, 10, 11]	0.17%
Efficiency while in Service (kWh/mi)	0.5	3.5	Efficiency unlikely outside these bounds based on other electric bus studies [8, 9, 10, 11]	0.09%
Energy Charged (kWh)	1	-	Energy Charged under 1 is unlikely for a bus operating in service	5.55%
Energy Consumed Driving (excluding recovered energy) (kWh)	1	-	Energy Consumed Driving under 1 is unlikely for a bus operating in service	4.28%
Energy Consumed Driving (including recovered energy) (kWh)	1	200	Energy Consumed Driving under 1 is unlikely for a bus operating in service; values over 200 unlikely based on route and average	4.69%
Energy Idled (kWh)	1	-	Energy Idled under 1 is unlikely for a bus operating in transit service	2.86%
Energy Used in Service (kWh)	1	-	Energy Used in Service under 1 is unlikely for a bus operating in service	3.37%
Energy Used Not in Service (kWh)	Selected Grouping - See Appendix B	Selected Grouping - See Appendix B	Selected grouping values unlikely based on trend of all data	5.96%
Energy Regenerated Driving (kWh)	1	-	Energy Regenerated Driving under 1 is unlikely for a bus operating in service	5.28%
Energy Used (kWh)	1	-	Energy Used under 1 is unlikely for a bus operating in service	2.64%
Regeneration Rate (%)	-	-	-	0.00%
State of Charge Used (%)	1, Selected Grouping – See Appendix B	Selected Grouping – See Appendix B	Selected grouping values unlikely based on trend of all data	14.30%

Source: Data from ViriCiti, analysis by CALSTART

8 Eudy, L., Prohaska, R., Kelly, K. & Post, M. (2016). *Foothill transit battery electric bus demonstration results*. Golden, CO: National Renewable Energy Laboratory

9 Eudy, L. & Jeffers, M. (2016). *Zero-emission bus evaluation results: King County Metro battery electric buses*. Golden, CO: National Renewable Energy Laboratory

10 CALSTART (2018). *San Joaquin Regional Transit District Electric Bus Demonstration*. Pasadena, CA: CALSTART

11 CALSTART (2018). *Zero Emission Re-Power Performance and Data Collection Summary Report*. Pasadena, CA: CALSTART

After identifying each parameter boundary, CALSTART copied all the data into a new Microsoft Excel tab and removed all outliers. Then, all data that was recorded on days when the buses traveled on the Observatory Route compared to the DASH A route was separated. Finally, summary statistics were calculated on every parameter for each bus again to obtain maximum, minimum, average, and median values without outliers.

4.1.2 Preparing LADOT Data

In addition to performance data from ViriCiti, LADOT emailed CALSTART monthly reports containing performance data on the electric buses. These files came in PDF format and were converted into a Microsoft Excel workbook with separate tabs for each bus. Due to differing deployment dates, data was not recorded by LADOT across the same time spans for every bus.

Table 12 shows a list of date ranges in which data was recorded per bus.

Table 12: LADOT Report Data Availability per Bus

LADOT Report Data Availability per Bus	
Electric Bus Number	**Dates for Which LADOT Data is Available**
17301	March 01, 2017 – April 30, 2019
17302	April 26, 2017 – April 30, 2019
17303	September 01, 2017 – April 30, 2019
17304	September 01, 2017 – April 30, 2019

Source: Data from LADOT, analysis by CALSTART

Like with the ViriCiti data, CALSTART first ran summary statistics for every parameter on each electric bus to determine the maximum, minimum, average, and median values. Next, scatterplots were created for every parameter to visually inspect the data for outliers. Upon visual inspection, upper and lower bounds were determined for which data that resided outside those bounds were considered outliers. As with ViriCiti data, outlier values were considered either unlikely to occur for a transit bus operating in service or impossible, such as Total Hours per Day of 140. These boundaries were determined for all buses simultaneously. Then, all data that was recorded on days when the buses traveled on the Observatory Route rather than the DASH A route was removed and CALSTART ran summary statistics on the refined set of data.

Table 13 shows a list of bounds for each parameter along with a justification for each bound. To see scatterplots of data over time for each parameter before and after the outliers were removed, see APPENDIX B: Outliers – Before and After Removal from the Data.

Table 13: LADOT Data Outlier Bounds for All Electric Buses

Parameter (unit)	Lower Bound	Upper Bound	Justification for Bounds	% Omitted
Total Miles (mi/day)	7	200	7 miles to complete 1 loop on DASH A Downtown Route; 200 miles is unlikely based on route length and average distance	0.81%
State of Charge Used (%/day)	1	-	State of Charge Used under 1 is unlikely for a bus operating in service	0.00%
kWh Used (kWh/day)	1	-	kWh Used under 1 is unlikely for a bus operating in service	0.68%
kWh Per Mile (kWh/mi)	0.5	3.5	Efficiency unlikely outside these bounds based on other electric bus studies [8, 9, 10, 11]	1.67%
kWh Charged (kWh/day)	1	-	Energy Charged under 1 is unlikely for a bus operating in service	1.41%
Revenue Total Hours (hours/day)	1	-	Revenue Total Hours under 1 is unlikely for a bus operating in service	1.37%
Total Hours (hours/day)	1	20	The only value above 20 hours is 140 hours, which is impossible	1.18%

Source: Data from LADOT, analysis by CALSTART

4.1.3 Analyzing Electric Bus Data Including Non-Revenue Service Drive Events Without Removing Outliers

CALSTART recognizes that the electric buses are sometimes used in ways that do not align with typical revenue service route patterns, such as short drive events including trips around the depot or longer drives to BYD's facility in Lancaster, CA for maintenance. While these drive events are not reflective of performance while the buses are on route, they do represent real usage for LADOT and should not be discounted. To ensure that these drive events are captured, CALSTART also analyzed performance data from ViriCiti without removing any outliers as discussed in Table 11 and Table 13.[12]

4.1.4 Comparing ViriCiti Data with LADOT Data

After preparing the ViriCiti data and the LADOT data separately, CALSTART compared similar parameters from each to corroborate the summary results from both data sources. To do this, average values were compared for ViriCiti's and LADOT's parameters on distance, energy used, overall energy efficiency, and energy charged.

It was noticed that there was a consistent difference in energy use (measured in kWh) and energy efficiency (measured in kWh/mi) between the two data sources. Namely, the data from LADOT manual records showed higher values compared to the ViriCiti data.

Table 14 shows these comparisons for each electric bus. See

12 While most outliers were not removed from the data for this particular analysis, we did remove the following data points due to being impossible or so unlikely that they are considered bad data: Bus 17304 Distance on June 21, 2018 (746.83 miles), Bus 17301 Overall Efficiency on October 13, 2018 (155.40 kWh/mi), Bus 17304 Overall Efficiency on August 07, 2018 (185.52 kWh/mi).

Table **6** for a reminder on the description of each ViriCiti parameter shown below.

Table 14: LADOT Results Versus ViriCiti Results for All Buses

	Bus	LADOT-Total Miles	LADOT-kWh Used	LADOT-kWh Per Mile	LADOT-kWh Charged
Average	17301	79.23	162.15	2.06	163.53
	17302	75.01	154.92	2.06	153.93
	17303	80.86	150.08	1.84	150.49
	17304	77.60	156.62	2.03	157.01
	Bus	**ViriCiti-Distance (miles)**	**ViriCiti-Energy Used (kWh)**	**ViriCiti- Overall efficiency (kWh/mi)**	**ViriCiti-Energy Charged (kWh)**
Average	17301	80.16	131.81	1.74	155.76
	17302	74.64	106.84	1.91	133.79
	17303	81.06	125.66	1.74	152.46
	17304	83.35	131.01	1.84	155.13
Percent Difference	17301	1.17%	20.64%	16.84%	4.87%
	17302	0.49%	36.74%	7.56%	14.00%
	17303	0.25%	17.71%	5.59%	1.30%
	17304	7.15%	17.81%	9.82%	1.20%

Source: Data from LADOT and ViriCiti, analysis by CALSTART

Note that average values have been rounded up from the data. To make sense of these differences, CALSTART contacted both ViriCiti and LADOT to ask how they calculated each parameter. While ViriCiti uses its DataHub (which is installed on the vehicle's controller area network Bus) to calculate energy use by multiplying voltage and amperage to obtain a value for power, LADOT records energy use by reading values on the charger boxes when the buses are plugged-in and unplugged. Thus, due to different forms of measurement and due to energy losses while charging the vehicle, energy use data are different between these two sources.

An important observation in Table 14 is that ViriCiti is recording energy use and efficiency from the vehicle side, while LADOT's data is based on energy use values read from the charger boxes. This is an important distinction because, while the electric bus in and of itself showed an average amount of energy used at 123.83 kWh/day, LADOT's chargers showed a higher average energy use of 155.94 kWh/day. This difference is most likely due to energy losses at different points of energy transfer, including conversion losses from converting AC power to DC power as energy moved from the charger boxes to the vehicle's battery. As LADOT's electricity bill reflects the amount of energy consumed on the grid side, it is important to understand both the performance of the vehicle as its own system and the performance of the vehicle as it interfaces with LADOT's facility, as it impacts the cost of operations.

Also, it is important to note the difference between Energy Used and Energy Charged from ViriCiti. One would assume these values should be the same or similar. However, Energy Charged is about 25 kWh higher than Energy Used per bus on average. While all reasons for this difference are not completely clear, there are some natural energy losses during charging, such as heat, that may explain this difference. In the case of LADOT's data, kWh Used and kWh Charged are very similar because LADOT recorded this data manually by reading the charging boxes as the buses were un-plugged and plugged-in each day.

4.2 CNG Bus Performance Data

To benchmark the performance of electric buses, CALSTART obtained performance data on two CNG buses. These two buses, numbers 17305 and 17306, were both model year 2017 El Dorado E-Z Rider II buses. LADOT sent CALSTART this data in two separate Microsoft Excel files. Each file contained the data shown in Table 8 for dates ranging from February 02, 2018 to November 07, 2018 for 17305, and February 05, 2018 to November 07, 2018 for 17306. To see a sample of this data from the source, view APPENDIX E: Raw Data Samples.

To prepare this data for analysis, the researchers converted miles per gallon into gallons per mile, and then compared it with the electric vehicles by converting gallons per mile into kWh per mile by multiplying it by 33.7.[13] After running these calculations, the same process was followed to eliminate outliers as was done for ViriCiti and LADOT performance data, by creating scatter plots for each parameter and visually inspecting the data. Outlier values were considered either unlikely to occur for a transit bus operating in service or impossible. Table 15 shows the bounds determined for each CNG bus parameter, along with a justification for each.

Table 15: Outlier Bounds for All CNG Buses

Parameter (unit)	Lower Bound	Upper Bound	Justification for Bounds	% Omitted
Miles Between (Distance) (mi/day)	1	200	7 miles to complete 1 loop on DASH A Downtown Route; 200 miles is unlikely based on route length and average distance	6.05%
Gallons of Fuel (GGE/day)	-	-	No bounds placed on this parameter as there were no data points that were impossible or unlikely.	0.00%
kWh per Mile (kWh/mi)	1	60	The only values below 1 in the data set are 0 or negative. The only values above 60 in the data set are 401.03 and 620.08, which are unlikely.	2.09%

Source: Data from LADOT, analysis by CALSTART

After removing outliers, the researchers calculated maximum, minimum, average, and median values for each parameter to compare to electric bus data. See APPENDIX B: Outliers – Before and After Removal from the Data, to see scatterplots of the data before and after outliers were removed.

13 33.7 is a standard conversion factor developed by the United States Environmental Protection Agency. See: https://nepis.epa.gov/Exe/ZyPDF.cgi/P100BAV0.PDF?Dockey=P100BAV0.PDF, p. 5.

4.3 Maintenance Data

The last set of data which was used in analysis is maintenance data for all electric buses and the two CNG buses. LADOT delivered this data to CALSTART in the form of paper records with data included on dates when maintenance occurred, separated by bus. CALSTART first logged all this data, as shown in Table 9, into a Microsoft Excel workbook, and separated PMI costs from work order costs.

Once all data was transcribed into Excel, the sum of each sub-cost (e.g. labor, parts, etc.) and the total maintenance cost for each bus was calculated separately. CALSTART also calculated the percent of each sub-cost as compared to the total maintenance cost for each bus. Then, to compare costs across buses, maintenance costs per day and per mile were estimated.

Upon seeing the differences in maintenance cost between electric and CNG buses, the researchers wanted more granularity in the drivers of cost, so the maintenance costs were determined for each part ordered and each part replaced per bus and per powertrain (electric versus CNG). To do this, CALSTART revisited the paper maintenance records and assigned categories to each part. For example, any parts ordered associated with lights or lamps were categorized as "lights" and any parts ordered associated with tires were categorized as "tires", and so on. The researchers followed this process for every bus, and then grouped the results by powertrain and by PMI and work order maintenance.

CHAPTER 5: Data Analysis and Results

5.1 Electric Bus Performance Analysis

The following sections show the results of data analysis on the electric buses only. As mentioned above, data was obtained from two sources: ViriCiti data loggers and manual data from LADOT. The two sources are shown side by side for instances in which data was collected on similar parameters from both sources. This section starts with results from operation on the DASH A Downtown Route.

5.1.1 DASH A Downtown Route

5.1.1.1 Active Days

Table 16 shows the number of active days for each electric bus from the beginning of the demonstration to the end of October 2018, as analysis started mid-November 2018.

Table 16: Active Days by Bus

Bus	Active Days	Time Range
17301	509	March 01, 2017 to October 31, 2018
17302	363	April 26, 2017 to October 31, 2018
17303	373	September 01, 2017 to October 31, 2018
17304	351	September 01, 2017 to October 31, 2018

Source: Data from LADOT, analysis by CALSTART

In this case the number of active days includes the number of days in which each bus traveled seven or more miles. Seven was chosen as the cutoff because one loop around the DASH A Downtown route is about seven miles. The four buses ranged between 20 to 27 active days per month. On average, the four buses were active about 24 days each month.

Table 17 shows the breakdown of active days per month for each bus.

Table 17: Active Days per Month by Bus

Month	17301	17302	17303	17304
March 2017	22	N/A	N/A	N/A
April 2017	17	3[14]	N/A	N/A
May 2017	17	24	N/A	N/A
June 2017	23	16	N/A	N/A
July 2017	25	25	N/A	N/A
August 2017	28	22	N/A	N/A
September 2017	11	2	25	21
October 2017	29	16	24	18
November 2017	28	16	30	25
December 2017	31	22	28	28
January 2018	31	28	24	27
February 2018	28	27	27	21
March 2018	31	27	29	22
April 2018	27	7	27	30
May 2018	29	20	31	29
June 2018	28	25	30	28
July 2018	24	16	23	30
August 2018	30	28	29	25
September 2018	27	24	21	24
October 2018	23	15	25	23
Average	**25**	**20**	**27**	**25**

Source: Data from LADOT, analysis by CALSTART

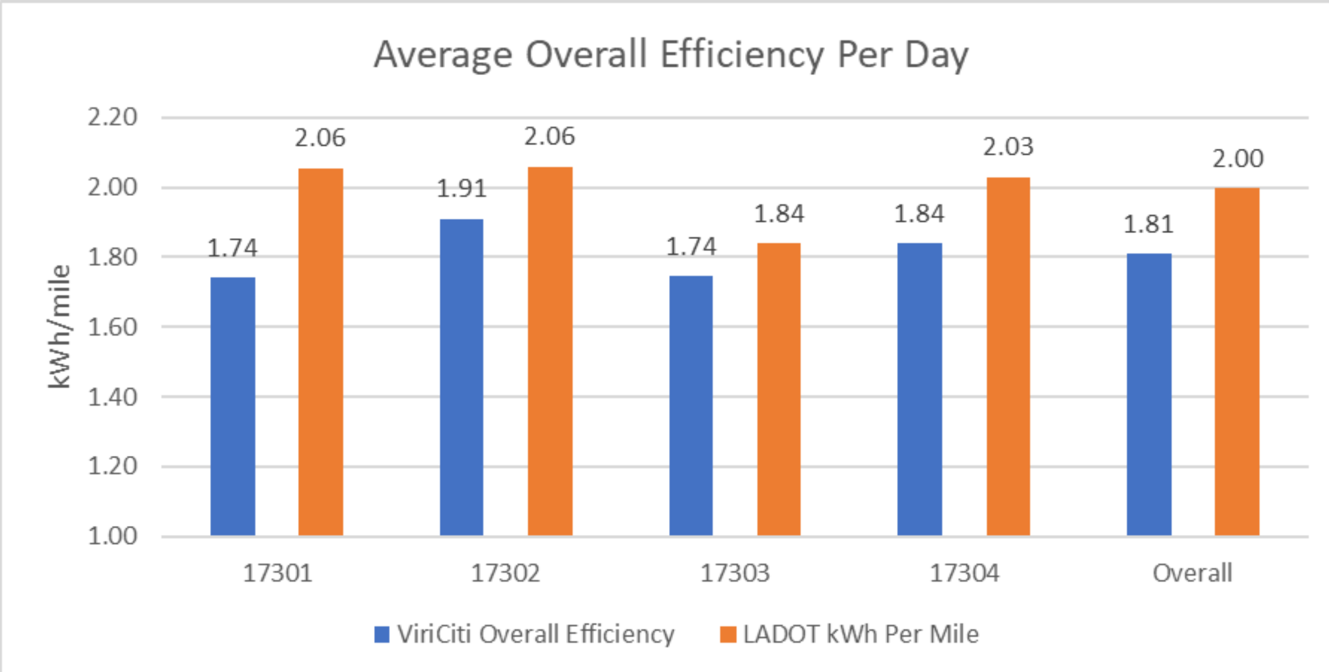
[14] Bus 17302 only has 3 active days in April 2017 because LADOT did not start recording data for this bus until April 26, 2017.

5.1.1.2 Efficiency

CALSTART also evaluated the efficiency with which each electric bus consumed energy (See

Table **6** and Table 7 for reminders on parameter definitions). Figure 9 shows the average overall efficiency per day for each electric bus.

Figure 9: Overall Efficiency per Day[15]



Source: Data from LADOT and ViriCiti, analysis by CALSTART

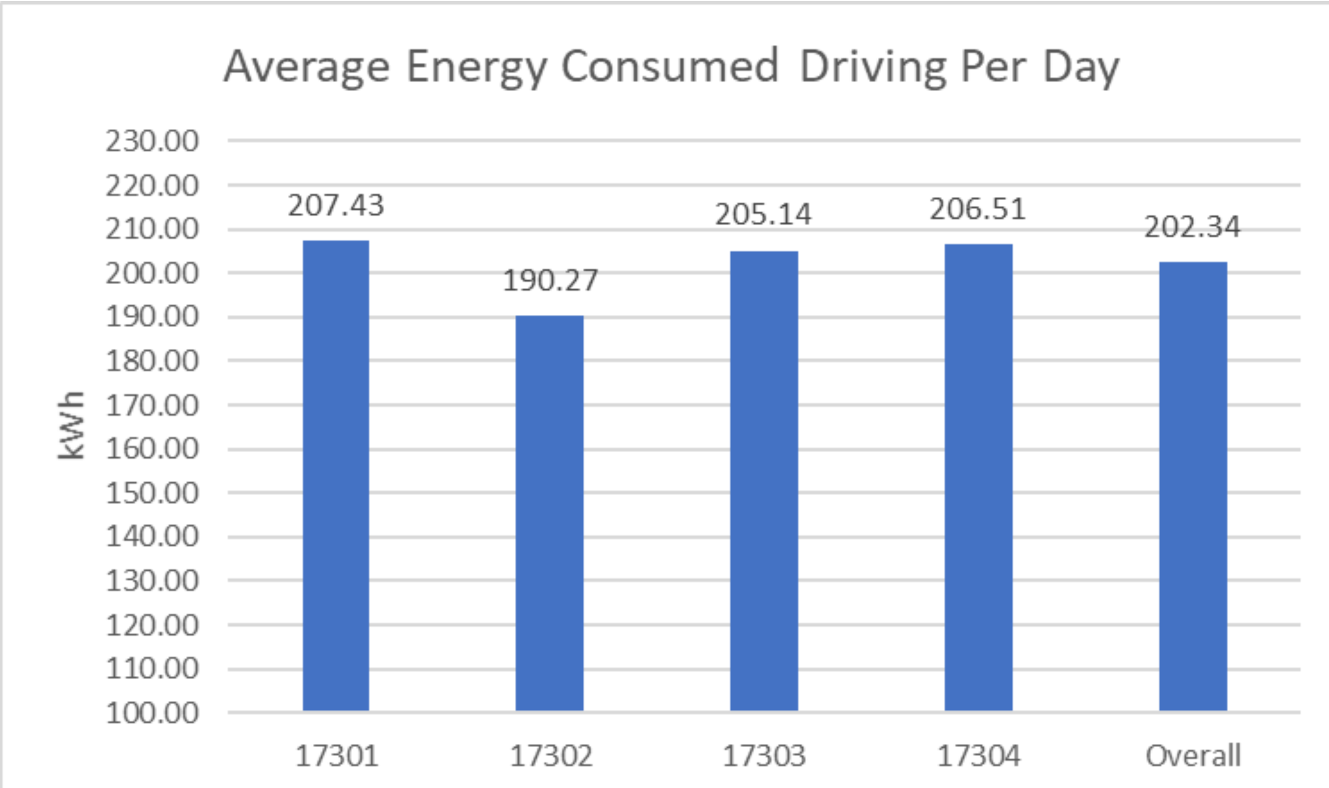
According to ViriCiti data most buses consumed between 1.74 to 1.91 kWh/mi. All buses performed in-line with expectations for a 35-foot bus considering what other studies have shown for similar 40-foot transit buses, which typically consume around 2.00 kWh/mi.[15] Of course, this depends on a variety of factors, including bus length, route dynamics, and environmental conditions. LADOT's manually-recorded data show worse levels of efficiency around 2.00 kWh/mi on average. As mentioned previously, these values were calculated by reading values on the chargers, measuring efficiency as energy was consumed from the charger to the wheel. ViriCiti data, however, was calculated using the vehicle's controller area network bus, measuring efficiency as energy was consumed only from the vehicle battery to the wheel and omitting any energy lost through conversion from the charger to the vehicle battery. Thus, ViriCiti data is showing results from the vehicle in and of itself, while LADOT data is showing vehicle performance as it interfaces with LADOT's facilities.

[15] Due to technical issues with the original results for Overall Efficiency from ViriCiti, CALSTART calculated Overall Efficiency manually by dividing Energy Used by Distance.

5.1.1.3 Energy Usage

Figure 10 shows the average energy that each bus consumed per day while driving, not factoring in regenerated energy from braking.

Figure 10: Energy Consumed Driving (Excluding Recovered Energy) per Day



Source: Data from ViriCiti, analysis by CALSTART

As you can see, average energy consumed driving remained relatively consistent among all buses, ranging between 190.27 kWh to 207.43 kWh on average. Note that the total battery capacity is 270 kWh. The inclusion of regenerative braking results in values smaller than those shown in Figure 10, as it recovers energy and recycles it back into the vehicle battery for use, as shown in Figure 11.

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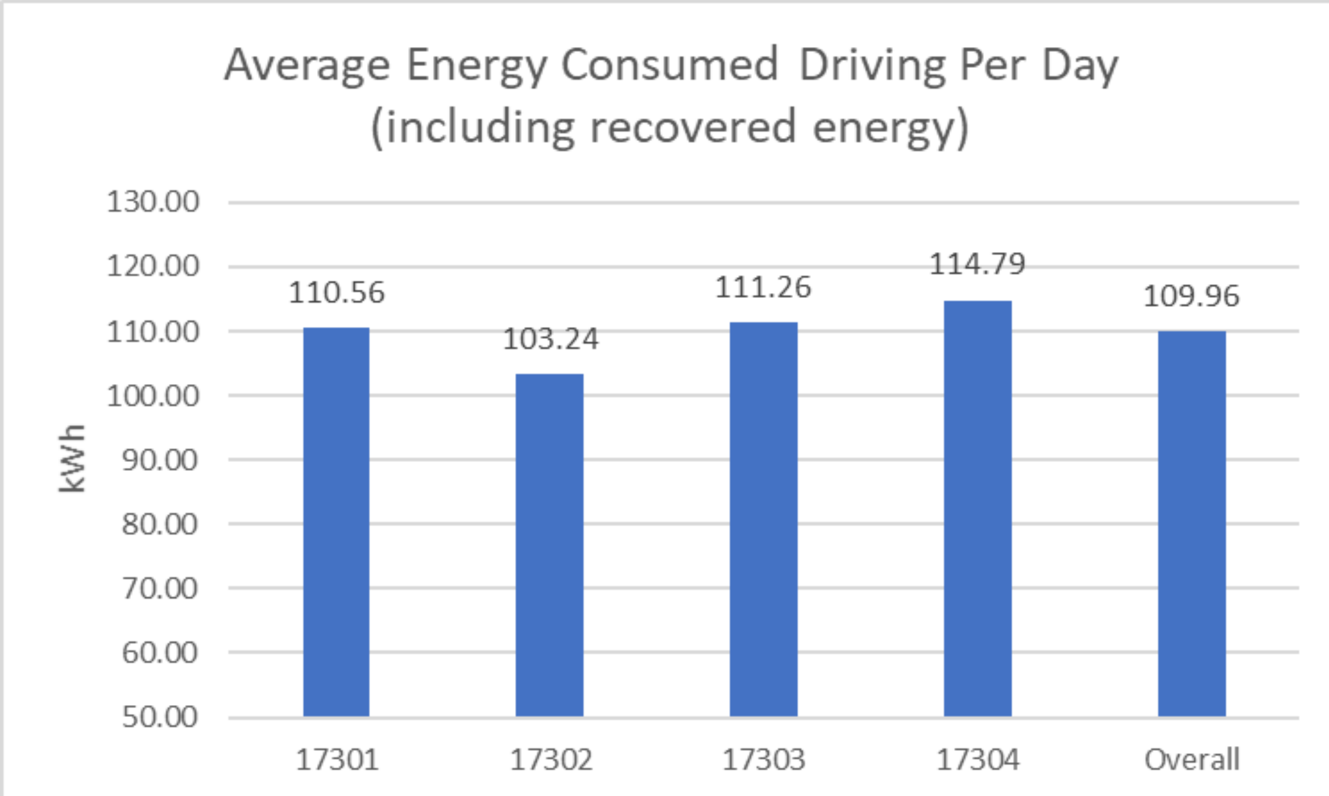
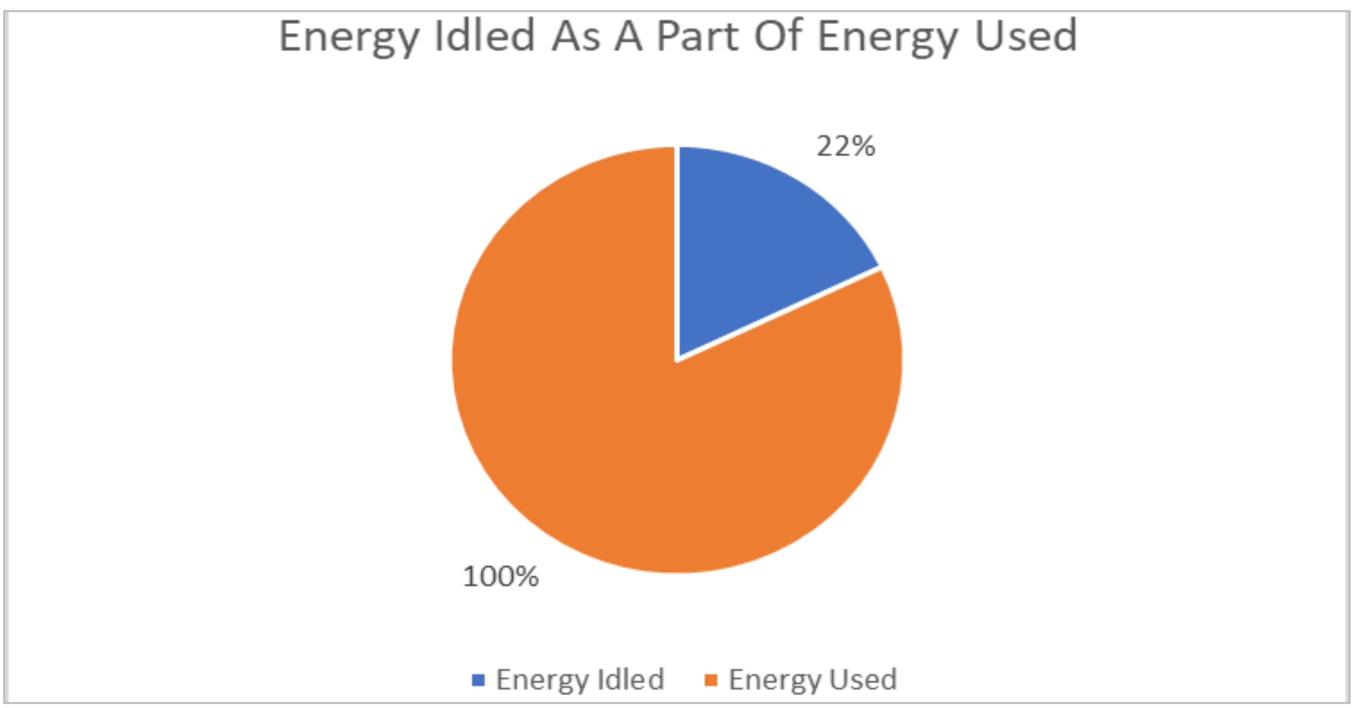
Figure 11: Energy Consumed Driving (Including Recovered Energy) per Day



Source: Data from ViriCiti, analysis by CALSTART

Figure 12 shows the amount of energy consumed while idling per day as a part of all energy used to power the vehicle.

Figure 12: Energy Idled as a Part of Energy Used



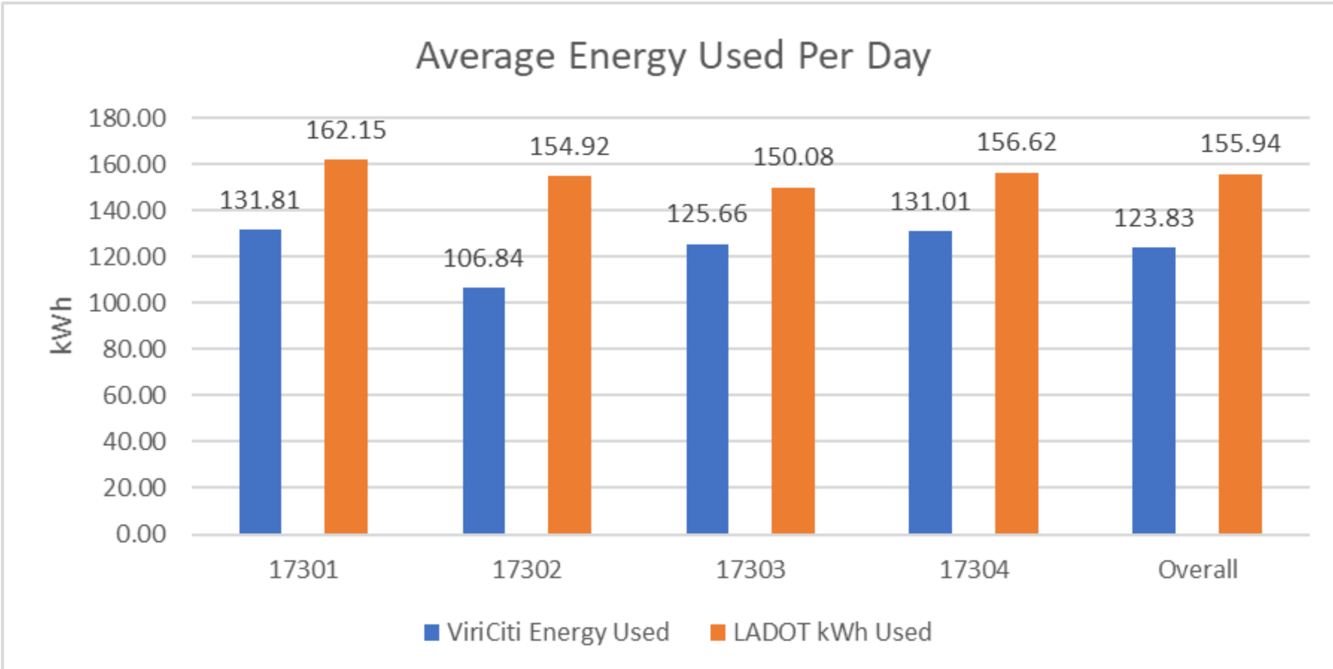
Source: Data from ViriCiti, analysis by CALSTART

These results represent 22 percent of all energy used while the vehicle was switched on (Energy Used shown in Figure 13) on average across all buses. Whether the bus is driving or idling there are multiple ways that the vehicle consumes energy apart from the powertrain, such as using the heating, ventilation and cooling system. Use of heating, ventilation and cooling systems is of particular interest because it is necessary in hot and cold temperatures and impacts overall vehicle efficiency by consuming energy that would otherwise be used by the powertrain, as will be shown in Figure 21. While data on energy consumed by running heating and cooling was not available for this study, another similar study on electric transit buses showed that it can consume up to 10 percent of overall energy used.[16]

[16] CALSTART (2018). Final Report for San Joaquin RTD EV Bus Deployment Program. Pasadena, CA: CALSTART

Figure 13 shows the total energy used per day while each bus was activated.

Figure 13: Energy Used per Day



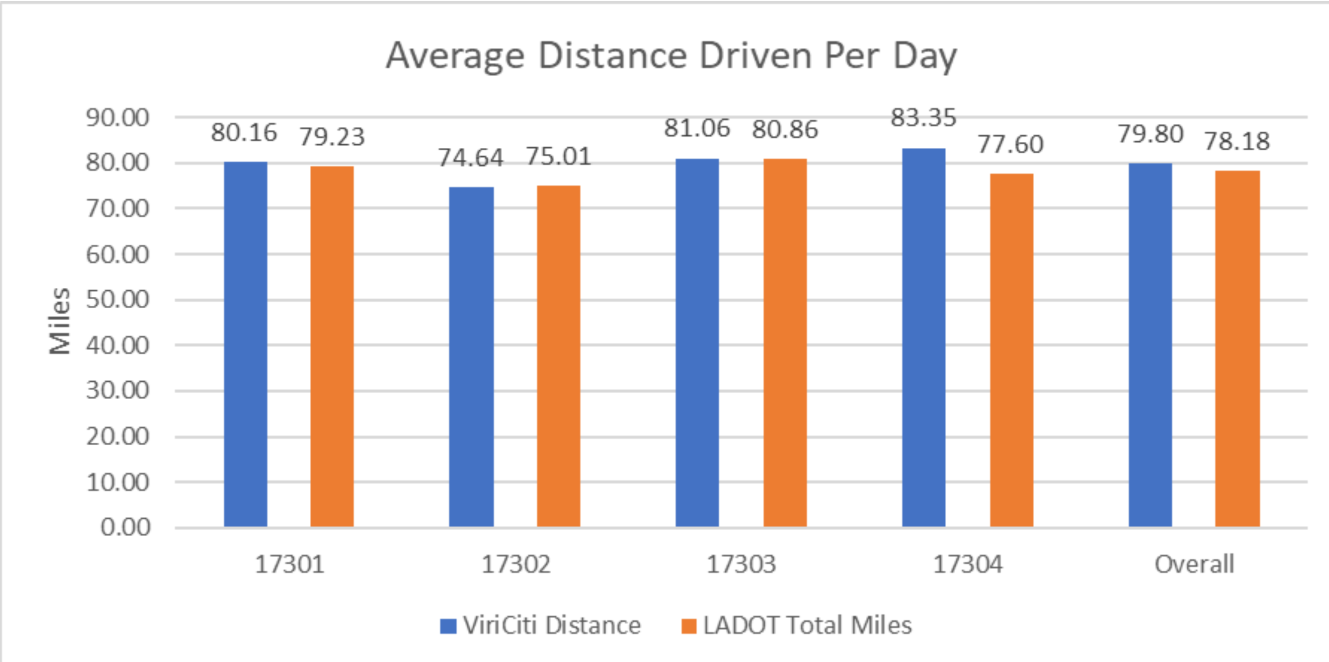
Source: Data from LADOT and ViriCiti, analysis by CALSTART

According to ViriCiti data, the average energy used per day was 123.83 kWh. According to LADOT manual data, the average energy used per day was higher at 155.94 kWh. Energy use did not vary much by bus, indicating that the buses were utilized similarly each day. The researchers sought to compare these results to other electric transit buses, but it was difficult to make a comparison due to the various factors that affect energy consumption (bus length, manufacturer, climate, miles driven per day, quality of regeneration, etc.). It can be assumed from the data, however, that these results are not atypical for a 35-foot bus operating under these conditions.

5.1.1.4 Distance

Figure 14 shows the distance driven by each bus per day.

Figure 14: Distance Driven per Day



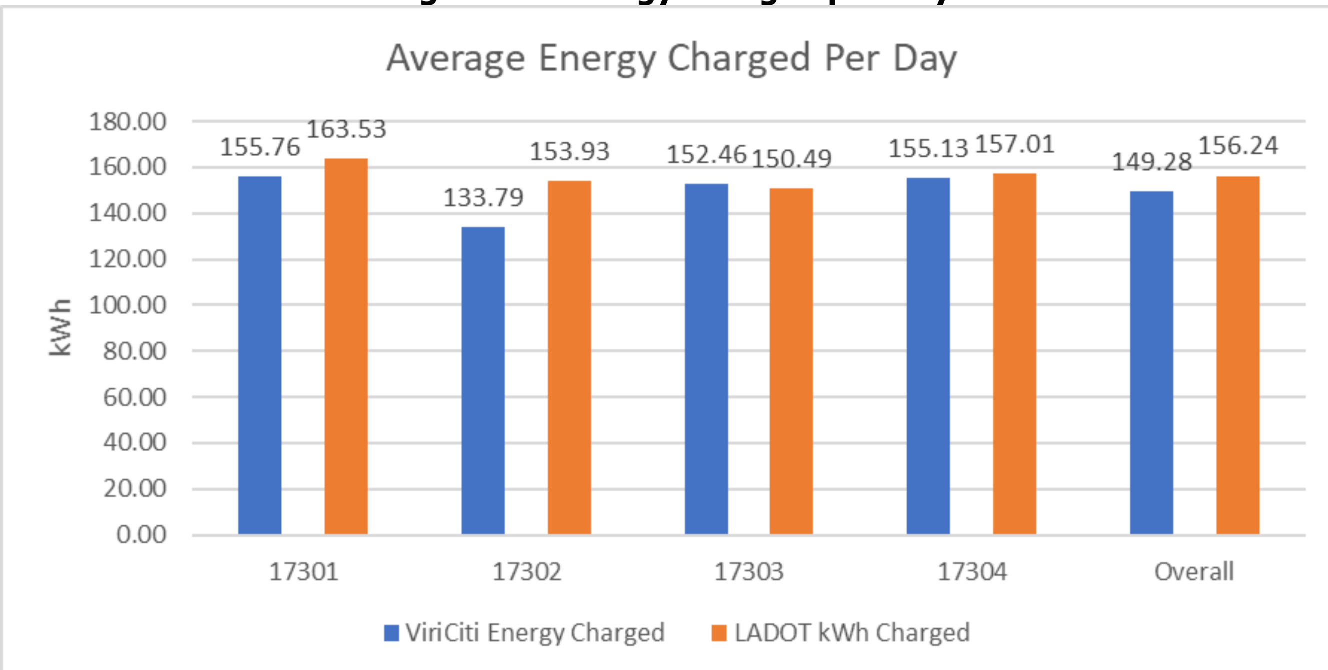
Source: Data from LADOT and ViriCiti, analysis by CALSTART

Most buses traveled very close to the average value of 79.80 miles per day. According to ViriCiti data, bus 17304 drove the most per day at 83.35 miles, followed by 17303, 17301, and then 17302. The average distance driven per day according to LADOT data was 78.18 miles with a range from the minimum distance to the maximum distance of just over four miles.

5.1.1.5 Charging

Figure 15 shows the amount of energy charged per day for each bus.

Figure 15: Energy Charged per Day

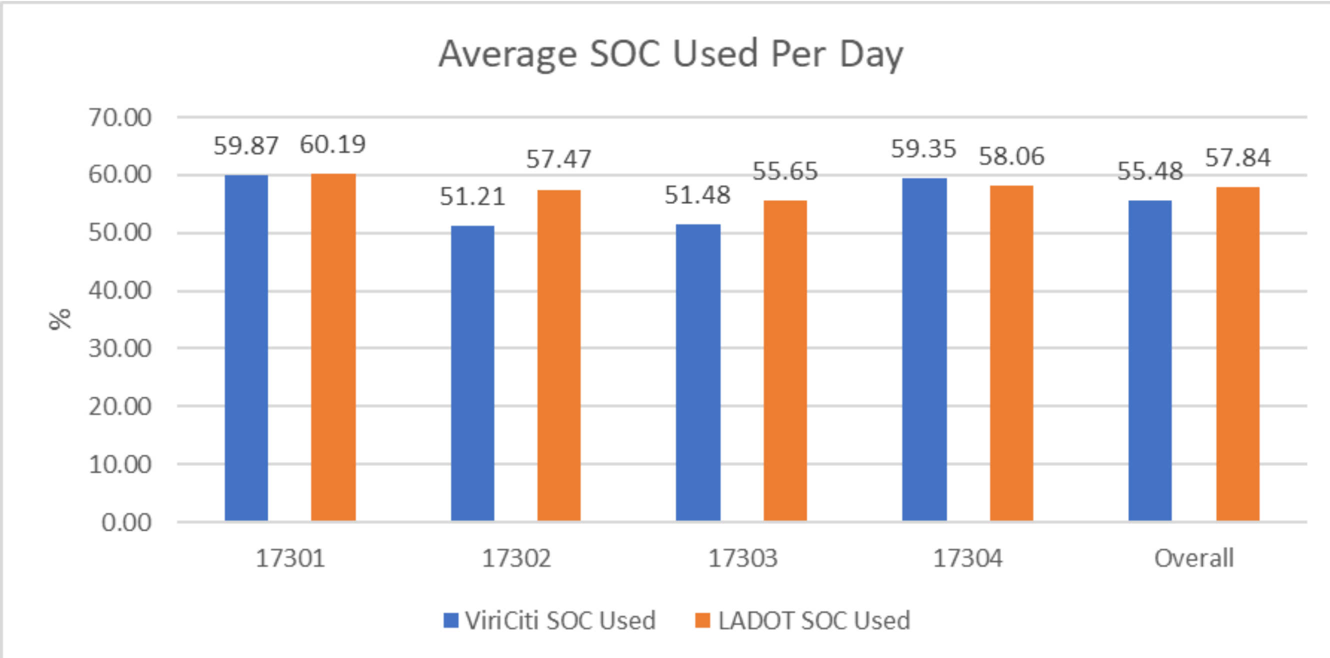


Source: Data from LADOT and ViriCiti, analysis by CALSTART

According to ViriCiti, bus 17301 charged the most at 155.76 kWh per day on average, followed by 17304, 17303, and 17302. This pattern is different with LADOT data, showing that 17301 charged the most followed by 17304, 17302, and 17303. All buses charged similar amounts with averages of 149.28 and 156.24 for ViriCiti and LADOT data, respectively. It is important to note that results for energy charged per day were similar to results for energy used, as would be expected given that energy used accounts for all energy consumed by the bus per day, including recovered energy.

Figure 16 shows the state-of-charge used (state of charge used) by each bus per day.

Figure 16: State of Charge Used per Day

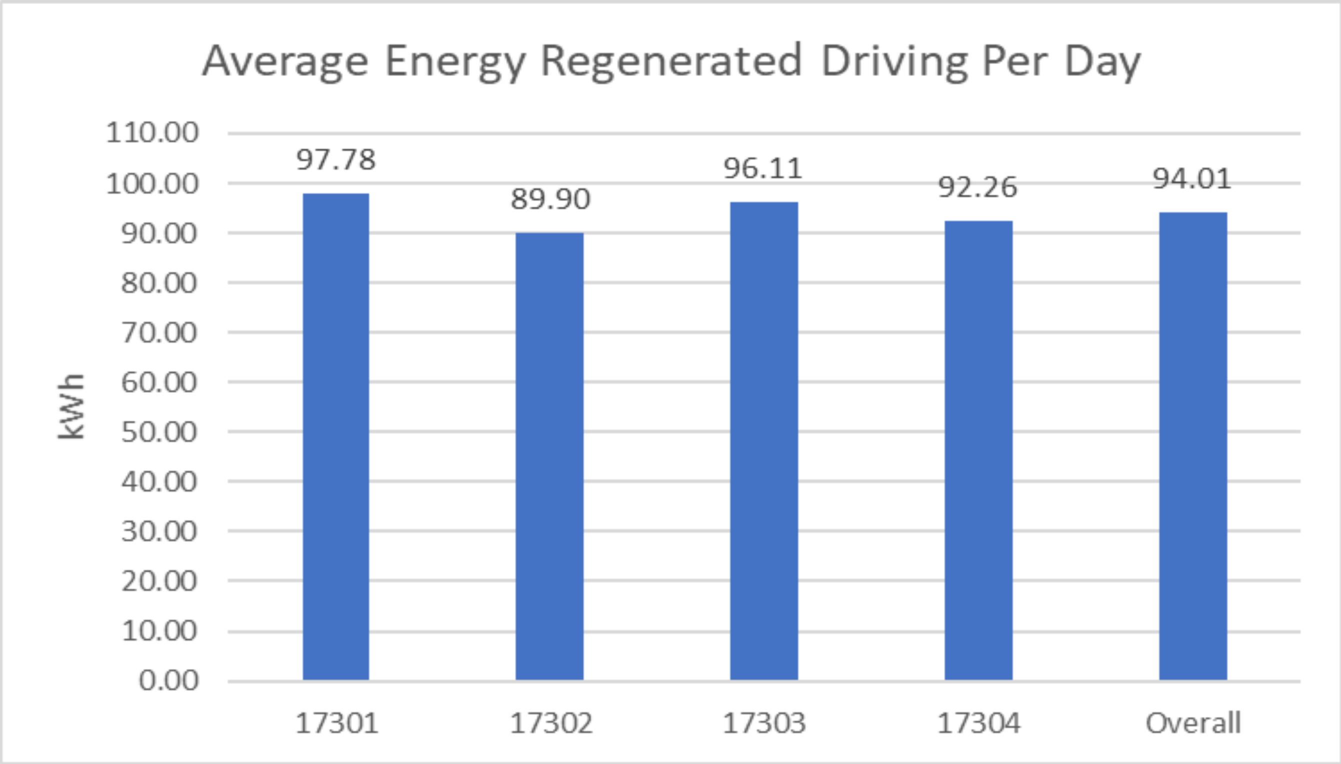


Source: Data from LADOT and ViriCiti, analysis by CALSTART

This data gives an indication of how much the buses' batteries were used before re-charging each day. According to ViriCiti, the average state of charge used across all buses was 55.48 percent of battery capacity, with 17301 using the most on average at 59.87 percent, followed by 17304, 17303, and 17302. LADOT's data showed similar results with an overall average of 57.84 percent. In some cases, bus operators might re-charge buses more frequently than necessary due to range anxiety: the fear that the bus might run out of charge while on route. However, state of charge Used may also be low due to route logistics. A route that is well within a bus's range can cause state of charge used to be low. The latter seems to be the case for LADOT. In this case, LADOT reported that they operated the electric buses for full shifts before returning them to the depot to charge overnight. Even with this style of dispatching, LADOT drivers drove the buses only slightly beyond the halfway mark of their battery capacity. While LADOT's DASH A Downtown and DASH Observatory route dynamics allowed for only overnight charging, other routes may require different dispatching and re-charging practices. A best practice in this regard is to know the range of the bus you are operating before a charge is required, know the number of miles you require the bus to travel on a specific route before re-charging, and to plan accordingly. Additionally, purchasing buses with a smaller battery if needed would lower costs significantly. Planning ahead of time by evaluating the requirements for each bus purchased, based on duty cycle and route profiles, can help transit properties better determine the bus specifications they need prior to purchase, minimizing costs.

Figure 17 shows the amount of time that each bus was plugged into the charger per day.

Figure 17: Charging Time per Day



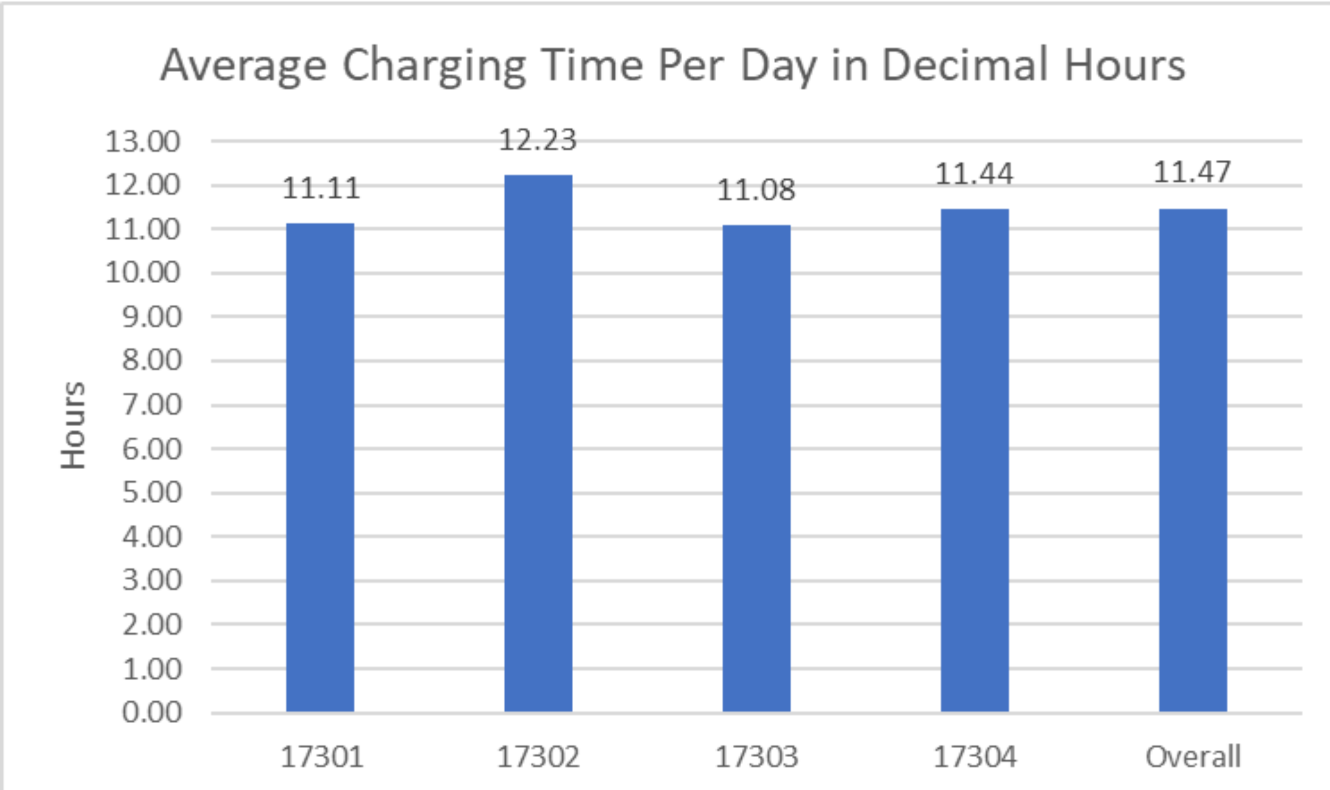
Source: Data from ViriCiti, analysis by CALSTART

CALSTART also examined how long and when each bus charged per day. On average, all buses connected to the chargers 11.47 hours per day, and this charging almost always took place overnight. While the buses were connected to the chargers for 11.47 hours per day, they did not take that long to charge. Based on the specifications of the electric buses and the chargers, they only take about four hours to reach a full charge.

5.1.1.6 Regeneration

Figure 18 shows the amount of energy regenerated while driving per day for each bus.

Figure 18: Energy Regenerated Driving per Day

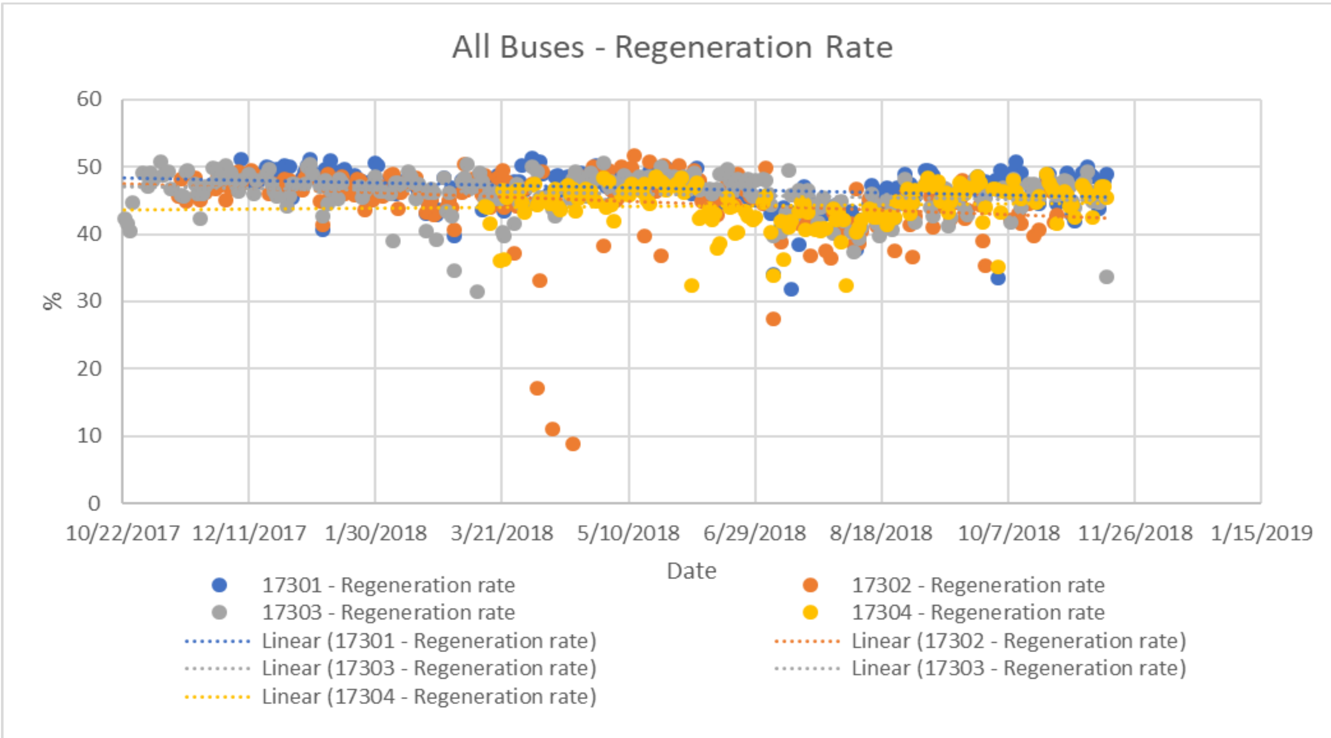


Source: Data from ViriCiti, analysis by CALSTART

Regeneration is the act of recovering energy from braking and recycling it into the battery of the bus. Bus 17301 regenerated the most energy at 97.78 kWh per day on average, followed closely by 17303, 17304, and 17302.

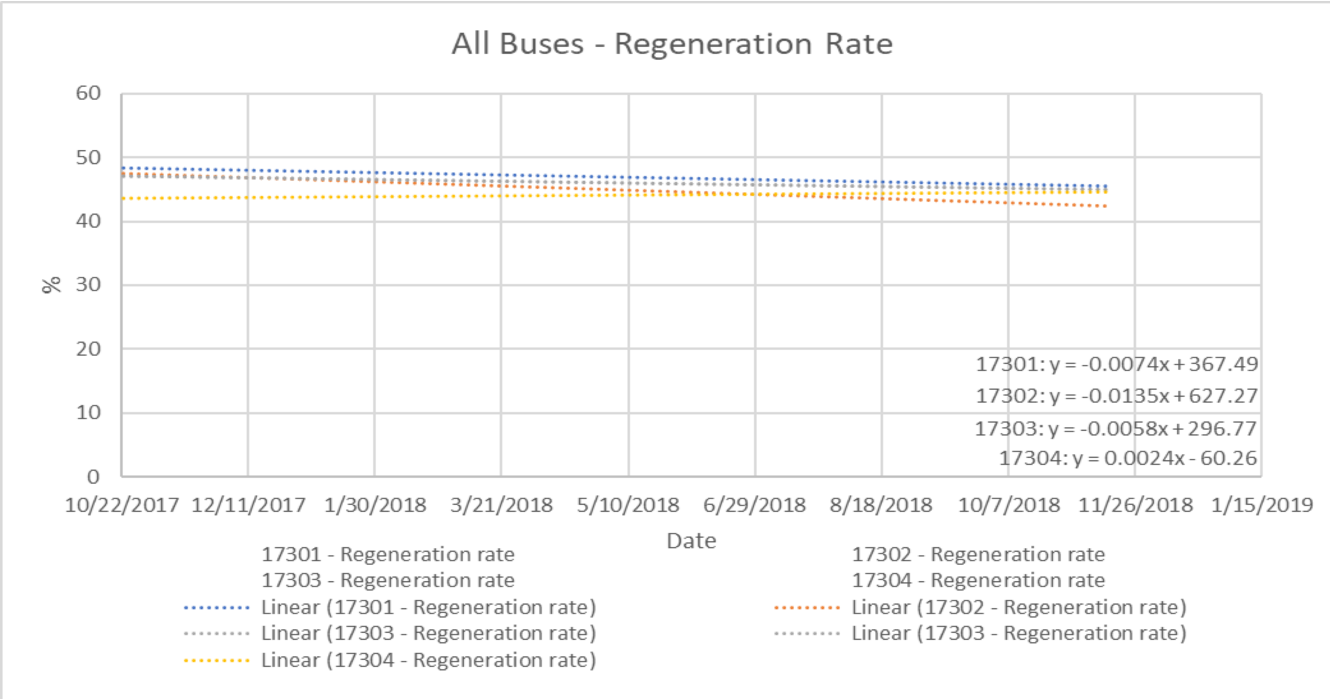
Figure 19 and Figure 20 show the regeneration rate for each bus for the entire time that each bus was deployed.

Figure 19: All Buses – Regeneration Rate Over Time



Source: Data from ViriCiti, analysis by CALSTART

Figure 20: Regeneration Rate Over Time (Trendlines Only)



Source: Data from ViriCiti, analysis by CALSTART

Regeneration rate is the amount of energy that is recovered by regenerative braking divided by itself plus the energy consumed by the bus while driving.

$$Regeneration\ Rate = \frac{Energy\ Regenerated}{Energy\ Driven + Energy\ Regenerated}$$

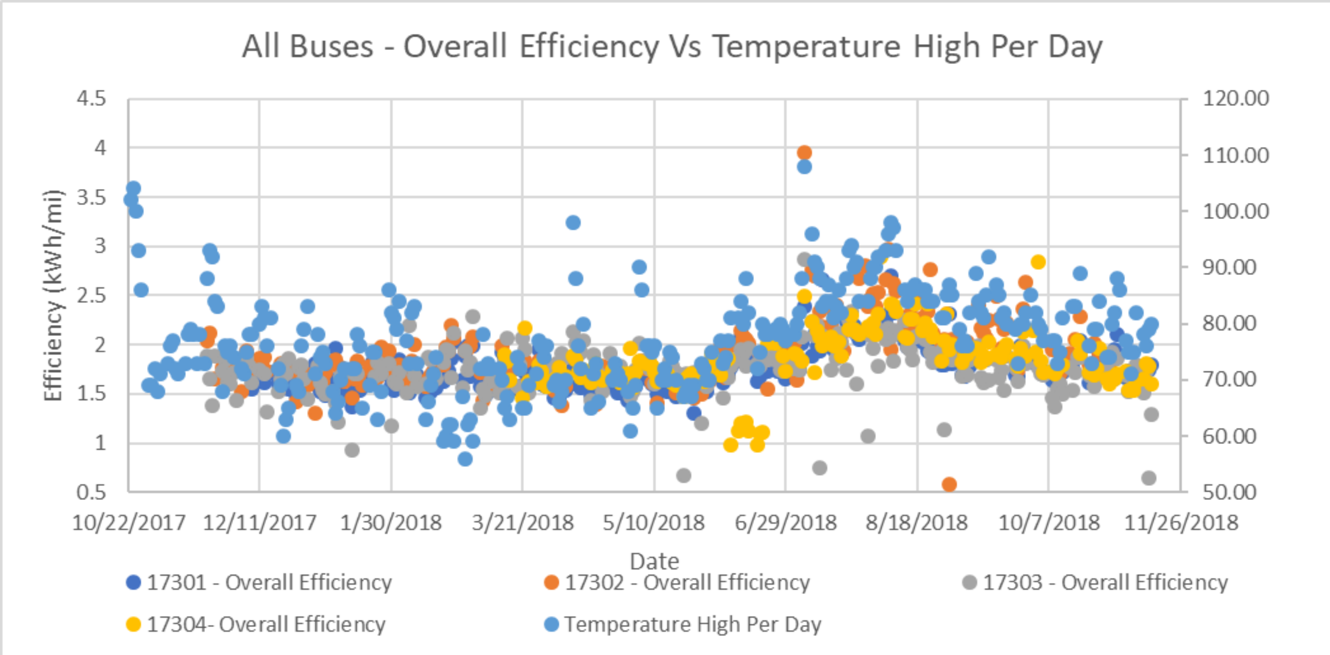
A higher regeneration rate indicates more efficient braking, which could educate us on how the drivers performed in driving the vehicle over time. While 17304 saw a very slight increase in regeneration rate over time, all other buses saw a net decrease in regeneration rate over time, indicating that braking became slightly less efficient as the demonstration continued. The potential reasons for this are unclear, and could include individual operator driving habits, quality of the regeneration system in the vehicle, and overall efficiency of the vehicle.

5.1.1.7 Energy Efficiency and Temperature

One additional pattern coming from the analysis was the discovery that the value for energy efficiency for all four buses rose sharply and then dropped from about May 2018 to October 2018. Note that a rise in energy efficiency value signal worsened efficiency while a drop in values signals improved efficiency. Upon review of this trend, it was discovered that this pattern correlates with the temperature high logged for each day.

Figure 21 shows the pattern of average daily energy efficiency plotted along with the temperature high of each day.

Figure 21: All Buses - Overall Efficiency Versus Temperature High Per Day



Source: Data from LADOT and ViriCiti, analysis by CALSTART

It seems that when temperature was highest, energy efficiency was also the worst. This could indicate that energy efficiency worsened with higher temperatures, likely due to running the bus's air conditioning system, which demands more energy from the batteries than running the powertrain alone. To validate the plots shown above, CALSTART also calculated the correlation coefficient for Overall efficiency per Day and Temperature High per Day for each bus, shown below in Table 18. A correlation coefficient indicates the strength of the correlation between these two variables. The closer the coefficient is to 1, the stronger the correlation. Indeed, all buses see a moderate positive correlation between these two variables, except 17303 which sees a weak positive correlation due to having a wider spread of efficiency data on high temperature days.

Table 18: Correlation Between Overall Efficiency per Day and Temperature High per Day

Correlation Between Overall efficiency per Day and Temperature High per Day	
Bus Number	**Correlation Coefficient**
17301	0.60
17302	0.63
17303	0.32
17304	0.51

Source: Data from LADOT and ViriCiti, analysis by CALSTART

5.1.2 DASH Observatory Route Compared to DASH A Downtown Route

As discussed in Section 2.2 Route Selection, the four electric buses also operated on LADOT's DASH Observatory Route, which includes an uphill climb from the Vermont/Sunset Metro Redline Station in the Little Armenia area of Los Angeles to Griffith Observatory, as well as downhill travel during its return to the Little Armenia area. This route also differs from the

DASH A Downtown route in that it operates at different hours of the day (10:00 AM to 10:30 PM compared to 6:00 AM to 6:30 PM), and the electric buses only serviced it on weekends. Given the altitude change of this route (750 feet), it is valuable to analyze the same measures that were analyzed in Section 5.1.1 DASH A Downtown Route and examine any differences in efficiency, energy use, charging, and regeneration. All figures within this section show data from ViriCiti only; they do not show data from LADOT sources.

Additionally, the electric buses did not drive the DASH Observatory Route on the same days, nor did they travel that route the same amount. Table 19 shows a listing of the number of days that each electric bus traveled the DASH Observatory route during our period of analysis.

Table 19: Number of Days which Electric Buses Traveled DASH Observatory

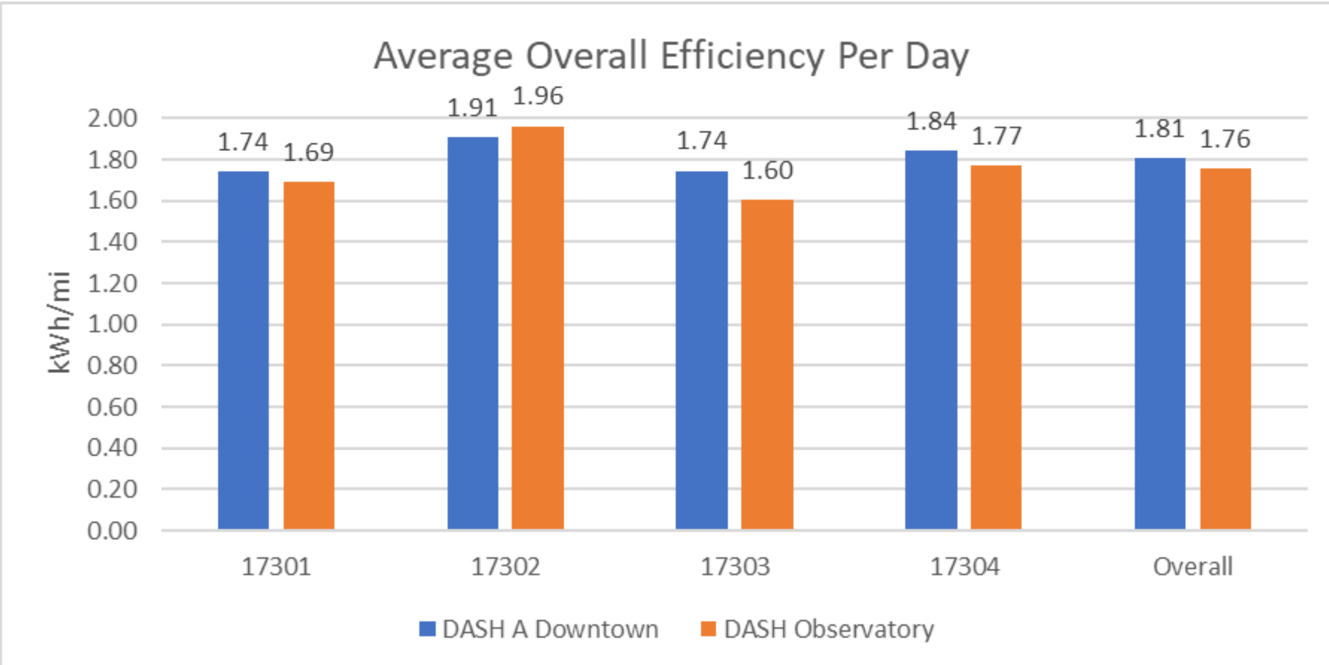
Bus Number	Number of Days with Observatory Route Recorded
17301	101
17302	57
17303	91
17304	76

Source: Data from LADOT and ViriCiti, Analysis by CALSTART

Some buses traveled this route less than others, especially 17302, which only traveled the route on 57 days. This should be kept in mind while reviewing the results below, as a smaller sample of data may lead to less stable averages.

Figure 22 shows the average overall efficiency of each bus on both the DASH A Downtown Route and the DASH Observatory Route.

Figure 22: Downtown Versus Observatory - Average Overall Efficiency Per Day



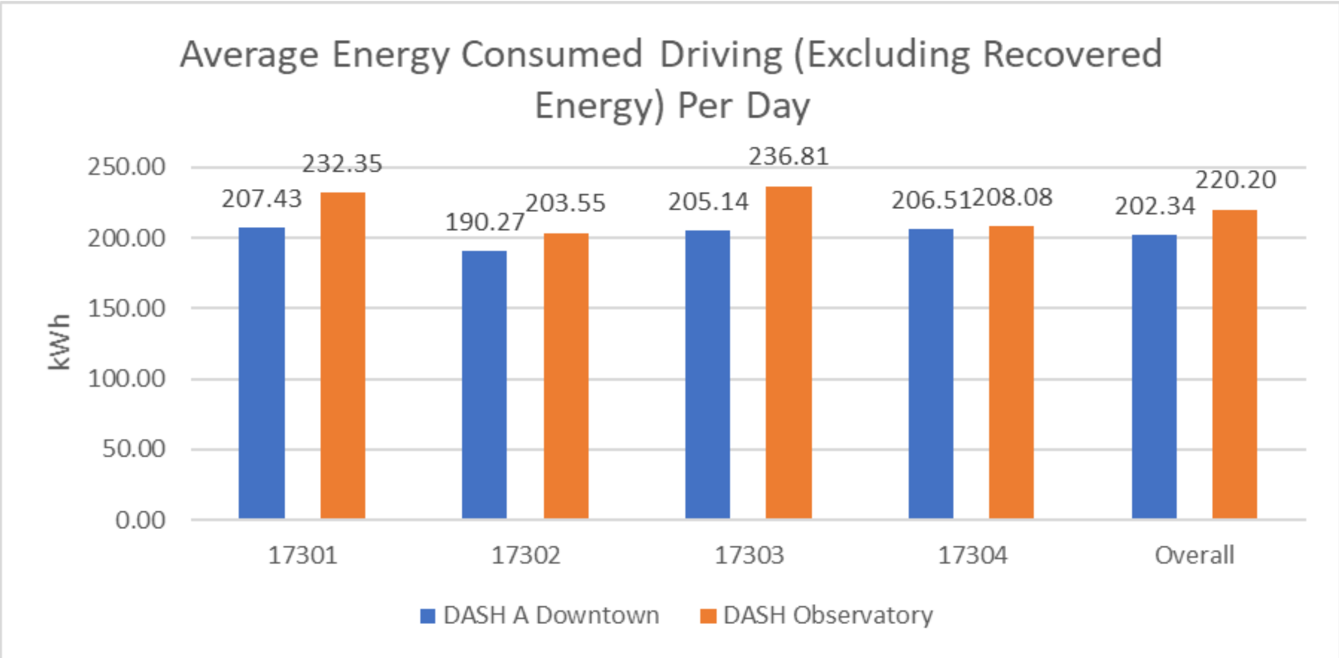
Source: Data from ViriCiti, analysis by CALSTART

Overall, average efficiency is not much different between the two routes, at 1.81 kWh/mi on the Downtown Route and slightly better at 1.76 kWh/mi on the Observatory Route. While it is not immediately clear why the buses experience improved efficiency on the DASH Observatory route, it may be due to the confluence of the following factors: downhill travel requires less work by the vehicle and there is less stop and go activity on the Observatory route than the DASH A Downtown route.

5.1.2.2 Energy Usage

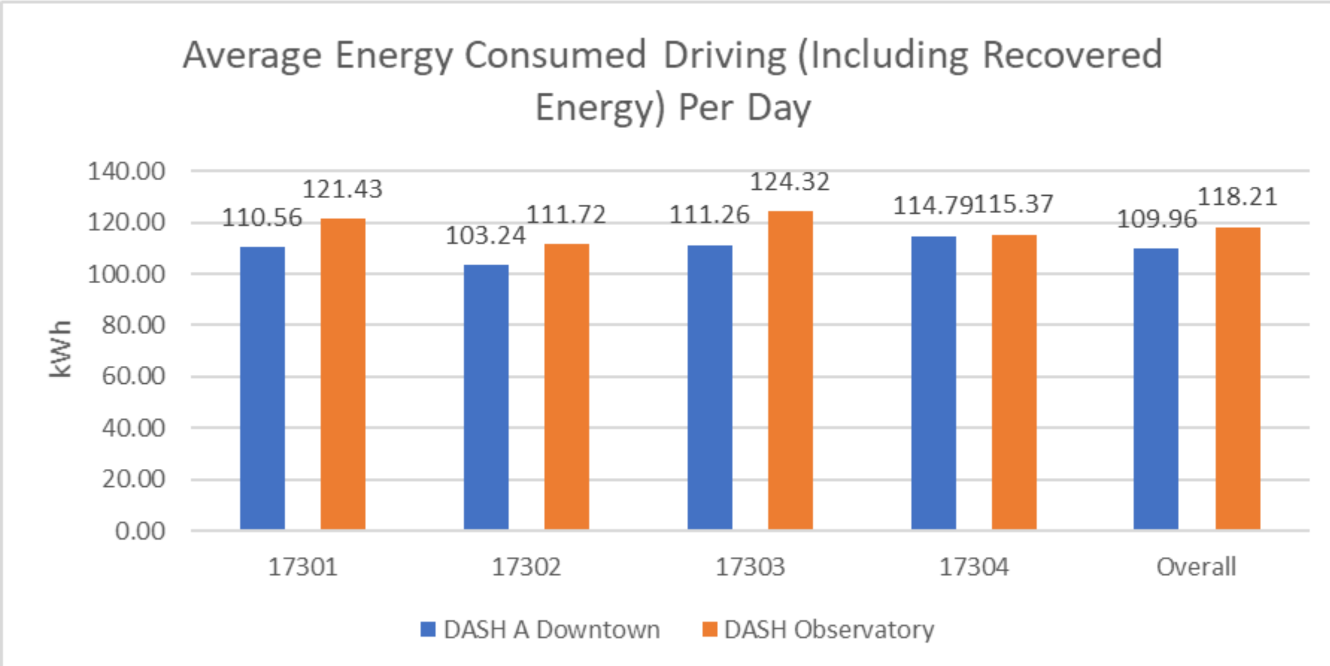
Figure 23 and Figure 24 show the average amount of energy consumed per bus per route while driving, excluding and including energy recovered through regeneration, respectively.

Figure 23: Downtown Versus Observatory - Average Energy Consumed Driving (Excluding Recovered Energy) Per Day



Source: Data from ViriCiti, analysis by CALSTART

Figure 24: Downtown Versus Observatory - Average Energy Consumed Driving (Including Recovered Energy) Per Day

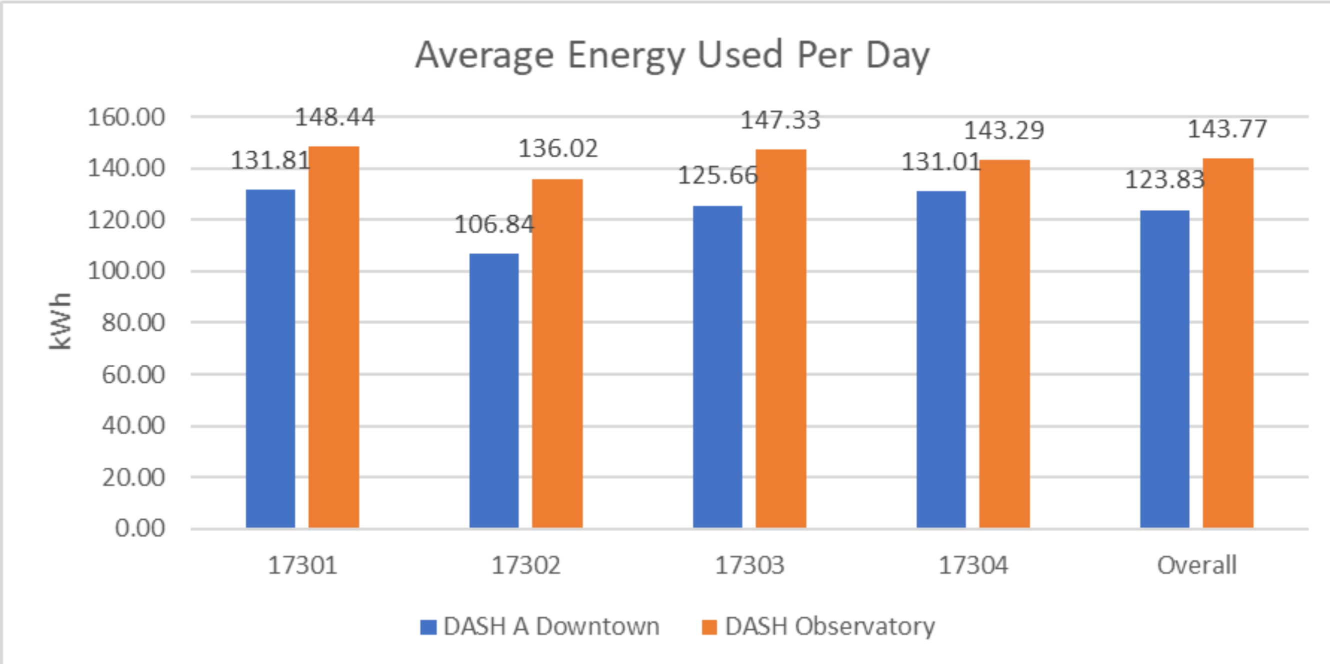


Source: Data from ViriCiti, analysis by CALSTART

Like overall efficiency, there is not much of a difference between average results on the Downtown Route versus the Observatory Route, both showing a 7 to 8 percent difference overall. The buses consumed more energy on average on the DASH Observatory route. While this might be partially attributable to the change in elevation on the DASH Observatory route, it is important to keep in mind that the buses also traveled a longer distance per day on average when serving this route compared to the DASH A Downtown route. Longer distances driven would cause more energy to be consumed.

Figure 25 shows the average amount of energy used by each bus per day per route.

Figure 25: Downtown Versus Observatory - Average Energy Used Per Day



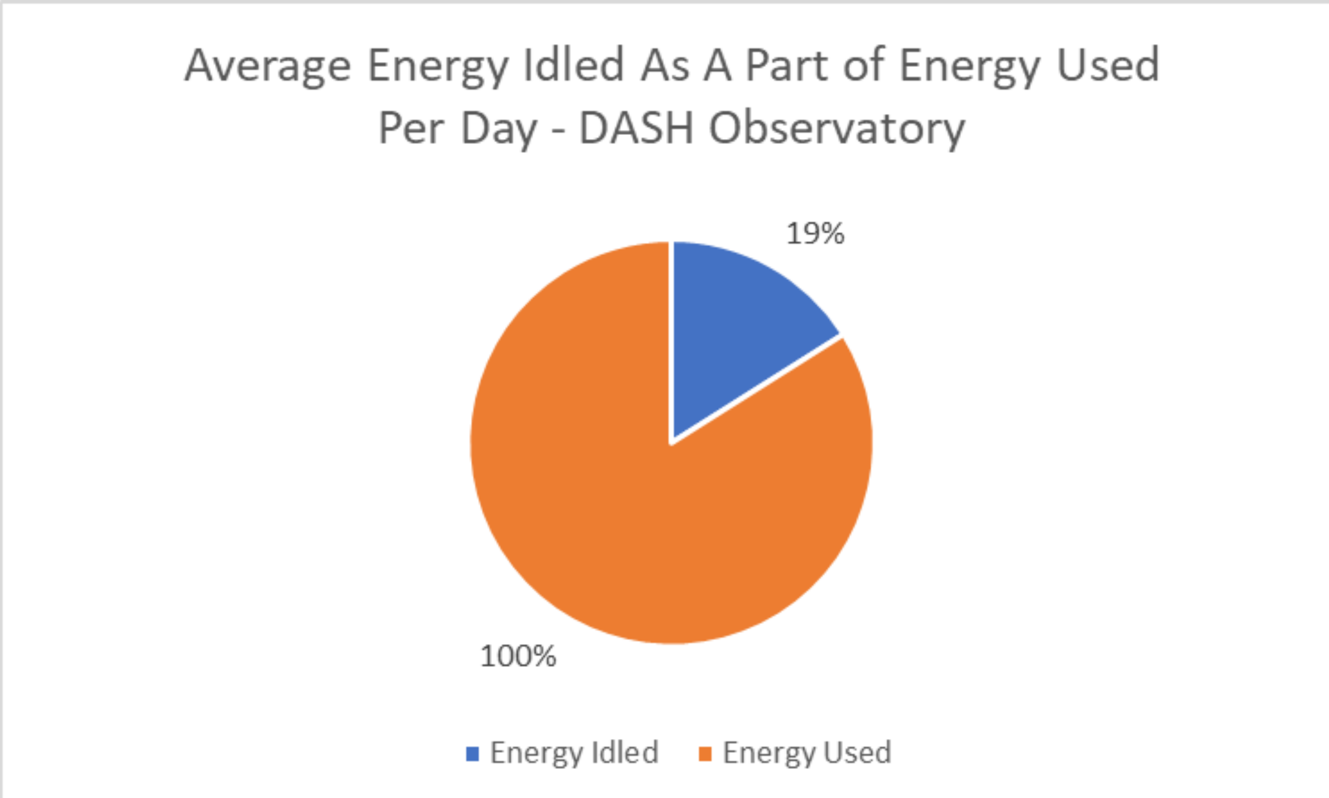
Source: Data from ViriCiti, analysis by CALSTART

As discussed previously, this parameter is different than Energy Consumed Driving in that it includes the sum of all energy used while the bus is turned on, including during idling and regeneration.[17] Again, the buses used more energy while traveling on the Observatory Route, and here is seen a somewhat larger difference between the Downtown and Observatory routes, about 15 percent overall.

17 Recovered energy from regeneration is considered a negative value in ViriCiti's calculations. Energy consumed can be thought of as energy taken from the battery while energy recovered is energy returned to the battery.

Figure 26 shows the amount of energy idled as part of overall energy used, on average per day.

Figure 26: DASH Observatory Only - Average Energy Idled as a Part of Energy Used Per Day



Source: Data from ViriCiti, analysis by CALSTART

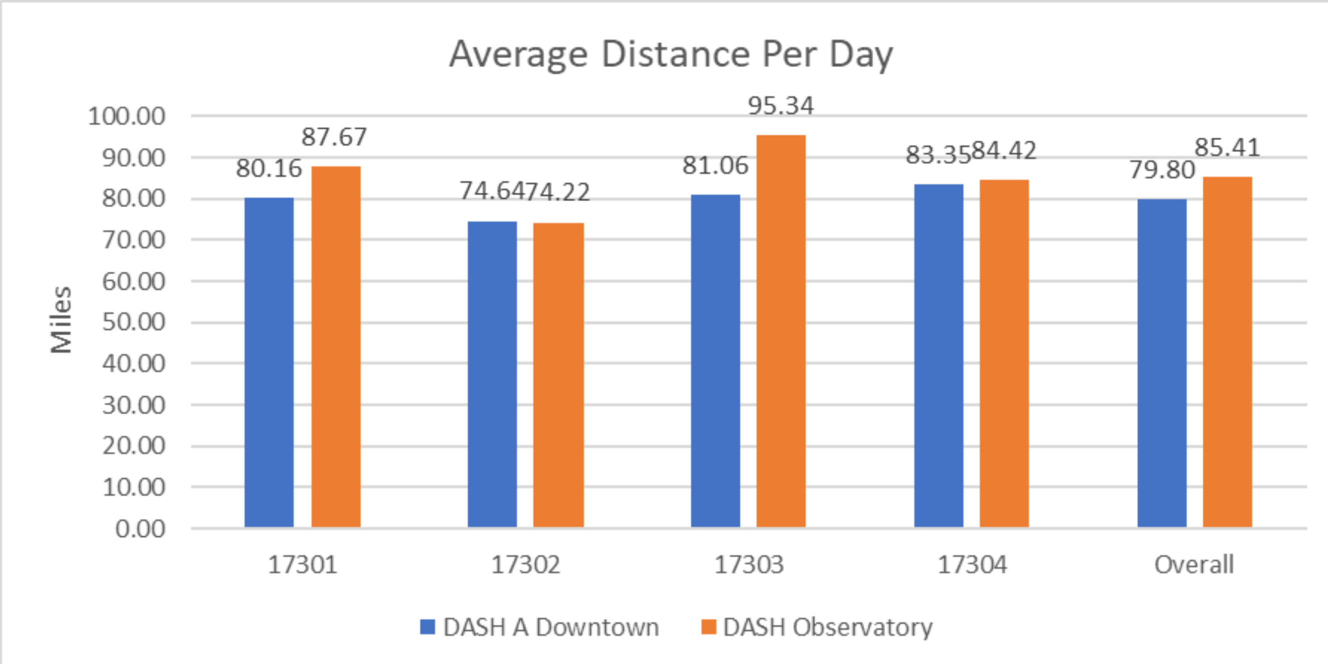
Compared to

Figure 12 which shows the same for electric bus operations on the DASH A Downtown Route, the buses showed a smaller percentage of energy used while idling on the Observatory Route. However, since the buses used more energy on average while traveling on the Observatory Route, they actually spent more energy idling on that route compared to the Downtown Route. At 22 percent of 123.83 kWh, buses consumed about 27.24 kWh idling on the Downtown Route, and at 19 percent of 143.77 kWh, buses consumed about 27.32 kWh idling on the Observatory Route.

5.1.2.3 Distance

Buses drove longer distances when covering the Observatory Route, on average. Compared to an overall average of 79.80 miles on the Downtown Route, buses drove 85.41 miles on the Observatory Route (Figure 27).

Figure 27: Downtown Versus Observatory - Average Distance Per Day



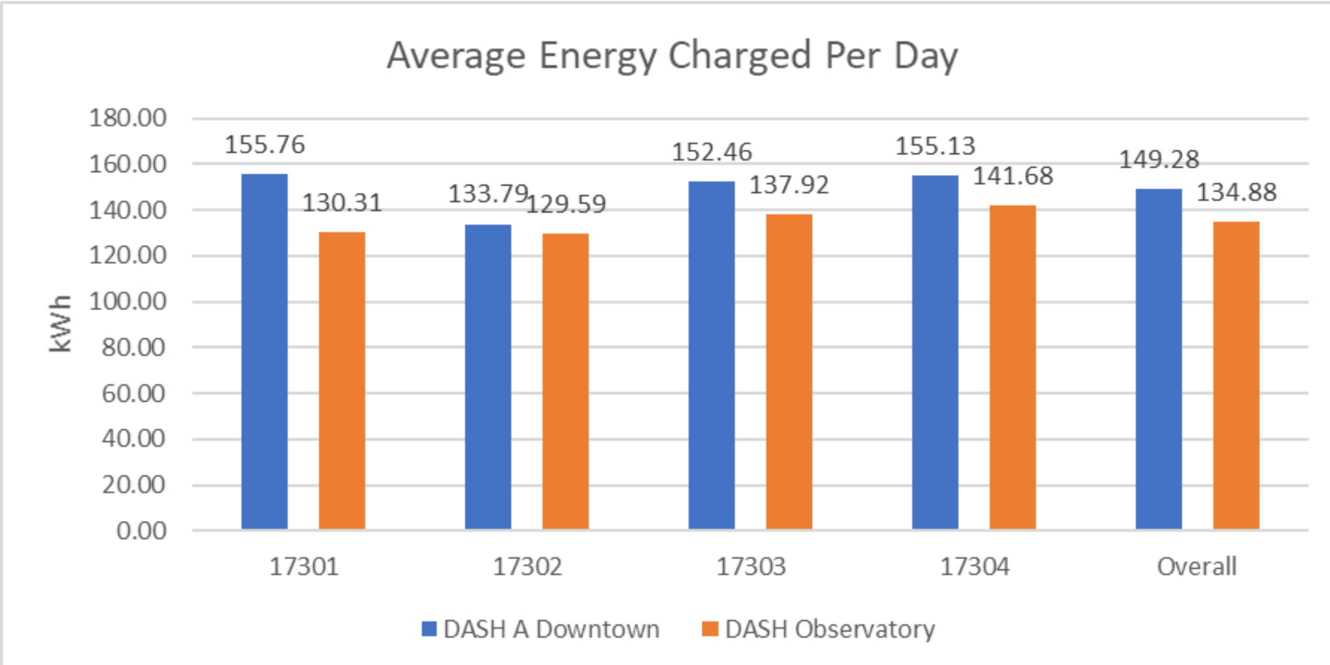
Source: Data from ViriCiti, analysis by CALSTART

5.1.2.4 Charging

Interestingly, while the buses drove longer distances on the Observatory Route, they charged less per day on days when covering that route.

Figure 28 shows the average energy charged per day per route.

Figure 28: Downtown Versus Observatory - Average Energy Charged Per Day



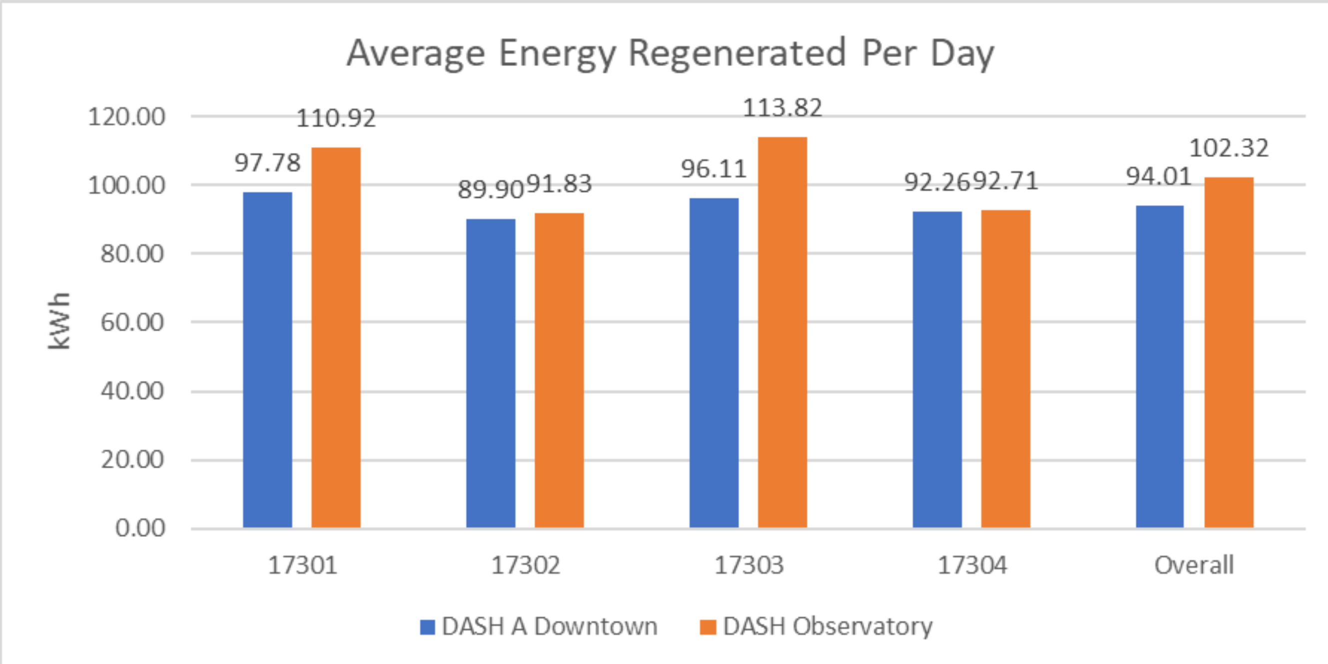
Source: Data from ViriCiti, analysis by CALSTART

While buses charged an average of 149.28 kWh per day on the Downtown Route, they charged 134.88 kWh per day on the Observatory Route, a 10 percent difference. This may be due to the higher average amount of energy recovered through regeneration while driving the Observatory Route. While the buses would likely consume a relatively large amount of energy going uphill on this route, they would have a chance to recover lost energy through regeneration as they travel downhill on their return toward Little Armenia. It could also be due to the time of day that the buses start on each route in the morning. If, for example, a bus traveled the DASH Observatory Route on a Sunday, ending at 10:30 PM, and then serviced the DASH A Downtown Route the following Monday morning, starting at 6:00 AM, the bus would have less time to charge than it would if it served the same route two days in a row.

5.1.2.5 Regeneration

Figure 29 shows the average amount of energy regenerated per day per route.

Figure 29: Downtown Versus Observatory - Average Energy Regenerated Per Day

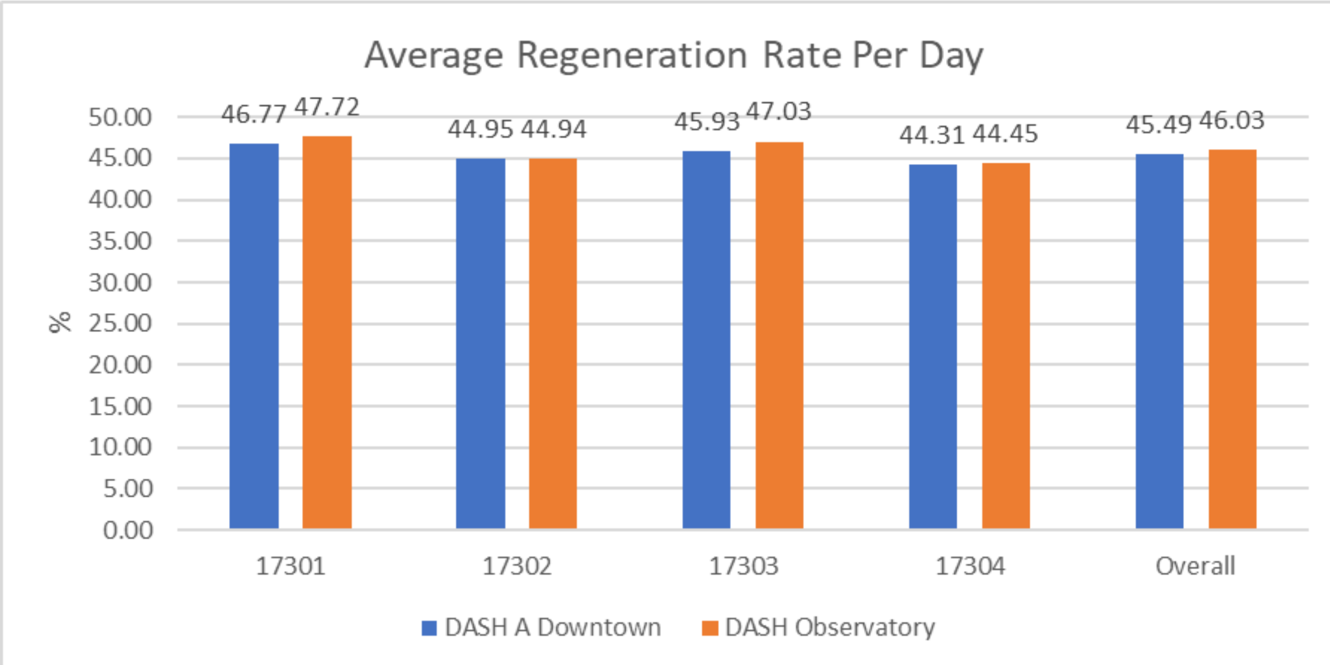


Source: Data from ViriCiti, analysis by CALSTART

As expected, buses recovered more energy through regeneration on the Observatory Route. While buses regenerated an average of 94.01 kWh per day on the Downtown Route, they regenerated 102.32 kWh per day on the Observatory Route, about an 8 percent difference. While this could be partially due to the elevation change on the DASH Observatory route, the longer average distance traveled per bus per day on that route likely has a part in this result as well.

Figure 30 shows the average regeneration rate per day per bus per route.

Figure 30: Downtown Versus Observatory - Average Regeneration Rate Per Day



Source: Data from ViriCiti, analysis by CALSTART

Buses showed almost no difference in regeneration rate on the Observatory Route compared to the Downtown Route at 46.03 percent and 45.49 percent, respectively. Figure 30 suggests that the change in topography on the DASH Observatory route compared to the DASH A Downtown route did not affect regeneration rates. It could be that the buses regenerated more energy while travelling downhill than uphill, evening out the sum of recovered energy per day, however more analysis is necessary to demonstrate this. Unfortunately, ViriCiti did not provide the researchers with a simple way to examine separate legs of the same trip so that this uphill- versus-downhill analysis could be conducted. The lowest resolution of ViriCiti data available is hour-by-hour averages. More granular analysis on the impact of topography on regeneration would be valuable for future studies.

5.1.3 Electric Bus Performance Analysis: Including Non-Revenue Service Drive Events (No Outliers Removed)

As discussed in Section 4.1.3 Analyzing Electric Bus Data Including Non-Revenue Service Drive Events Without Removing Outliers, LADOT operated the buses outside what would be considered normal service on multiple occasions. Short drive events on days when the buses were out of service for maintenance or other reasons do not count as active days in this study's analysis, however, they do represent real usage for LADOT and should not be discounted. The same applies to long drive events on days when a bus traveled to BYD's facility in Lancaster, CA for maintenance or some other reason. To understand the impact of these trips on overall average results, CALSTART analyzed performance data from ViriCiti and

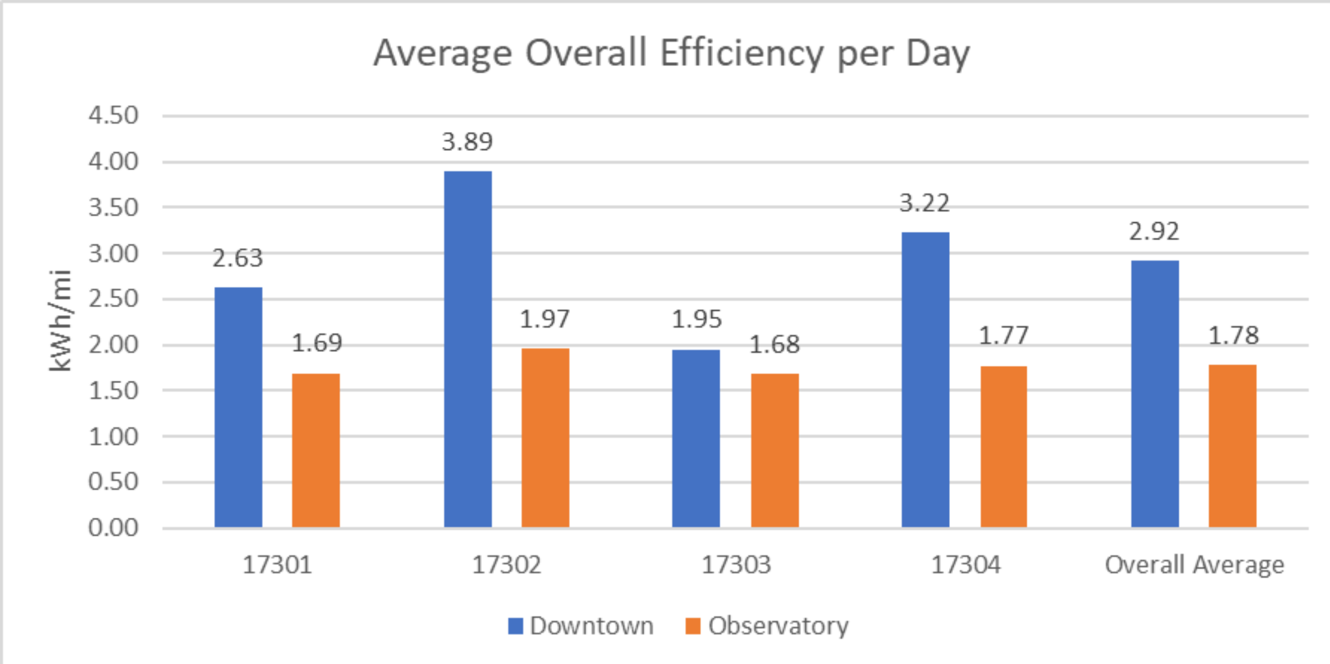
LADOT without removing any of the outliers listed in Section 4.1 Electric Bus Performance Data,[18] which capture these short and long drive events outside of normal revenue service.

Overall, the major takeaway from this analysis is that the inclusion of outlier data points does not change the distance or energy usage results in any significant way, but efficiency results do change due to the short distances covered. When the researchers calculate daily average values for distance and energy use, results generally decrease compared to those calculated by omitting outliers, but only slightly. This is due to most outliers consisting of short drive events under the active day cutoff of 7 miles per day. The exceptions to this are the three measures of efficiency: Efficiency While Driving, Efficiency While in Service, and Overall Efficiency. Results for these parameters generally increase compared to results calculated by removing outliers. However, the reason for this change is due, again, to short drive events not representative of normal revenue service. For example, on November 11, 2018 Bus 17301 was out of service for maintenance. ViriCiti reports that it traveled 0.19 miles that day, using 9.27 kWh of energy, leading to an Overall Efficiency result of 49.72 kWh/mile (Note: this result uses rounded values for distance and energy use, leading to 49.72 kWh/mile).

18 While most outliers were not removed from the data for this particular analysis, we did remove the following data points due to being impossible or so unlikely that they are considered bad data: Bus 17304 Distance on June 21, 2018 (746.83 miles), Bus 17301 Overall Efficiency on October 13, 2018 (155.40 kWh/mi), Bus 17304 Overall Efficiency on August 07, 2018 (185.52 kWh/mi).

Figure 31 shows the average overall efficiency per day for each electric bus. Overall, the efficiency increased for both routes compared to prior analysis with outliers removed at 2.92 kWh/mi on the DASH A Downtown route and 1.78 kWh/mile on the DASH Observatory route. Analysis with outliers removed showed 1.81 kWh/mile and 1.76 kWh/mile, respectively.

Figure 31: Average Overall Efficiency per Day (ViriCiti) (No Outliers Removed)



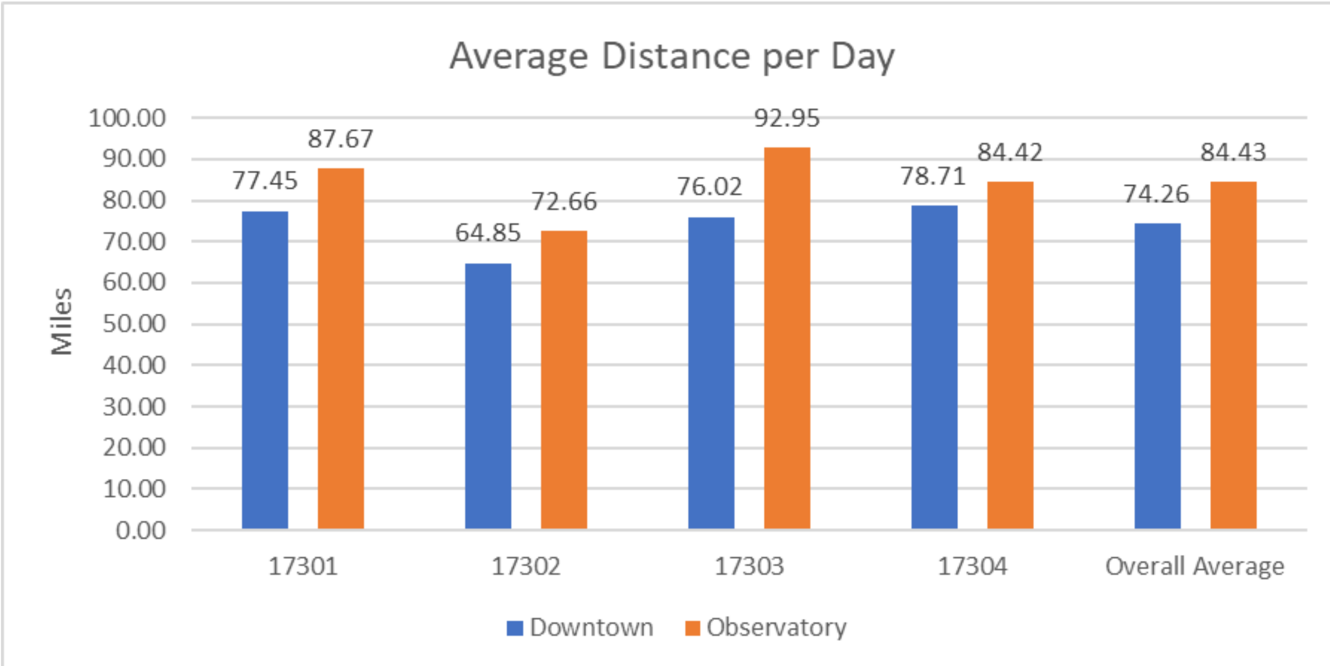
Source: Data from ViriCiti, analysis by CALSTART

Efficiency results are much higher on the DASH A Downtown route than the DASH Observatory route, likely because the buses only traveled the DASH Observatory route on select weekends. Not only did the DASH A Downtown route have a larger sample of dates to analyze, it was also driven on weekdays when short drive events due to maintenance are more likely to occur.

It is important to reiterate that these efficiency results do not reflect efficiency during typical revenue service operation. Relatively high (poor) efficiency readings are expected at low mileage, which is the cause for the results seen here. These results are seen on days in which the buses traveled less than the active day cutoff of 7 miles.

Figure 32 shows average distance traveled per day dropped compared to the prior analysis omitting outliers, but only slightly. DASH A Downtown shows an average of 74.26 miles and DASH Observatory shows an average of 84.43 miles, compared to 79.80 miles and 85.41 miles, respectively.

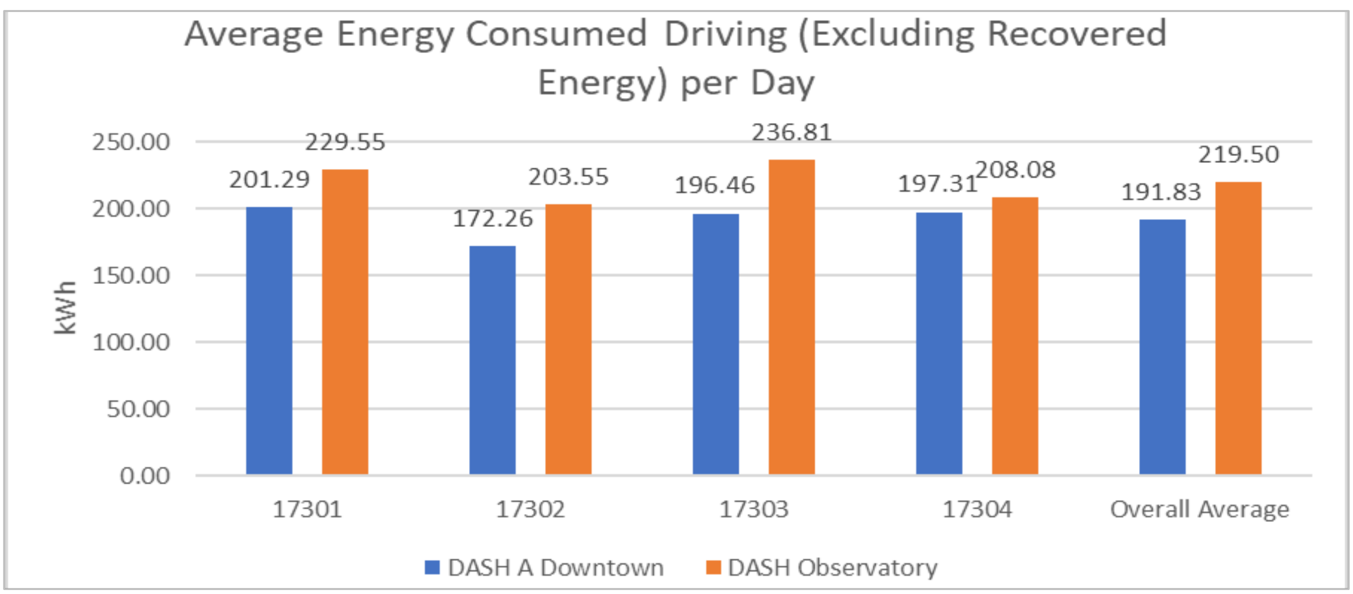
Figure 32: Average Distance per Day (ViriCiti) (No Outliers Removed)



Source: Data from ViriCiti, analysis by CALSTART

Figure 33 shows Average Energy Consumed Driving (Excluding Recovered Energy) follows suit with the DASH A Downtown route showing 191.83 kWh and the DASH Observatory route showing 219.50 kWh, compared to 202.34 kWh and 220.20 kWh, respectively.

Figure 33: Average Energy Consumed Driving (Excluding Recovered Energy) per Day (ViriCiti) (No Outliers Removed)

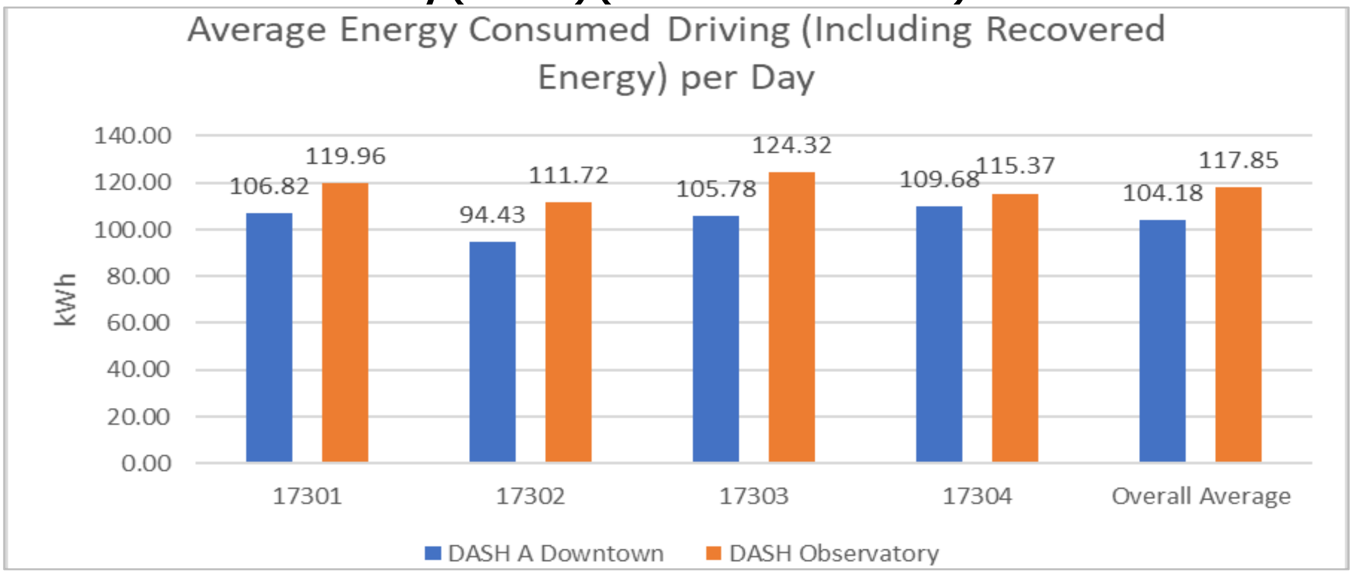


Source: Data from ViriCiti, analysis by CALSTART

Figure 34 shows the same trend applies for Average Energy Consumed Driving (Including Recovered Energy). Compared to results with outliers excluded at 109.96 kWh for the DASH A

Downtown route and 118.21 kWh for the DASH Observatory route, results including outliers show 104.18 kWh and 117.85 kWh, respectively.

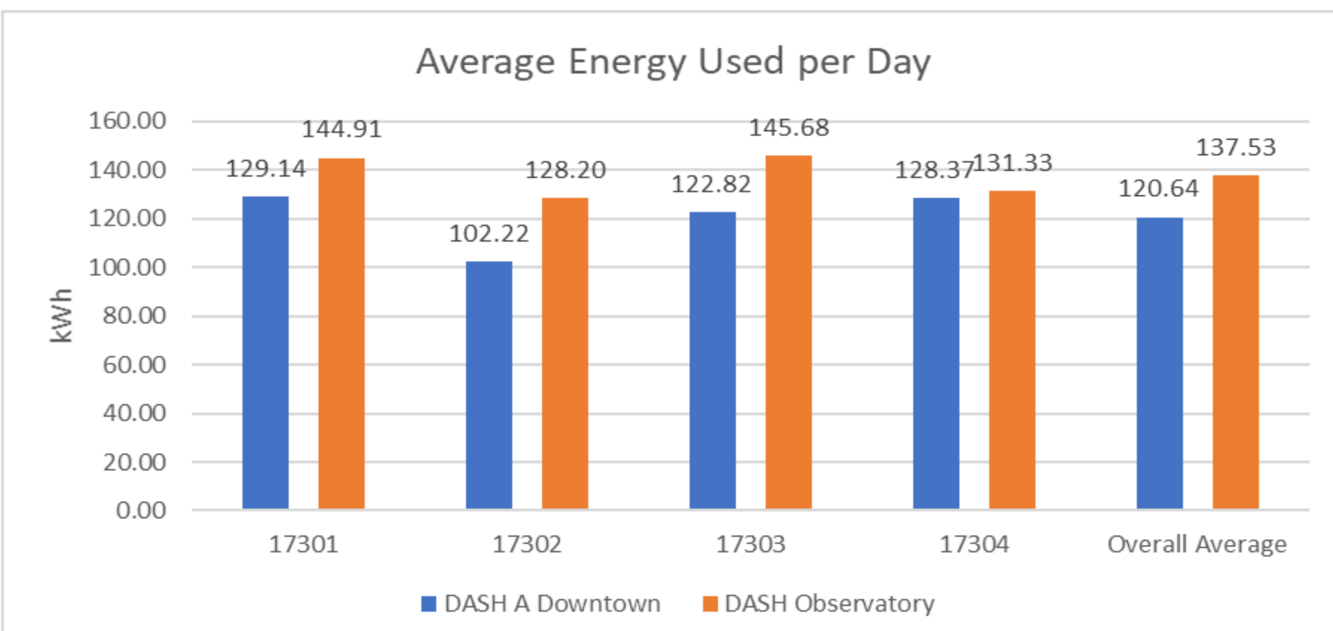
Figure 34: Average Energy Consumed Driving (Including Recovered Energy) per Day (ViriCiti) (No Outliers Removed)



Source: Data from ViriCiti, analysis by CALSTART

Figure 35 shows that Average Energy Used per day also decreases slightly from 123.83 kWh on DASH A Downtown and 143.77 on DASH Observatory to 120.64 kWh and 137.53 kWh when including outliers, respectively.

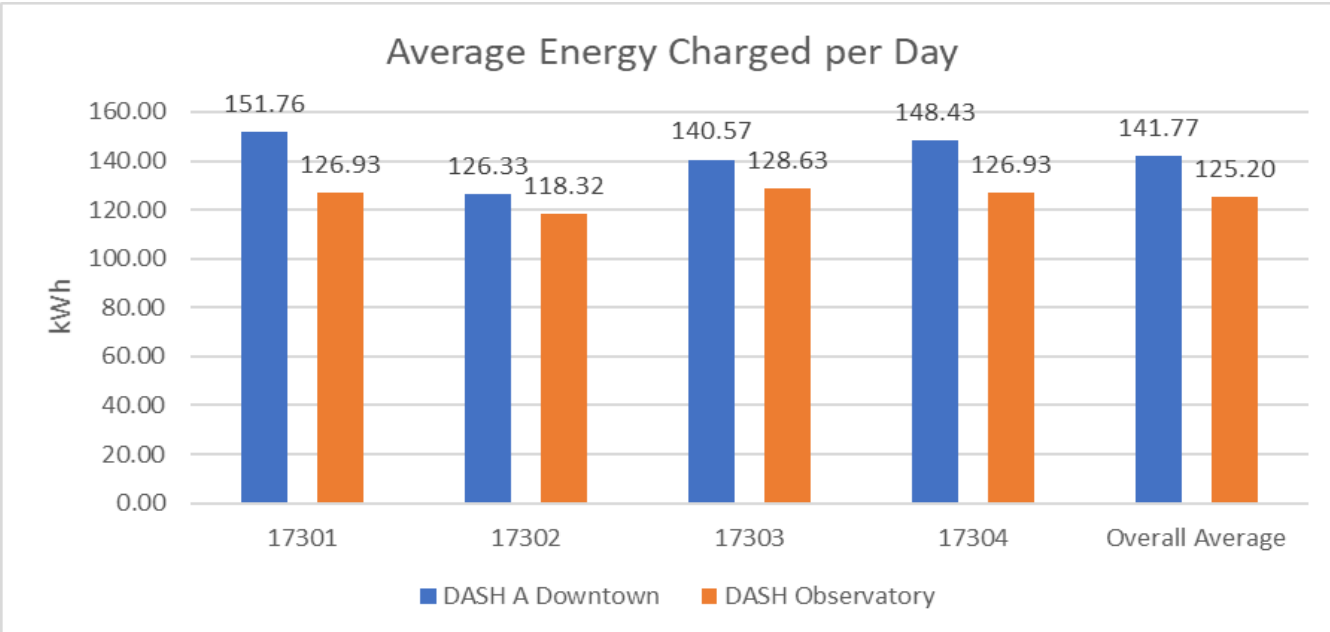
Figure 35: Average Energy Used per Day (ViriCiti) (No Outliers Removed)



Source: Data from ViriCiti, analysis by CALSTART

Figure 36 shows that Average Energy Charged per day drops slightly as well, from 149.28 kWh on DASH A Downtown and 134.88 kWh on DASH Observatory to 141.77 kWh and 125.20 kWh, respectively.

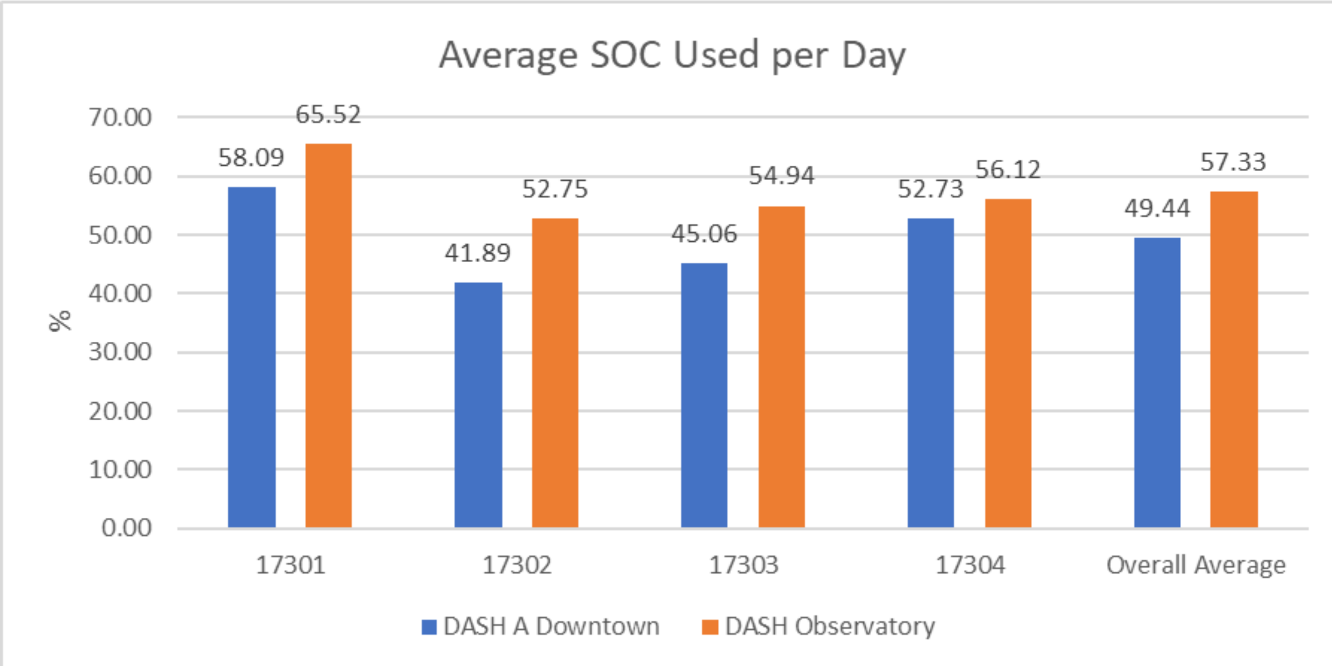
Figure 36: Average Energy Charged per Day (ViriCiti) (No Outliers Removed)



Source: Data from ViriCiti, analysis by CALSTART

Figure 37 shows that Average state of charge Used per day increases slightly on the DASH Observatory route, from 56.67 percent to 57.33 percent, but decreases on the DASH A Downtown route from 55.48 percent to 49.44 percent.

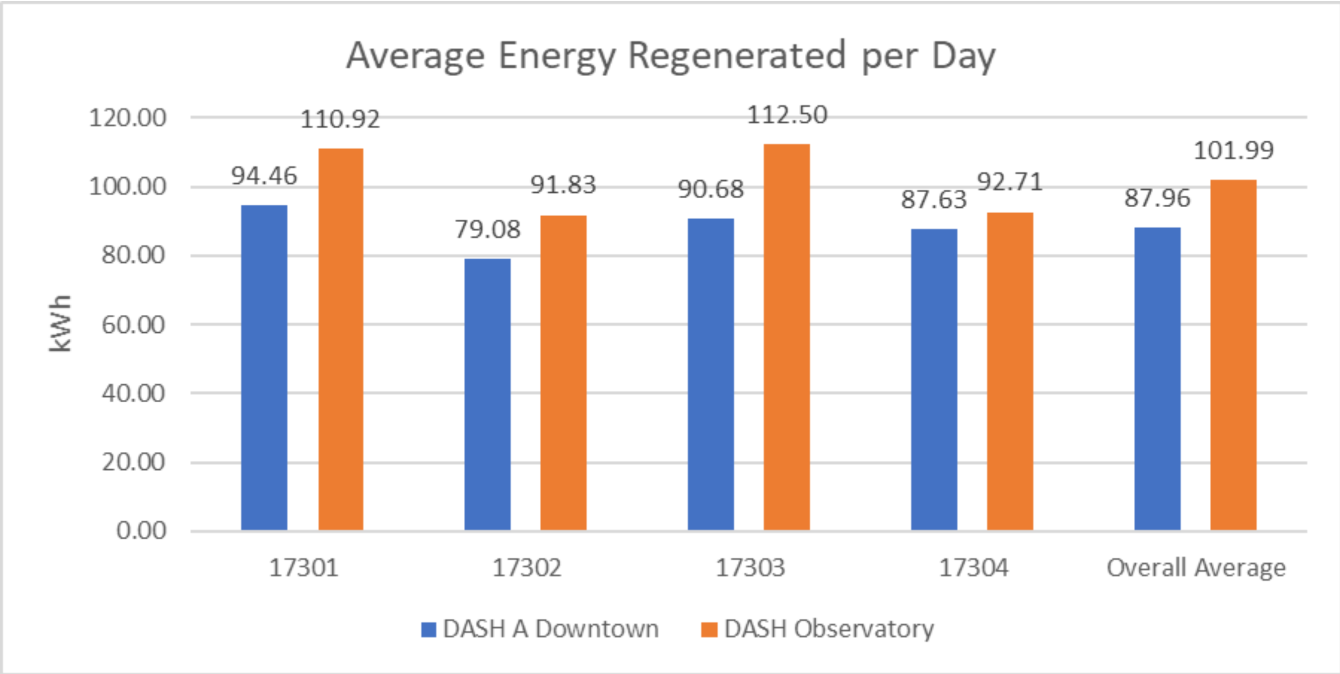
Figure 37: Average State of Charge Used per Day (ViriCiti) (No Outliers Removed)



Source: Data from ViriCiti, analysis by CALSTART

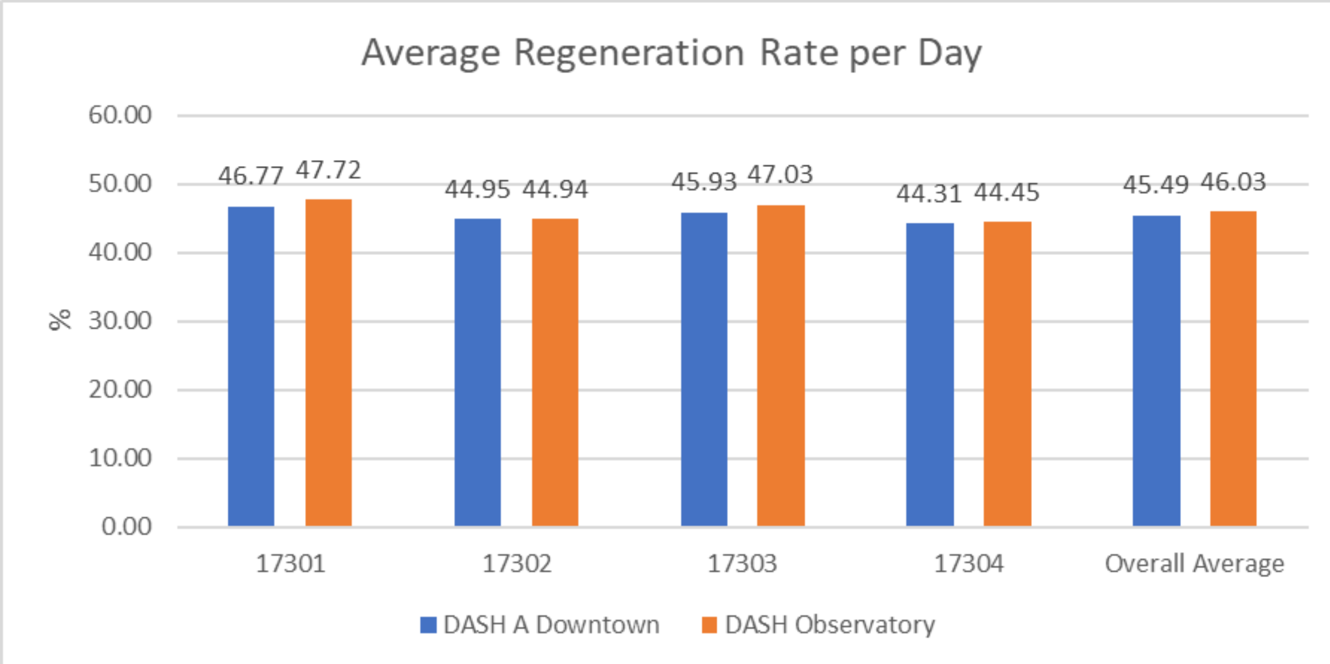
Figure 38 shows that while average Energy Regenerated per day decreases slightly for both routes, Figure 39 shows that average Regeneration Rate per day stays the same. Energy Regenerated decreases from 94.01 kWh on DASH A Downtown and 102.32 on DASH Observatory to 87.96 kWh and 101.99 kWh, respectively. However, regeneration rate stays at 45.49 percent for DASH A Downtown and 46.03 percent for DASH Observatory.

Figure 38: Average Energy Regenerated per Day (ViriCiti) (No Outliers Removed)



Source: Data from ViriCiti, analysis by CALSTART

Figure 39: Average Regeneration Rate per Day (ViriCiti) (No Outliers Removed)



Source: Data from ViriCiti, analysis by CALSTART

In addition to examining daily average results, it is also important to understand how these short and long drive events impact the amount of energy charged into the vehicles as a sum rather than an average. This analysis is important for LADOT to consider as short drive events made while the buses were out of service do contribute to overall energy use, and thus they also contribute to operating costs. This is included in the calculations for fueling and charging costs which are shown later in the report. As will be seen in Section 5.4 Comparative Analysis Overall: Performance, Maintenance, and Emissions, the per mile fuel cost for the electric buses uses LADOT data and excludes no outliers other than days with zero kWh Charged recorded. Therefore, it captures the sum of all energy charged into the vehicle from the grid and, unlike ViriCiti data, does not reflect any energy loss from the charger to the vehicle.

5.2 CNG Bus Performance Analysis

To evaluate the performance of CNG buses, the researchers focused on fuel cost per mile and energy efficiency. First, the per mile fuel cost was analyzed for the CNG buses at GGE. Table 20, Table 21, and Table 22: Per Mile CNG Cost (High Price Scenario) show these calculations.

Table 20: Per Mile CNG Cost (Low Price Scenario)

Low Price Scenario		
	17305	17306
Gallons of Fuel Consumed (17305: 279 days / 17306: 276 days)	7,705.70	7,491.60
Projected Annual Gallons of Fuel Consumed (Assume 359 days[19])	9915.22	9744.51
CNG GGE Price	$2.28	$2.28
Annual Cost of CNG GGE (Assume 359 days[19])	$22,606.70	$22,217.48
Per Day Cost of CNG GGE (Assume 359 days[19])	$62.97	$61.89
Average Daily Miles Driven	82.83	83.27
Per Mile Cost of CNG GGE	$0.76	$0.74

Source: Data from LADOT, analysis by CALSTART

Table 21: Per Mile CNG Cost (Average Price Scenario)

Average Price Scenario		
	17305	17306
Gallons of Fuel Consumed (17305: 279 days / 17306: 276 days)	7705.70	7491.60
Projected Annual Gallons of Fuel Consumed (Assume 359 days[19])	9915.22	9744.51
CNG GGE Price	$2.53	$2.53
Annual Cost of CNG GGE (Assume 359 days[19])	$25,085.51	$24,653.61
Per Day Cost of CNG GGE (Assume 359 days[19])	$69.88	68.67
Average Daily Miles Driven	82.83	83.27
Per Mile Cost of CNG GGE	$0.84	$0.82

Source: Data from LADOT, analysis by CALSTART

Table 22: Per Mile CNG Cost (High Price Scenario)

High Price Scenario		
	17305	17306
Gallons of Fuel Consumed (17305: 279 days / 17306: 276 days)	7705.70	7491.60
Projected Annual Gallons of Fuel Consumed (Assume 359 days[19])	9915.22	9744.51
CNG GGE Price	$2.78	$2.78
Annual Cost of CNG GGE (Assume 359 days[19])	$27,564.31	$27,089.74
Per Day Cost of CNG GGE (Assume 359 days[19])	$76.78	$75.46
Average Daily Miles Driven	82.83	83.27
Per Mile Cost of CNG GGE	$0.93	$0.91

Source: Data from LADOT, analysis by CALSTART

CNG GGE prices were provided to us by LADOT who reviewed their own records to find minimum, average, and maximum CNG prices. In the low price scenario, CNG costs $0.76 and $0.74 per mile at GGE for buses 17305 and 17306, respectively. In the average price scenario, CNG costs $0.84 and $0.82 per mile at GGE for buses 17305 and 17306, respectively. In the high price scenario, CNG costs $0.93 and $0.91 per mile at GGE for buses 17305 and 17306, respectively. To compare this with electric bus efficiency CALSTART first converted miles per gallon to gallons per mile, and then to kWh per mile through the 33.7 conversion factor

19 CALSTART assumes 359 days by taking 365 and subtracting the following holidays as listed in Section 2.2 Route Selection: New Year's Day, Memorial Day, Independence Day, Labor Day, Thanksgiving Day, and Christmas Day. It is assumed that the buses travel on weekends due to their use on the DASH Observatory Route on Saturdays and Sundays.

mentioned in Section 4.2. On average, bus 17305 consumed 15.69 kWh per mile, and bus 17306 consumed 15.42 kWh per mile. Table 23: CNG Bus Energy Efficiency shows the efficiency of both CNG buses on average.

Table 23: CNG Bus Energy Efficiency

Bus and Measure	Miles Per Gallon	Gallons Per Mile	kWh/Mile
17305 Average	2.31	0.47	15.69
17306 Average	2.18	0.46	15.42

Source: Data from LADOT, analysis by CALSTART

5.3 Comparative Maintenance Analysis

5.3.1 Aggregate Maintenance Analysis

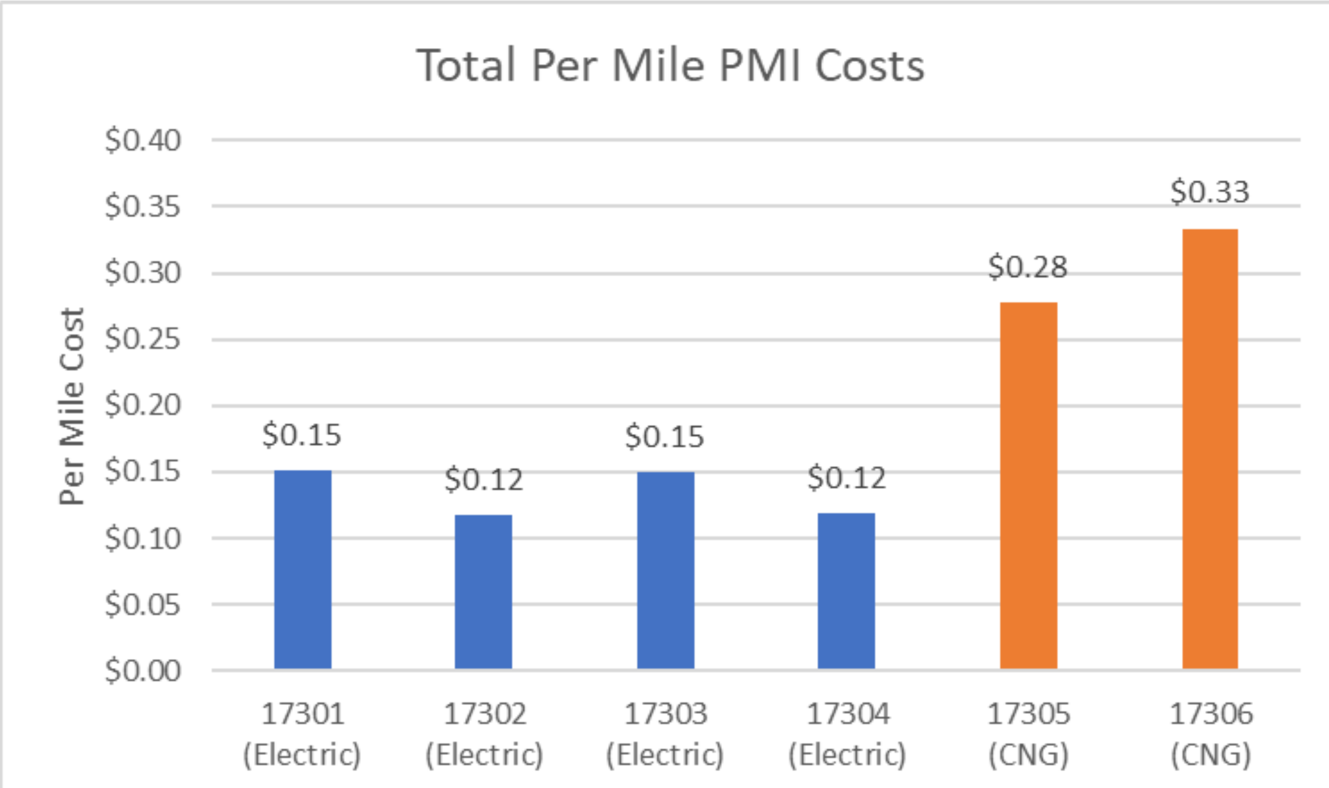
In addition to performance data, maintenance data was collected and analyzed for both the electric buses and the CNG buses. It is important to note that the buses for which data was collected are all relatively new buses (model year 2017), so the maintenance data available is not representative of long-term costs associated with operating these buses. Also, since all four electric buses are under warranty by BYD, the maintenance costs incurred by LADOT are not representative of all maintenance costs associated with the electric buses.[20, 21] However, this data does give us insight into the difference between electric and CNG bus maintenance that occurs routinely (PMI) and some insight into unplanned repairs.

20 BYD's general warranty spans the first two years of operation at 100,000 miles bumper to bumper. The warranty covers all aspects of the bus except cosmetic damage or damage caused by accident. It does not cover the cost of repair on tires, windows, mirrors, or other damage caused by passengers or operators, nor does it cover the facility-side charging infrastructure for the buses. All propulsion related systems on the bus are covered by a 5-year, 350,000-mile warranty. Finally, the battery is covered by a 12-year warranty with a promise to maintain at least 70 percent capacity.

21 CALSTART requested data on warranty-covered maintenance from BYD and LADOT, but it was not made available to CALSTART by the time that this report had to be submitted to the CEC.

Figure 40 shows the PMI per mile for each bus, electric and CNG.

Figure 40: Total per Mile PMI Costs

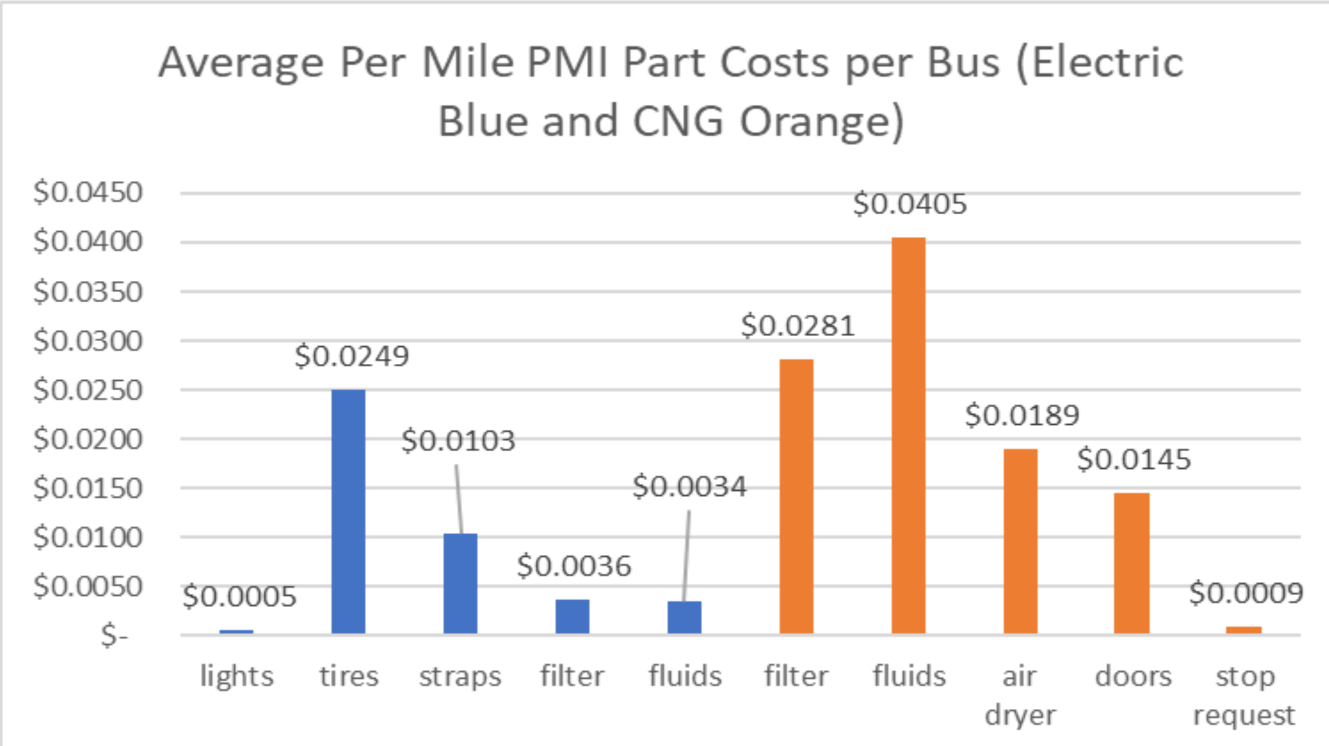


Source: Data from LADOT, analysis by CALSTART

On a per mile basis, the CNG buses saw higher preventative maintenance costs than the electric buses at an average of $0.31 per mile versus $0.14 per mile.

Figure 41 shows the average per mile cost of each part ordered for preventative maintenance per bus.

Figure 41: Per Mile PMI Part Costs

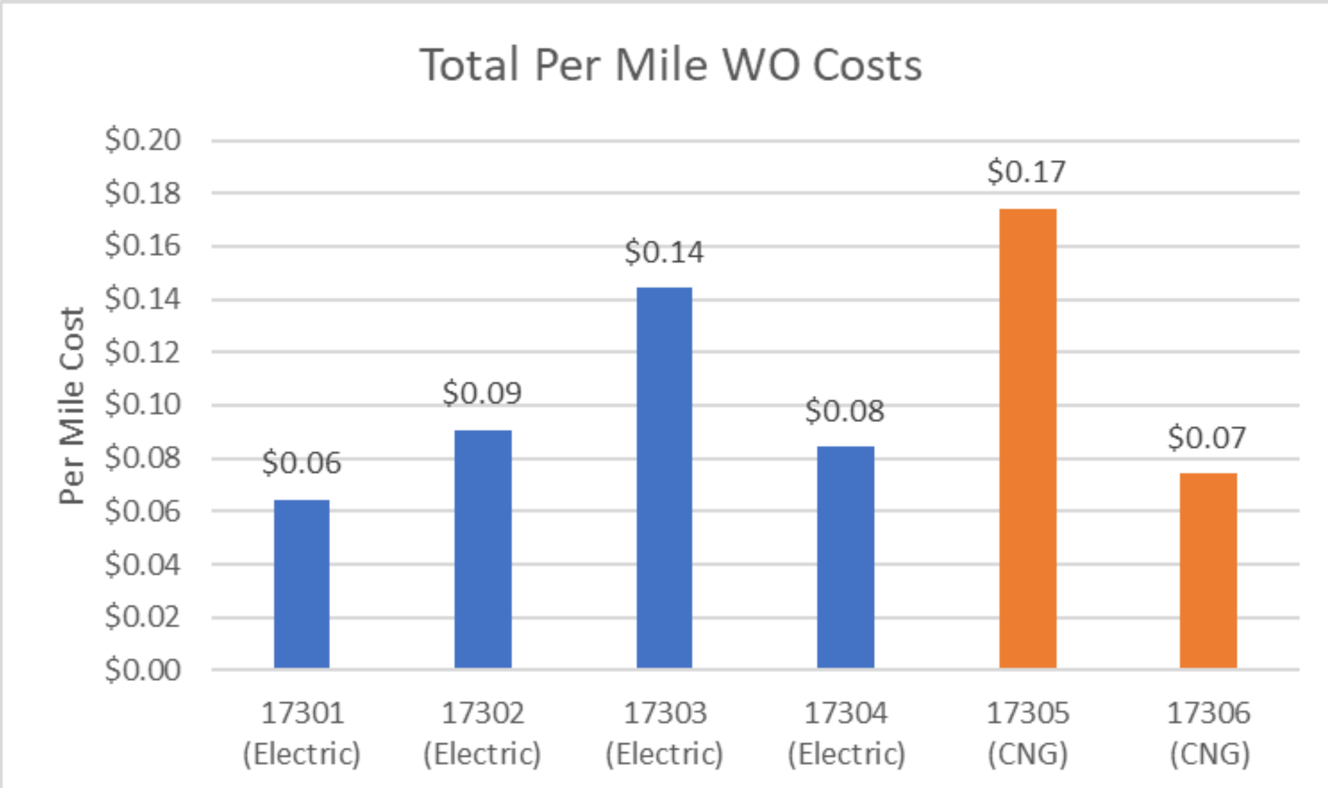


Source: Data from LADOT, analysis by CALSTART

The two items that were common between electric buses and CNG buses were filters and fluids. While the CNG buses changed filters and fluids during routine engine oil changes, the electric buses changed filters for the buses' air compressors and replaced oil gear fluids less frequently than the CNG buses' engine oil. CNG buses spent about 8 times more on filters than electric buses, and they spent about 12 times more on fluids than electric buses, as would be expected due to the motor type. Taking filters and fluids out of the calculation, both bus types spent almost the same on preventative maintenance per mile on average, albeit on different parts. The electric buses spent a significant amount of money replacing tires during preventative maintenance. In both instances in which a tire was replaced during PMI maintenance it was due to one-off problems: a flat tire and a bent valve stem.

Figure 42 shows the unplanned maintenance costs per mile for each bus.

Figure 42: Total Per Mile Work Order Costs

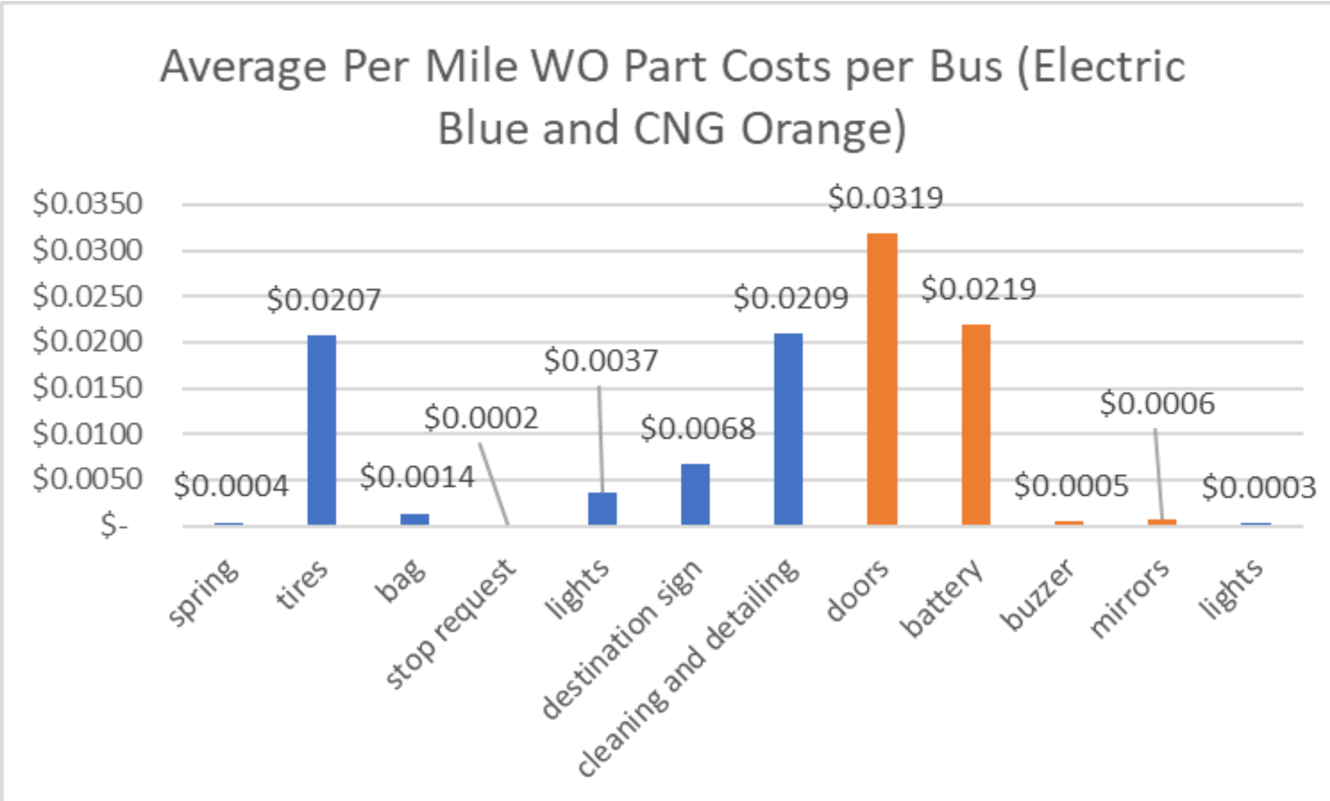


Source: Data from LADOT, analysis by CALSTART

While CNG buses spent more than electric buses on average ($0.13 and $0.09, respectively), there are some electric buses that spent more than CNG buses (17302, 17303, and 17304 compared to 17306).

A breakdown of average part costs per bus during unplanned maintenance can be seen in Figure 43.

Figure 43: Per Mile Work Order Part Costs

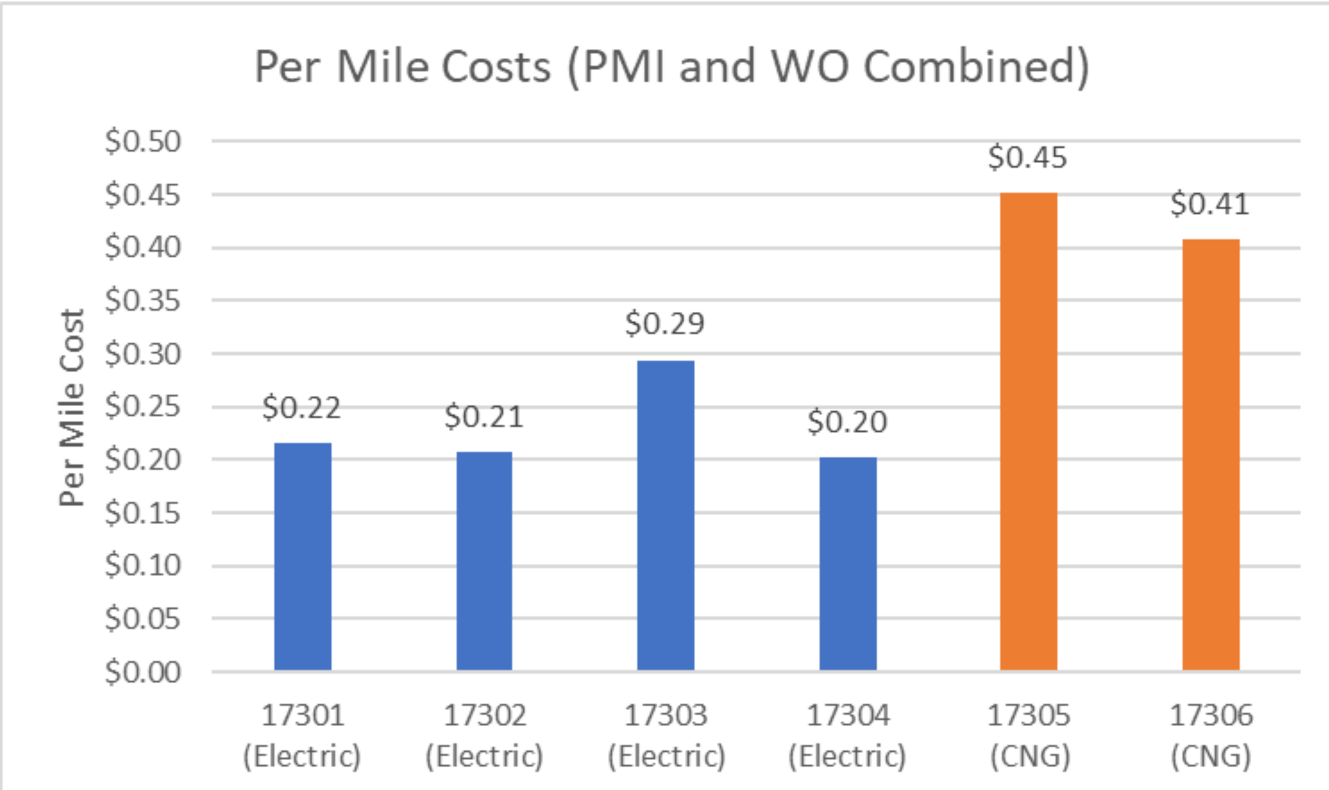


Source: Data from LADOT, analysis by CALSTART

The only comparable part between the two is lights, on which electric buses spent 12 times more than CNG buses on average. Apart from this, the average electric bus spent the most on tires, cleaning, and detailing while the average CNG bus spent the most on door and battery repairs. Like PMI costs, unplanned tire replacements were relatively costly for the electric buses. These repairs were due to one-off issues: another flat tire in one case and a tire with a damaged side wall in another case.

Figure 44 shows per mile costs for both preventative and unplanned maintenance across all buses.

Figure 44: Per Mile Costs (PMI and work order Combined)



Source: Data from LADOT, analysis by CALSTART

Combined, CNG buses cost an average of $0.43 per mile while electric buses cost an average of $0.23 per mile.

5.3.2 Major Electric Bus Maintenance Issues

While, in aggregate, the electric buses performed better than the CNG buses in terms of maintenance cost, there were a couple recurring issues with the electric buses that should be noted. First, LADOT experienced ongoing issues with Bus 17302's onboard charging system. The bus was out of service the entire month of September 2017, except for 1.5 hours of revenue service. LADOT sent the bus to BYD for repair and upon inspection BYD discovered that the cooling system surrounding the onboard charging components was damaged. BYD repaired the bus and it returned to revenue service on October 10, 2017.

Separately, 17302 experienced charging issues again in March and April 2018. It was out of service for 4 days in March and for 17 days in April. LADOT and BYD found water leakage in the battery due to a cracked battery pack cover. While the issue was corrected and repaired, it occurred again in January and February 2019. The bus was placed out of service from January 24, 2019 to February 01, 2019 and returned to revenue service that day. However, on February 02, 2019 the bus experienced charging issues again and was placed out of service. It returned to revenue service on February 04, 2019 and February 05, 2019, but was taken out of service for inspection after experiencing charging issues yet again on February 06, 2019.

BYD found significant moisture in the battery pack and removed it. The bus was then placed back into revenue service.

Numerous other maintenance issues occurred with the electric buses, prompting repairs by LADOT and BYD. These included multiple repairs to the wheelchair ramps, stuck charging pins, the air conditioning system, and stuck stop requests. These issues, however, were less recurrent than Bus 17302's charging and battery issues.

5.3.3 Maintenance and Service Issues Prior to October 2017 & BYD's Warranty

As mentioned previously, buses 17303 and 17304 were not put into service until September 2017. Bus 17301 started service in March 2017 and bus 17302 started in April 2017. From March 2017 through September 2017, buses 17301 and 17302 experienced numerous maintenance issues that are not reflected in the maintenance costs provided above. Table 24 shows a breakdown of maintenance issues for 17301 and 17302 prior to October 2017.

Table 24: Maintenance and Service Issues Prior to October 2017 for 17301 and 17302

Bus Number	Date	Issue
17301	03/02/2017	Charging system issues
17301	03/06/2017	Hanover and Syncromatics systems issues
17301	03/20/2017 – 03/22/2017	Automated Passenger Count (APC) system issues
17301	04/24/2017 – 04/28/2017	Multiple issues: electrical wires, annunciator, drive booster fan, Hanover GPS system, Hanover door signal, switch panel, mirror issues
17301	05/07/2017 – 05/09/2017	Brake issues
17301	05/11/2017 – 05/13/2017	Driver-side mirror issues
17302	05/01/2017 – 05/09/2017	At BYD for repairs
17301	06/16/2017	Multiple issues found during PMI: mirror, curb assist light, missing rivets, missing battery pack ground cable, loose radiator, leveling valve rods, drive motor cooling hose issues
17301	06/27/2017	Air conditioner issues
17302	06/04/2017 – 06/15/2017	Repairs due to an accident
17302	06/22/2017 – 06/24/2017	Checked by BYD for reported issue with lack of air pressure
17302	08/05/2017 – 08/10/2017	Air conditioner issues
17301	09/12/2017 – 09/27/2017	Repairs due to an accident
17302	All of 09/2017 except 1.5 hours of service	Charging system issues

Source: LADOT

It is important to note that all of the electric buses were under warranty by BYD, and therefore the maintenance costs incurred by LADOT do not represent all maintenance that took place on the buses. BYD's general warranty spans the first two years of operation at 100,000 miles bumper to bumper. The warranty covers all aspects of the bus except cosmetic damage or damage caused by accident. It does not cover the cost of repair on tires, windows, mirrors, or other damage caused by passengers or operators, nor does it cover the facility-side charging infrastructure for the buses. All propulsion related systems on the bus are covered by a 5-year, 350,000-mile warranty. Finally, the battery is covered by a 12-year warranty with a promise to maintain at least 70 percent capacity.

CALSTART requested data on warranty-covered maintenance performed on the electric buses, but this data was not made available to CALSTART by the date of submission for this report.

5.4 Comparative Analysis Overall: Performance, Maintenance, and Emissions

On average, the electric buses performed significantly better than CNG buses in terms of efficiency and per mile fuel and maintenance costs. Overall, the electric buses saw an average efficiency that was over eight-times better than the CNG buses. Table 25 shows a comparison of average distance, speed, and efficiency for the electric and CNG buses.

Table 25: Comparison of Electric Bus Performance to CNG Bus Performance

Parameters Compared	CNG Bus	Electric Bus
Average Miles per Day	83.05	79.80
Average Speed (mph)	11.01 (assumed to be same as electric bus)	11.01
Average Overall Efficiency (gge/mi) | (kWh/mi)	0.47 | 15.56	0.05 | 1.81

Source: Data from LADOT and ViriCiti, analysis by CALSTART

Table 26 shows a comparison of per mile fuel and maintenance costs between the electric and CNG buses.

Table 26: Per Mile Cost Comparison

Parameters Compared	CNG Bus	Electric Bus
Fuel Cost per Mile	$0.83	$0.23
Maintenance Cost per Mile	$0.44	$0.23
Total Cost per Mile	$1.27	$0.46

Source: Data from LADOT and ViriCiti, analysis by CALSTART

As can be seen, the electric buses cost less per mile on average in both fuel consumption and maintenance costs. As discussed previously, one reason for the difference in maintenance cost is that CNG buses spent significantly more money on filters and fluids for preventative maintenance than electric buses. Additionally, the four electric buses were under warranty with BYD, lowering the total maintenance costs incurred by LADOT.

The estimated fuel cost per mile for the electric buses is relatively low compared to similar studies on electric transit buses. The reason for this is low base-hour electricity rates with no demand charges from LADOT's utility, Los Angeles Department of Water and Power (LADWP), during LADOT's preferred overnight depot charging.

To calculate this value, LADWP-provided utility bills including LADOT's total electricity usage at the depot were obtained. As the four electric bus chargers were not sub-metered, the utility bills contained electricity costs for the entire facility, of which the chargers were only one part. Despite this, the utility bills also listed time-of-use rates every month for their time-of-use periods: Base, Low Peak, and High Peak. Of course, the rates increased with the Base period charging the lowest rate and High Peak charging the highest rate.

Along with the utility bills, the monthly reports that LADOT prepared for CALSTART were also used, which contained the total amount of energy charged per bus per day, along with the times at which each bus started service and ended service each day. From conversations with LADOT CALSTART knew that the buses charged overnight. With that knowledge, the assumption was made that the End Time listed for each day in the monthly reports represented the time at which the bus was plugged-into the charger, and the Start Time the next day represented the time at which the bus was unplugged from the charger. This allowed us to estimate the hours at which the buses charged each night. This analysis found that the electric buses charged during Base hours 93.01 percent of the time, during Low Peak hours 6.60 percent of the time, and during High Peak hours 0.39 percent of the time.

Using the percentage of time that the buses charged at each time-of-use period in combination with the time-of-use electricity rates, the total amount of energy charged across all buses, and the total number of miles driven across all buses CALSTART estimated fuel, or charging, costs per mile. Since the average Base hour electricity rate was $0.11/kWh, and since LADWP did not include any demand charges during Base hours, LADOT realized very low charging costs at $0.23 per mile.

Given the savings on operating costs, LADOT has an estimated simple payback period on the premium coming with an electric bus purchase of about 10 years. This estimate, however, uses the purchase price of the first four 35-foot electric buses manufactured by BYD. Since then the price has dropped from $778,000 to $720,000, which lowers the payback period to just under 8 years.

Table 27 shows a breakdown of the payback period estimate.

Table 27: Payback Period Estimate

Parameters	CNG Bus	Electric Bus
Total Cost per Mile	$1.27	$0.46
Average Miles per Day	83.05	79.80
Assume 359 Days[19] per Year	359	359
Estimated Total Annual Operation Cost	$37,864.99	$13,178.17
Annual Operational Savings	-	$24,686.81
Bus Price	$525,132.56	$778,000.00
Bus Price Premium	-	$252,867.44
Estimated Years to Break Even ($778,000 Purchase Price)	-	10.24
Estimated Years to Break Even ($720,000 Purchase Price)	-	7.89
HVIP Voucher	-	$120,000
Estimated Years to Break Even ($720,000 - $120,000 = $600,000)	-	3.03

Source: Data from LADOT and ViriCiti, analysis by CALSTART

The State of California does have an incentive program providing funds for the purchase of qualifying low and zero-emission vehicles: The HVIP. At the time of writing this report, the HVIP incentive amount for BYD's 35-foot, electric coach bus was $120,000.00. While LADOT could use these incentives to lower the cost of future bus purchases, there would remain a premium on the electric buses of about $75,000. However, use of the full incentive on the most recent BYD bus purchase price ($720,000) would bring down the estimated payback period on that premium to just over 3 years.

Operation of the electric buses also realized significant emissions and fuel reductions.

Table 28 shows estimates for the annual emissions reduced by replacing one CNG bus with an electric bus.

Table 28: Annual Emissions Reductions per Bus

	CO_2	CO	NOx	Total Hydrocarbon	Particulate Matter	Totals
Average Kilograms per Mile	3.396	0.0135	0.00081	0.00311	0.00001	3.41343
Average Miles per Day for Electric Bus	79.80	79.80	79.80	79.80	79.80	-
Estimated Average Kilograms Avoided per Year (assuming 359 days[19] per year)	97,300	386.75	23.21	89.10	0.29	97,800

Source: Data from Engine, Fuel, and Emissions Engineering, Inc. and ViriCiti, analysis by CALSTART

This data was calculated through an in-use emissions test conducted by CALSTART with the contractor Engine, Fuel, and Emissions Engineering, Inc. The results of this test were summarized in a report by CALSTART released on March 1, 2018[22] (See APPENDIX C: In-Use Emissions from a CNG Bus in Urban Downtown Service). According to this test, replacing one CNG bus with an electric bus results in an estimated 97,800 kg of emissions (CO2, CO, NOx, total hydrocarbons, and particulate matter) avoided annually. Most of these emissions reductions come in the form of CO2 at 92,289.29 avoided annually, an equivalent of removing about 22 typical passenger vehicles from the road each year.[23]

22 LeCroy, C. (2018). In-use emissions from a CNG bus in urban downtown service. Pasadena, CA: CALSTART.

23 United States Environmental Protection Agency. (2018, May 10). Greenhouse gas emissions from a typical passenger vehicle. In US EPA. Retrieved from EPA website https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle

Table 29 shows the estimated annual fuel avoided by replacing one CNG bus with an electric bus, as well as the estimated annual fuel cost savings by doing the same.

Table 29: Annual Fuel Avoided and Fuel Cost Savings

Average Projected Annual GGE of CNG (Assume 359[24] days)	9,830
Average Cost of CNG per GGE	$2.53
Average Annual Fuel Cost Avoidance	$24,870
Electric Bus Fuel Cost per Mile	$0.23
Average Miles per day	79.80
Assume 359 Days[19] per Year	359
Estimated Annual Electricity Fuel Cost	$6,590
Difference Between Annual CNG and Electricity Costs (Annual Savings)	$18,280

Source: Data from LADOT and ViriCiti, analysis by CALSTART

Annual fuel avoided was estimated by simply taking the amount of CNG (in GGE) consumed for the dates reported by LADOT in the data they provided us, and then projecting that number to 359 days per year.[19] This resulted in an estimated annual fuel avoidance of 9,829.87 GGE of CNG. At an average cost of CNG of $2.53 per GGE, this would result in an estimated savings of $24,869.57 per year. When compared to the estimated annual electricity cost from charging one bus, LADOT would see an average net savings of $18,280.48 per bus.

In terms of reliability, the electric buses were out of service more than the CNG buses. From January 01, 2017 to March 31, 2019 CNG bus 17305 was out of service 19 days and CNG bus 17306 was out of service 21 days, for an average of 20 days. By comparison, the electric buses were out of service an average of 27 days over shorter time spans.

Table 30 shows the number of days that each electric bus was out of service during the demonstration.

Table 30: Bus Reliability Results

Electric Bus Number	Date That the Bus Started Service	Days Out of Service Through March 31, 2019
17301	March 01, 2017	24
17302	April 26, 2017	42
17303	September 01, 2017	18
17304	September 01, 2017	24
	Average Across All Electric Buses	**27**

Source: Data from LADOT, Analysis by CALSTART

24 CALSTART assumes 359 days by taking 365 and subtracting the following holidays as listed in Section 2.2 Route Selection: New Year's Day, Memorial Day, Independence Day, Labor Day, Thanksgiving Day, and Christmas Day. It is assumed that the buses travel on weekends due to their use on the DASH Observatory Route on Saturdays and Sundays.

5.5 Association of Efficiency and Energy Consumption with Distance, Speed, and Temperature

Figure through Figure in APPENDIX A: Plots of Regression Results, show the association between overall efficiency and energy consumption with average distance driven, average speed, and the temperature high of each day measured. By plotting these variables against each other a better understanding is developed on how distance, speed, and temperature affect efficiency and energy consumption. For efficiency, there is a negative association with distance driven. This indicates that average efficiency per day improves at higher average distances driven per day. The relationship between distance and energy consumption is positive. As you would expect, more energy is consumed at longer distances driven. For efficiency, there is a slight negative association with speed. This indicates that average efficiency per day may improve slightly at higher average speeds. The reason for improved efficiency might not be higher speeds, however. It may be the case that the bus has higher average speeds on days which it drives with less stop and go activity. Of course, more research is required to determine this. The relationship between speed and energy consumption is relatively flat, indicating little effect of speed on energy consumption. As for temperature, it has a positive association with efficiency and with energy consumption. This indicates that average daily efficiency worsens on days with higher temperatures. In line with previous discussion from Section 5.1.1.7 Energy Efficiency and Temperature, the cause for this may be the air conditioning system, which draws energy from the battery in addition to what is needed by the powertrain, worsening overall efficiency of the vehicle.

CHAPTER 6: Major Conclusions

This report set out to analyze the performance of four electric BYD transit buses in comparison to CNG buses that operate in LADOT's fleet. CALSTART analyzed measures of vehicle performance, operation, maintenance, charging, and cost of ownership. The rest of this section highlights a few major takeaways from our findings.

6.1 Electric Bus Versus CNG Bus Efficiency

Overall, the electric buses outcompeted the CNG buses in terms of efficiency. At an average of 1.81 kWh per mile, the electric buses were over eight times more efficient than their CNG counterparts, which had an average efficiency of 15.56 kWh per mile, or 0.47 GGE per mile (2.2 miles per gallon equivalent). The electric bus efficiency was also slightly better than what other studies on similar battery electric buses have found, typically being around 2.00 kWh per mile. [8,9,10,11]

6.2 Electric Bus Versus CNG Bus Operating costs

The CNG buses had average fuel costs of $0.83 per mile and maintenance costs of $0.44 per mile for a total cost of $1.27 per mile. In comparison, the electric buses saw average fuel costs of $0.23 per mile and maintenance costs of $0.23 per mile for a total cost of $0.46 per mile, less than half the cost of CNG buses. Granted, this does not factor in any capital costs associated with installing infrastructure needed to fuel the electric buses or CNG buses. It is important to note that fuel costs of $0.23 per mile are relatively low compared to other studies on electric transit buses. LADOT can attribute this to their preference for overnight depot charging at a low Base electricity rate of about $0.11/kWh with no demand charges during Base hours.

6.3 Electric Bus Versus CNG Bus Annual Emissions and Fuel Reductions

In addition to operational performance, replacing CNG buses with electric buses contributed to significant emissions and fuel reductions as outlined in Table 28 and Table 29. By replacing one CNG bus with an electric bus, LADOT reduced an estimated total of 97,800 kg of emissions per bus per year, the equivalent of taking about 22 typical passenger vehicles off the road, or 88 for four buses. Of course, this does not consider emissions emitted through the generation of electric power on the grid to charge the buses.

6.4 Estimated Annual Fuel Savings

As for fuel avoidance, an average fuel avoidance per bus was estimated at 9,830 GGE of CNG annually. At an average cost of $2.53 GGE of CNG, this leads to an average annual cost avoidance of $24,870, which is lowered to $18,280 when factoring in the estimated average annual cost of charging an electric bus.

6.5 Maintenance Savings and Cost Reductions

CALSTART also found potential for maintenance savings by switching to electric buses, although this should be taken with some reservations as the buses evaluated in this study are model year 2017. Additionally, the four electric buses were under warranty with BYD, which lowered the maintenance costs incurred by LADOT. Extended studies should be done to assess long-term maintenance costs associated with electric transit bus operation. With the data provided, our study showed that, on average, electric buses saw a total per mile maintenance cost of $0.23 compared to $0.43 for CNG buses, driven primarily by differences in the replacement of filters and fluids during preventative maintenance and more expensive CNG-bus part replacement during unplanned maintenance.

While the data showed some evidence of maintenance cost savings, LADOT did experience some recurring issues that put the buses out of service. Bus 17302 experienced multiple outages due to charging system issues and a cracked battery pack cover leading to water damage. Part of the cost of repairs made to correct these issues were incurred by BYD given their warranty on the vehicles. This should be taken into consideration when evaluating the true cost of maintenance, as well as its impact on the reliability of the electric vehicles. While CALSTART requested data on warranty-covered maintenance from BYD and LADOT, this data was not made available by the time of submission for this report.

6.6 Electric Bus Versus CNG Bus Service

As shown in Table the electric buses were out of service 27 days on average from the start of their service through March 31, 2019. By comparison, the two CNG buses were only out of service 20 days on average from January 01, 2019 through March 31, 2019. Bus 17302 stood out as it had a total of 42 days out of service, due primarily to the recurring maintenance issues it experienced throughout the demonstration.

Higher temperatures were associated with worse energy efficiency measurements, likely due to energy consumption by the heating, ventilation and cooling system.

An additional takeaway from this report regards the impact of temperature on efficiency. As seen in, higher temperatures are associated with worse measures of efficiency. While it is understood that there is an association between these two, further research is needed to investigate the marginal effect of temperature on efficiency. By understanding how much temperature change and heating, ventilation and cooling system energy consumption impacts efficiency, manufacturers may incorporate this knowledge into future design and engineering of more efficient electric buses.

6.7 Estimated Payback Period

While the initial purchase price of electric buses tends to be higher than conventional buses, LADOT would see lower operating costs for the electric buses. These lower operating costs would allow LADOT to break even on the cost premium between the electric buses and the CNG buses in about 10 years.

As mentioned previously, $778,000 was the cost of the first round of 35-foot transit buses that BYD made. Since then, the base purchase price of this bus has dropped to $720,000. At this price, the estimated payback period drops to just under 8 years, assuming the same annual operational savings. If LADOT used HVIP incentives to lower the purchase price of the buses, the payback period estimate drops to just over 3 years. These payback period estimates do not include capital costs for charging and CNG fueling infrastructure.

CHAPTER 7: Discussion

7.1 Further Considerations for LADOT

This study showed that, under the conditions presented in this report, the business case for investing in electric transit buses is positive for LADOT. As discussed above, the electric buses were superior to CNG buses in efficiency and operating costs. It is important to note, however, that these results are limited to the purchase and operation of only four electric buses; the addition of more electric buses will present additional costs and challenges for LADOT. Additionally, maintenance costs incurred by LADOT did not include the costs of warranty-covered repairs made by BYD, and as such did not represent all maintenance issues the buses experienced. This should be considered as it impacts both the true cost of operating electric transit buses and the reliability of such vehicles. As LADOT scales up its electric transit bus fleet the puzzle of incorporating more buses into their operations will become more complicated.

First, the premium on the purchase price of electric buses compared to CNG buses is significant. If LADOT decides to replace more of its CNG fleet with electric buses, they will see large initial costs to obtain the buses. In addition to this, more charging infrastructure will have to be installed to meet the energy demands of a larger electrified fleet. The process of adding additional charging infrastructure would need to be managed closely, as it takes time and would increase capital costs. The State of California does have an incentive program providing funds for the purchase of qualifying low and zero-emission vehicles: The HVIP. At the time of writing this report, the HVIP incentive amount for BYD's 35-foot, electric coach bus is $120,000.00.[25] While LADOT could use these incentives to lower the cost of future bus purchases, there remains a premium on the electric buses of about $75,000.[26]

More electric buses also means higher demand for electricity, which may increase operating costs for the electric buses. While it varies from utility to utility, many utilities levy demand charges on properties that consume more than an agreed-upon level of energy consumption per month. While, in this study, LADOT benefitted from overnight depot charging at rates that did not include any demand charges, the addition of more buses may change this result. As LADOT's fleet grows, its demand for energy will increase and will have to be managed more closely to avoid demand charges if possible, and to minimize costs overall.

This presents another challenge: charging optimization. While only four electric buses may be relatively simple to schedule for revenue service and for charging, doing the same for tens or hundreds of buses is more complex. Differing from refueling CNG buses, charging a fleet of electric buses presents new challenges in avoiding costly demand charges and in deploying the

25 California HVIP BYD C8M 35 All-Electric Coach Bus Webpage https://www.californiahvip.org/vehicles/byd-c8m-35-battery-electric-coach-bus/

26 Electric bus price of $720,000 – $120,000 incentive - CNG bus price of $525,132.56 = $74,867.44.

buses on time given the time it takes to charge each bus. If LADOT chooses to replace its CNG bus fleet with electric buses, it will need to determine whether plug-in depot charging, overhead opportunity charging, or a combination of both makes the most sense for their operations.

Finally, LADOT should take maintenance challenges associated with operating a new technology into account. While it was not reflected in the maintenance cost information, this study found evidence of two recurring maintenance problems on one of the electric buses: on-board charger cooling system issues and a recurring battery pack cover crack. Due to the technology, these issues could not occur on the CNG buses and it will be important for LADOT to work with BYD and any other electric bus OEM they may choose to undergo the training necessary to repair these electric bus issues.

In summary, this study found that the four electric buses performed well for LADOT. However, LADOT should take the results of this report with the insight that the addition of more electric buses will present further challenges when it comes to managing capital costs, operating costs, charging practices, charging infrastructure development, and scheduling.

7.2 Further Considerations for Other Transit Fleets

This study provides valuable insights for other transit fleets who may be interested in exploring battery electric transit bus technology. While the results here are limited in scope, there are some important takeaways for other fleets across California and the United States. In summary, this study has shown that battery electric transit buses are a viable option for urban transit route operation, and that under the correct circumstances they can perform better than CNG buses in terms of efficiency and operating costs. Along with these takeaways, however, other transit fleets should consider the following limitations of this study.

First, this study was performed in Los Angeles, CA which has a warm-to-hot climate year-round. As mentioned previously, temperature is shown to have an impact on vehicle efficiency. While this study showed evidence of worsened efficiency during the hottest months in Los Angeles, it did not capture any data on the impact of cold weather on efficiency. It is likely that cold weather may impact efficiency in similar ways due to the operation of the vehicle's heating system, but further studies should be completed to confirm this.

Additionally, this study was conducted in downtown Los Angeles, an urban setting. Electric buses may perform differently in rural or suburban environments. Additionally, while there are certainly elevation changes in Los Angeles, more mountainous or hilly areas may see differing results. While this study showed some slight difference in energy use and regeneration when the buses operated on the DASH Observatory Route, the results were not much different than that of the DASH A Downtown Route and could be attributed partly to longer distances traveled on the former route, not just elevation change.

Next, more research on maintenance costs of electric transit buses would be valuable. As the technology is relatively new, long-term maintenance data is not yet available. This study provided an analysis of maintenance data for buses that were only model year 2017. Additionally, maintenance costs may vary from one transit agency to another, depending on how they structure payment for maintenance services.

Finally, other fleets should consider their local utility's rate design. Every utility charges different rates for energy usage that can vary by time of day and day of the week. Depending on the transit fleet's schedule of operation, charging patterns may be different, and energy costs will likely differ from that of LADOT. To fully assess how the addition of electric transit buses may impact the electricity bill, fleets should consider their utility's rate structure as well as their anticipated charging schedule.

Overall, this study showed that electric transit buses can benefit a transit fleet in terms of both vehicle performance and operating costs. Compared to the CNG buses, LADOT's four electric buses showed better efficiency, lower operating costs, reduced emissions and fuel usage, and a simple payback period that is within the expected life of the bus. This study only included the operation of four buses, however, and it was limited in environmental and geographical scope. Both LADOT and other transit agencies will benefit from understanding the results of this study, along with additional considerations mentioned herein.

GLOSSARY

CARBON DIOXIDE (CO^2) - A colorless, odorless, non-poisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. CO^2 is the greenhouse gas whose concentration is being most affected directly by human activities. CO^2 also serves as the reference to compare all other greenhouse gases (see carbon dioxide equivalent).

CARBON MONOXIDE (CO) - A colorless, odorless, highly poisonous gas made up of carbon and oxygen molecules formed by the incomplete combustion of carbon or carbonaceous material, including gasoline. It is a major air pollutant on the basis of weight.

COMPRESSED NATURAL GAS (CNG) - Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

GREENHOUSE GASES (GHG) – Any gas that absorbs infra-red radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), halogenated fluorocarbons (HCFCs), ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

HYBRID AND ZERO-EMISSION TRUCK AND BUS VOUCHER INCENTIVE PROJECT (HVIP) – A project launched in 2009 by the California Air Resources Board in partnership with CALSTART to accelerate the purchase of cleaner, more efficient trucks and buses in California.[27]

KILOWATT (kW) - One thousand (1,000) watts. A unit of measure of the amount of electricity needed to operate given equipment. On a hot summer afternoon a typical home, with central air conditioning and other equipment in use, might have a demand of four kW each hour.

KILOWATT-HOUR (kWh) - The most commonly-used unit of measure telling the amount of electricity consumed over time. It means one kilowatt of electricity supplied for one hour. In 1989, a typical California household consumes 534 kWh in an average month.

LOS ANGELES DEPARTMENT OF TRANSPORTATION (LADOT) - a municipal agency that oversees transportation planning, design, construction, maintenance and operations within the City of Los Angeles.

LOS ANGELES DEPARTMENT OF WATER AND POWER (LADWP) - The acronym for Los Angeles Department of Water and Power; an electric, municipal utility serving the greater Los Angeles, California, region.

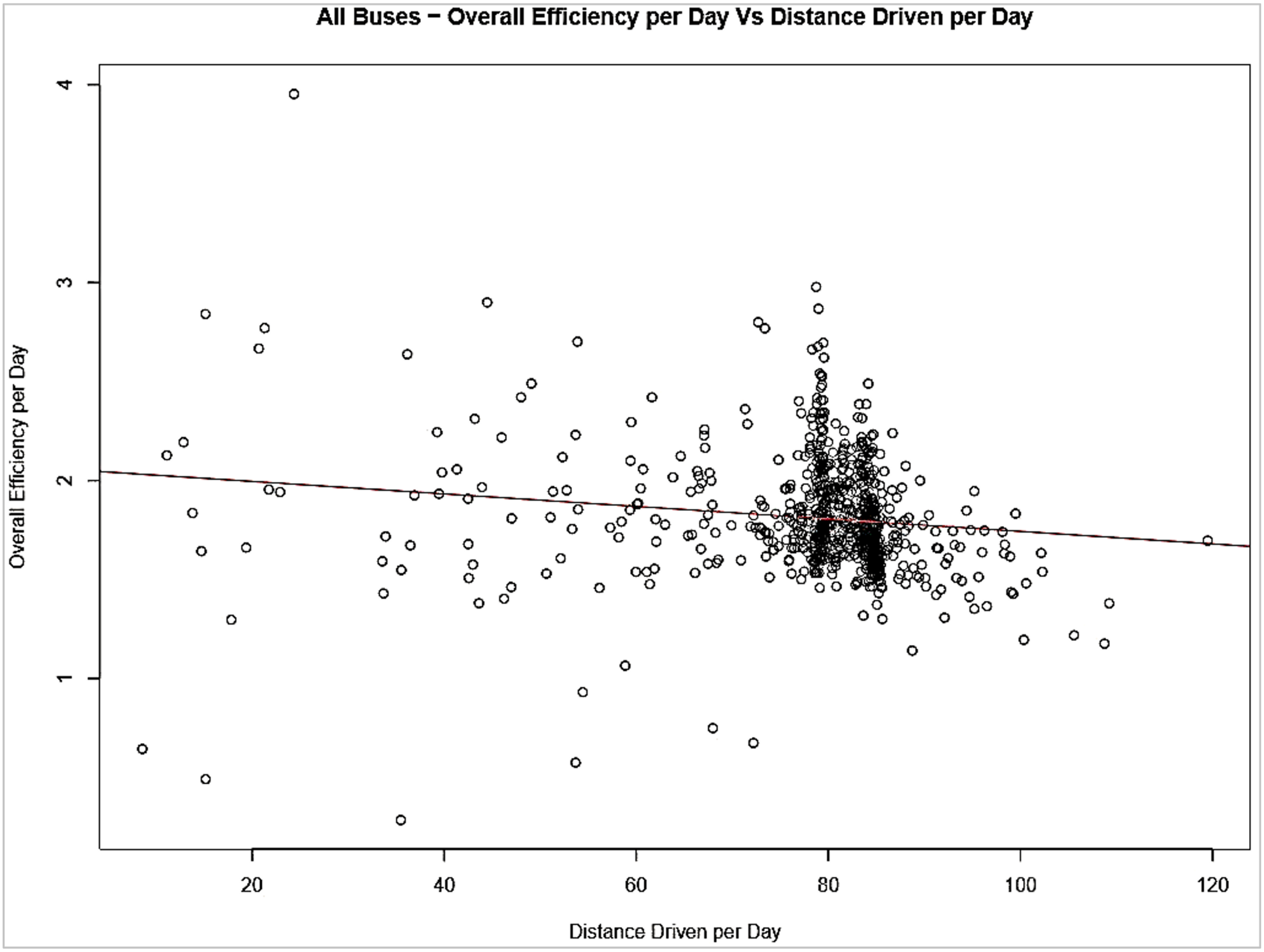
NITROGEN OXIDES (NOx) - Oxides of nitrogen that are a chief component of air pollution that can be produced by the burning of fossil fuels.

27 California HVIP Website https://www.californiahvip.org/

PREVENTIVE MAINTENANCE INSPECTION (PMI) - A routine inspection for the equipment to make it from one planned service to the next planned service without any failures caused by fatigue, neglect, or normal wear (preventable items).

APPENDIX A:
Plots of Regression Results[28]

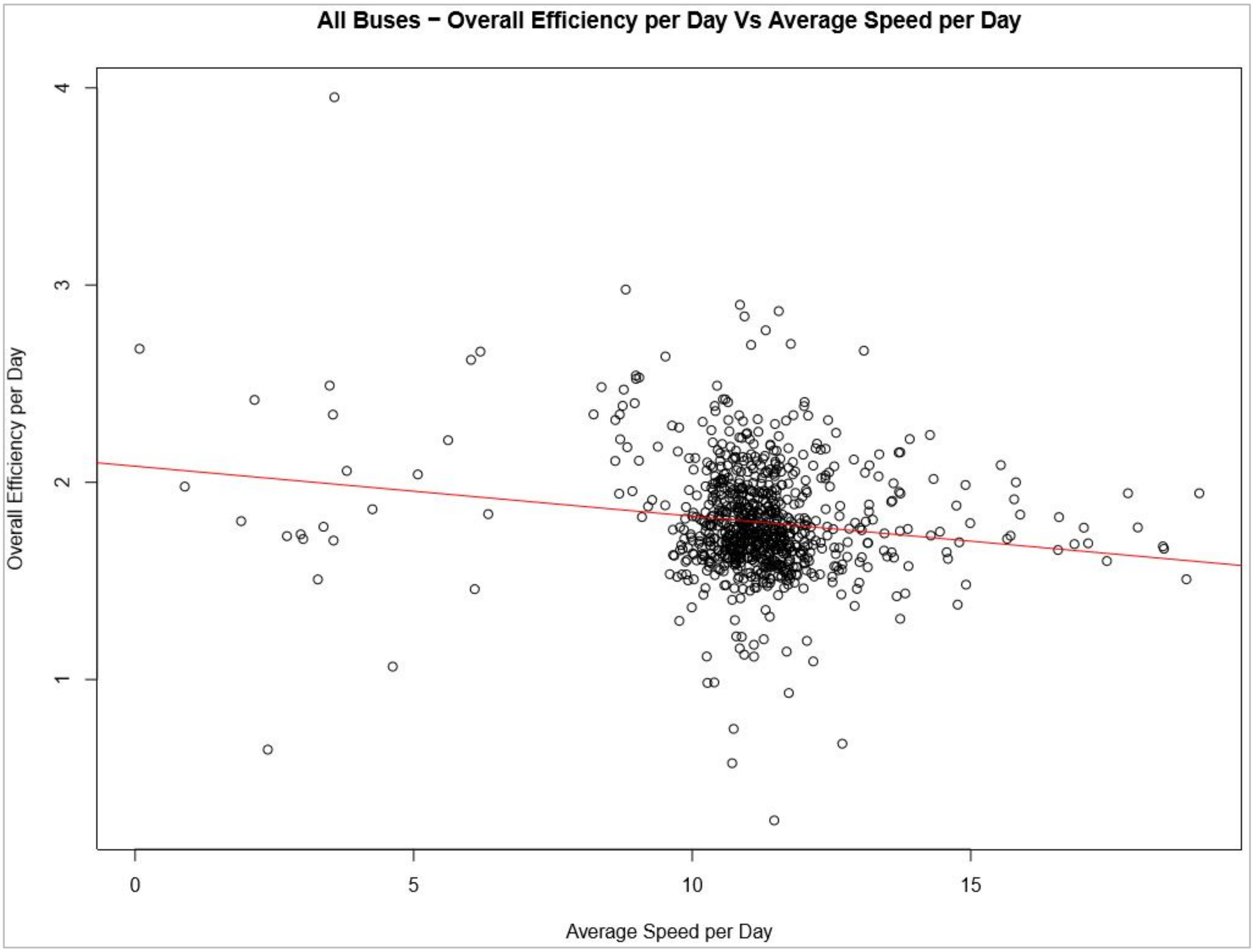
Figure A-1: All Buses - Overall Efficiency per Day Versus Distance Driver per Day



Source: Data from ViriCiti, analysis by CALSTART

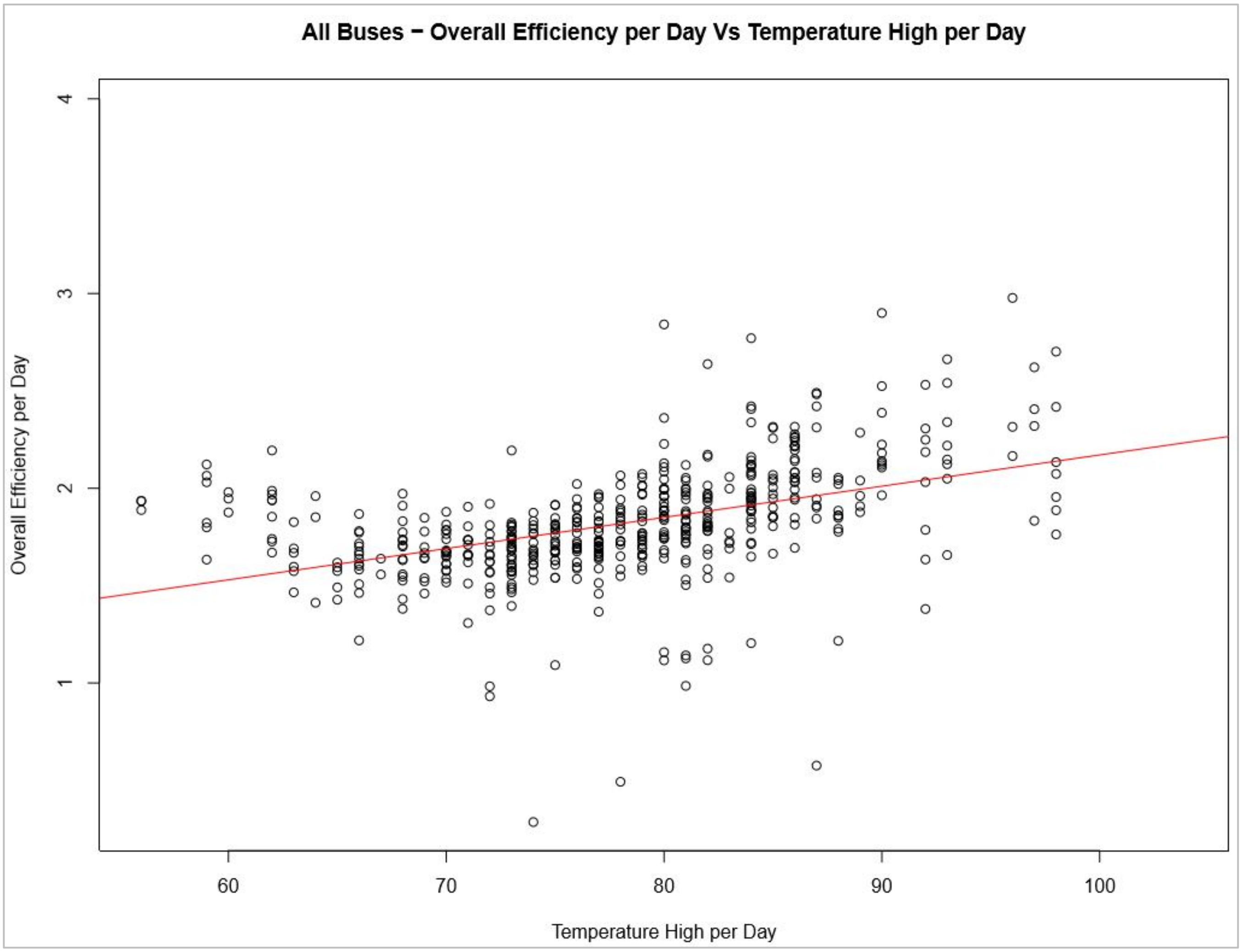
28 Note that for plots showing Distance Driven per Day, all observations over 120 miles were considered outliers for this analysis and were removed, as they were skewing correlation results.

Figure A-2: All Buses - Overall Efficiency per Day Versus Average Speed per Day



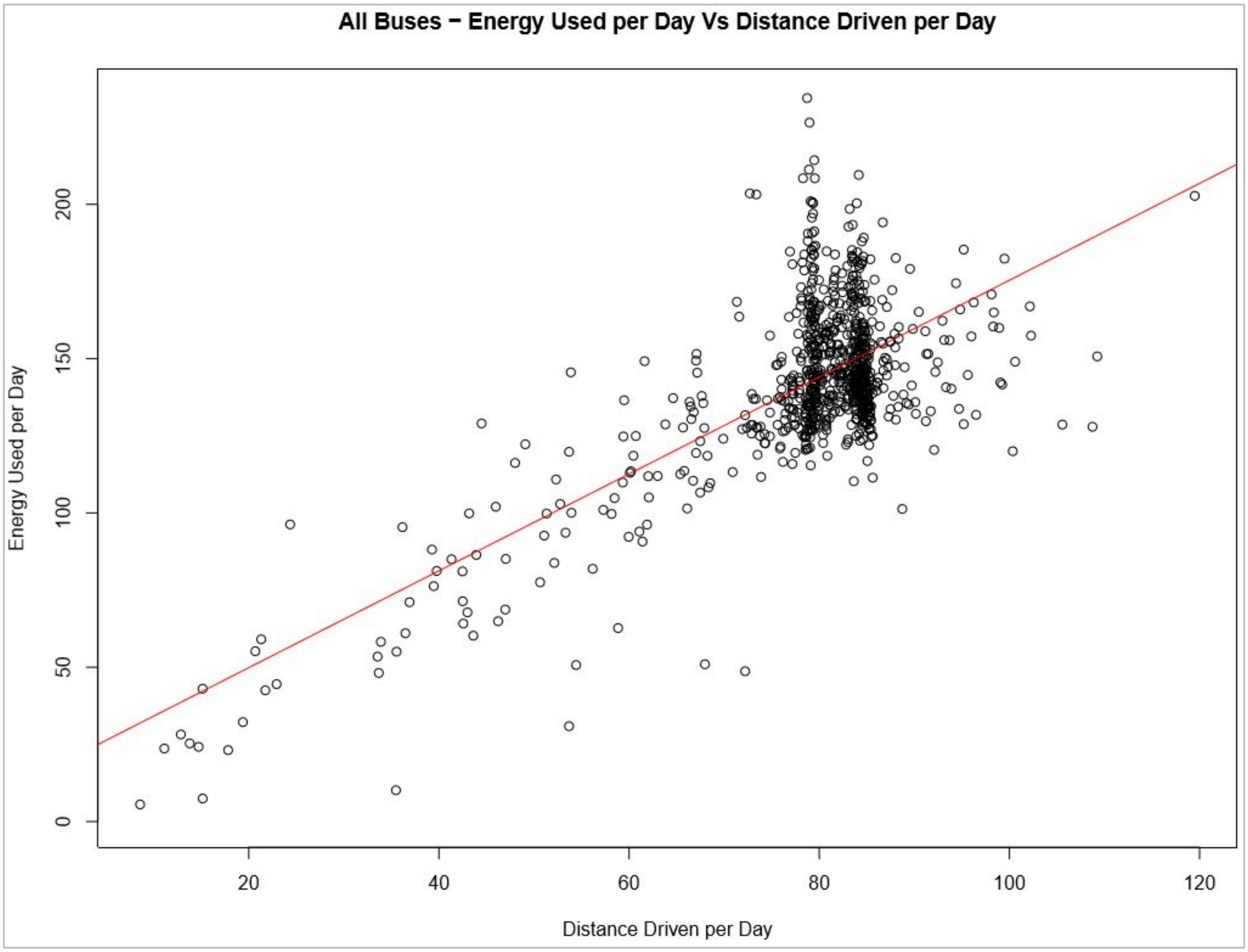
Source: Data from ViriCiti, analysis by CALSTART

Figure A-3: All Buses - Overall Efficiency per Day Versus Temperature High per Day



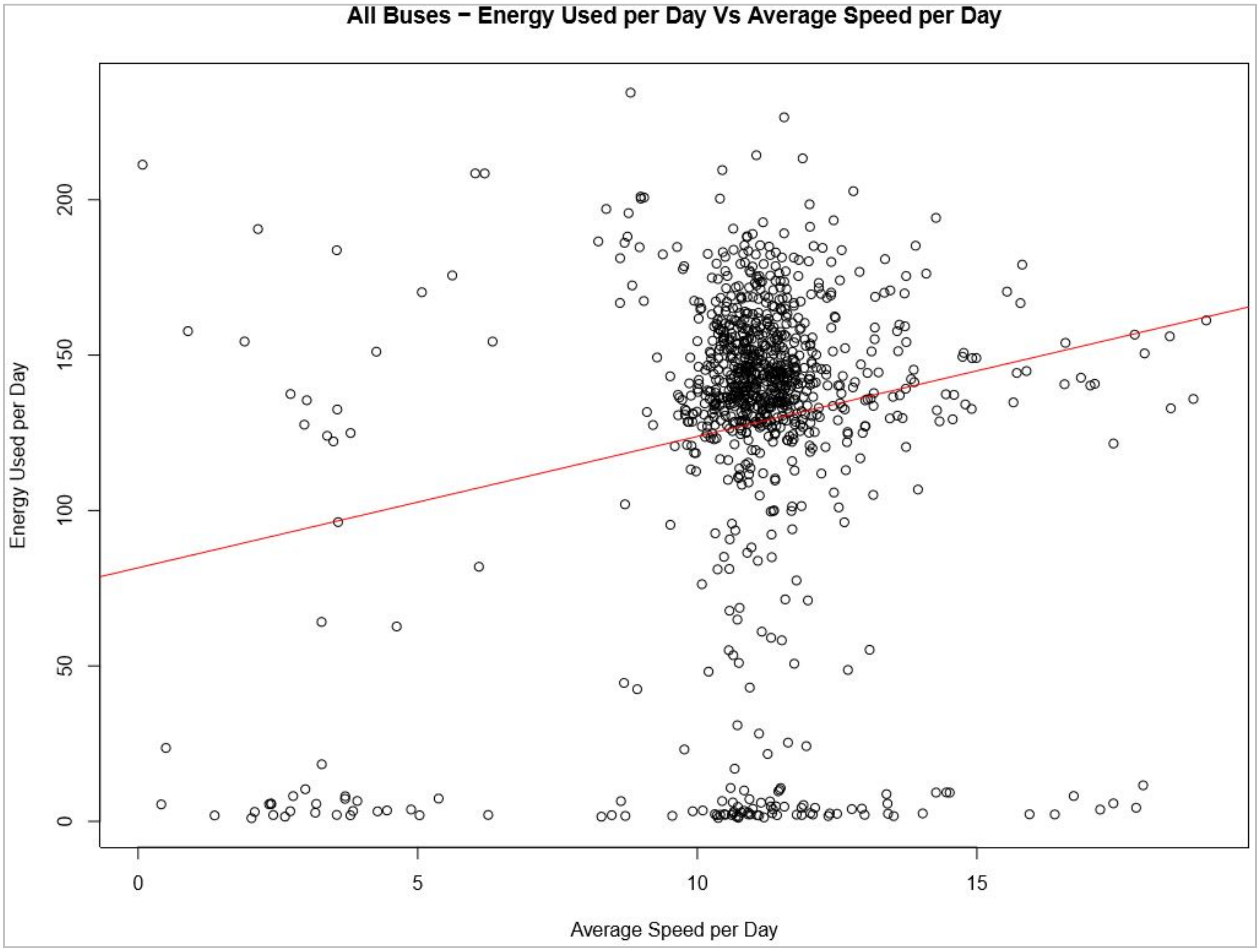
Source: Data from LADOT and ViriCiti, analysis by CALSTART

Figure A-4: All Buses - Energy Used per Day Versus Distance Driven per Day



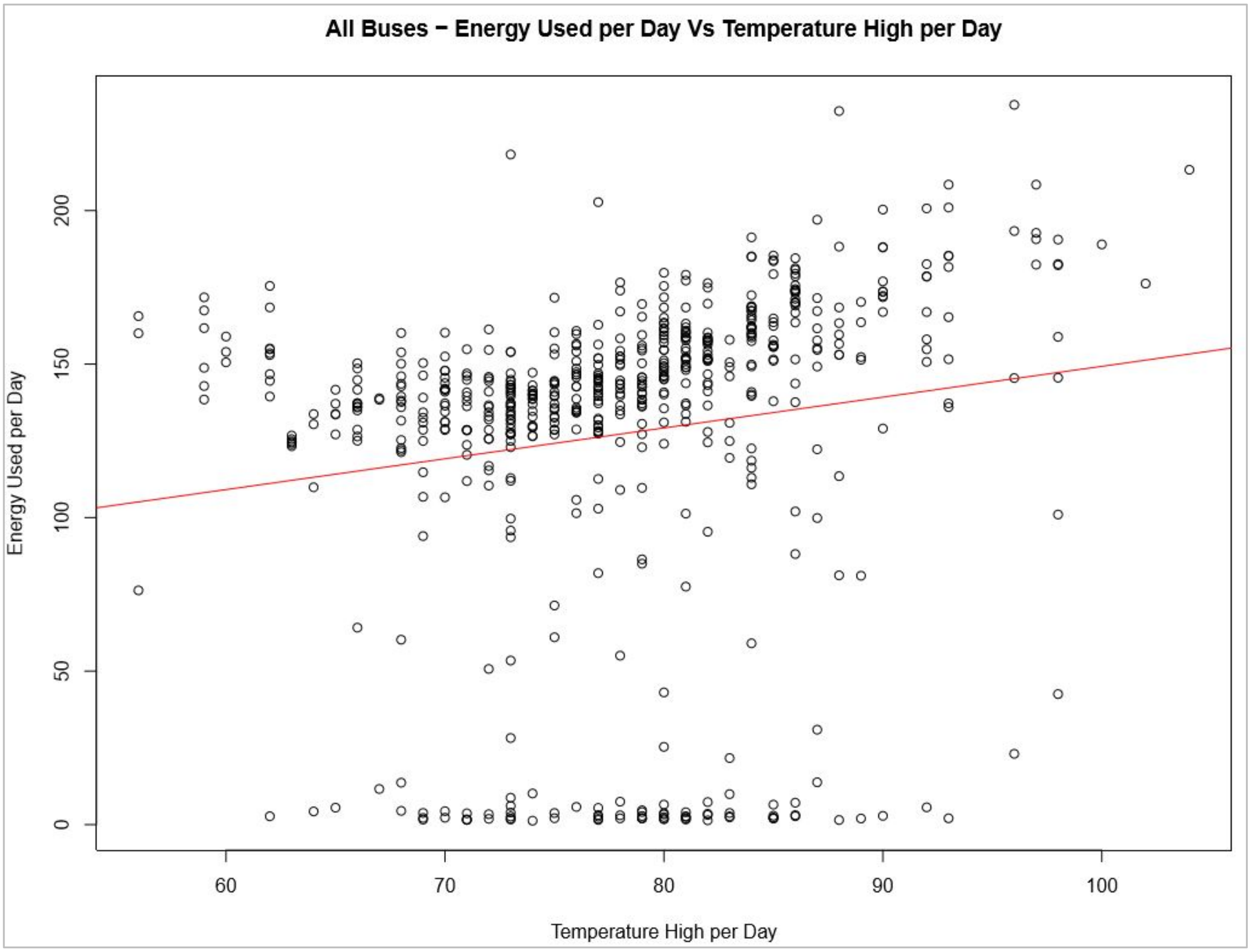
Source: Data from ViriCiti, analysis by CALSTART

Figure A-5: All Buses - Energy Used per Day Versus Average Speed per Day



Source: Data from ViriCiti, analysis by CALSTART

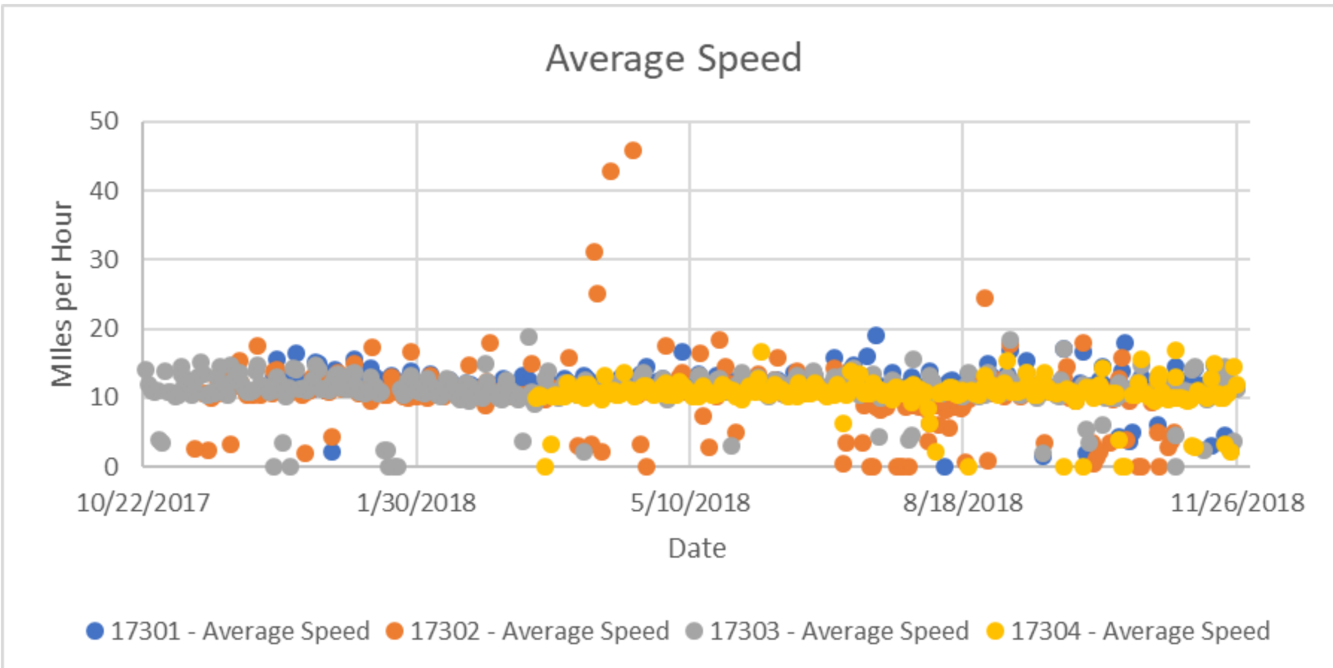
Figure A-6: All Buses - Energy Used per Day Versus Temperature High per Day



Source: Data from LADOT and ViriCiti, analysis by CALSTART

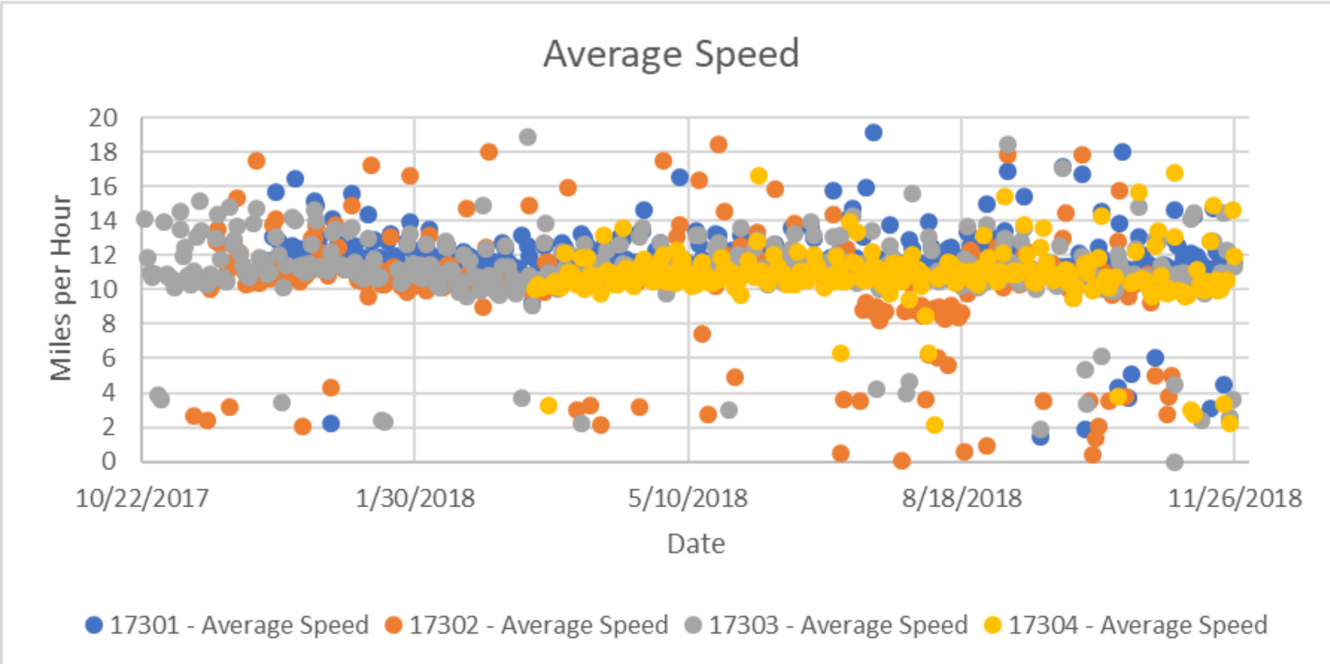
APPENDIX B:
Outliers – Before and After Removal from the Data

Figure B-1: All Buses - Average Speed Before Removing Outliers (ViriCiti)



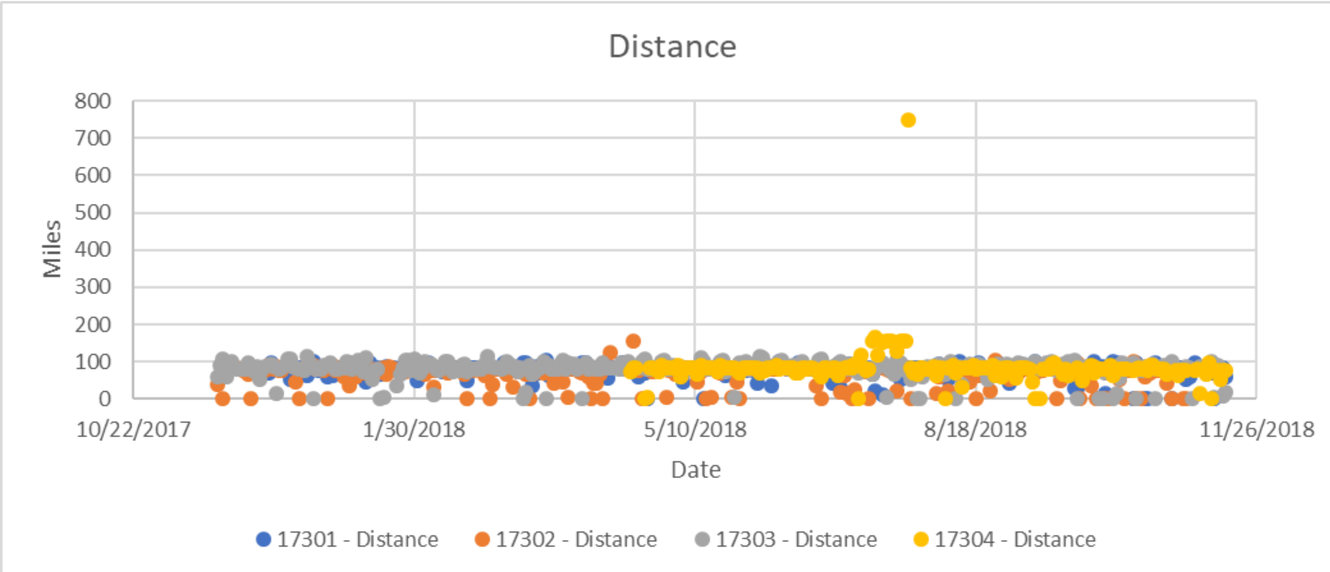
Source: Data from ViriCiti, analysis by CALSTART

Figure B-2: All Buses - Average Speed After Removing Outliers (ViriCiti)



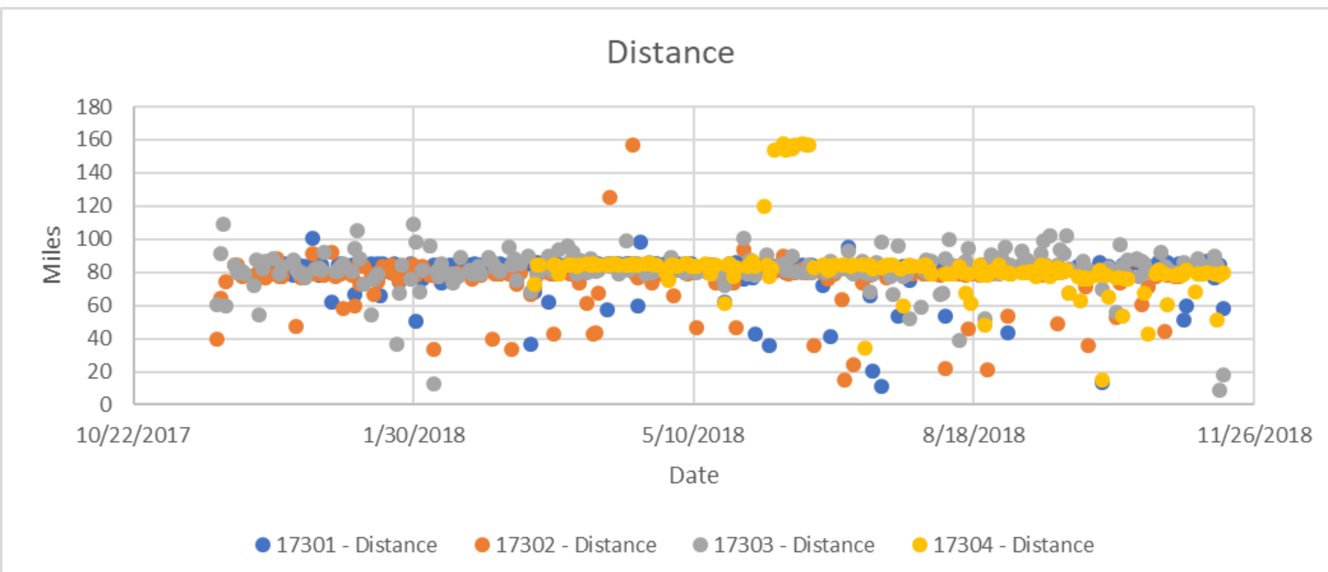
Source: Data from ViriCiti, analysis by CALSTART

Figure B-3: All Buses - Distance Before Removing Outliers (ViriCiti)



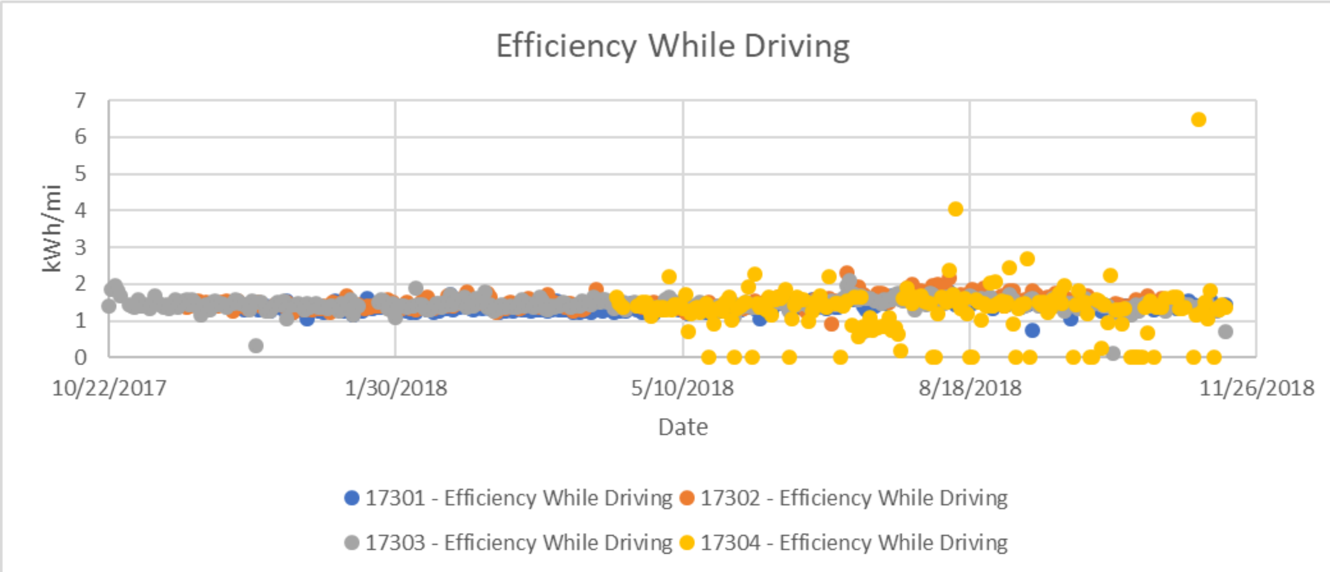
Source: Data from ViriCiti, analysis by CALSTART

Figure B-4: All Buses - Distance After Removing Outliers (ViriCiti)



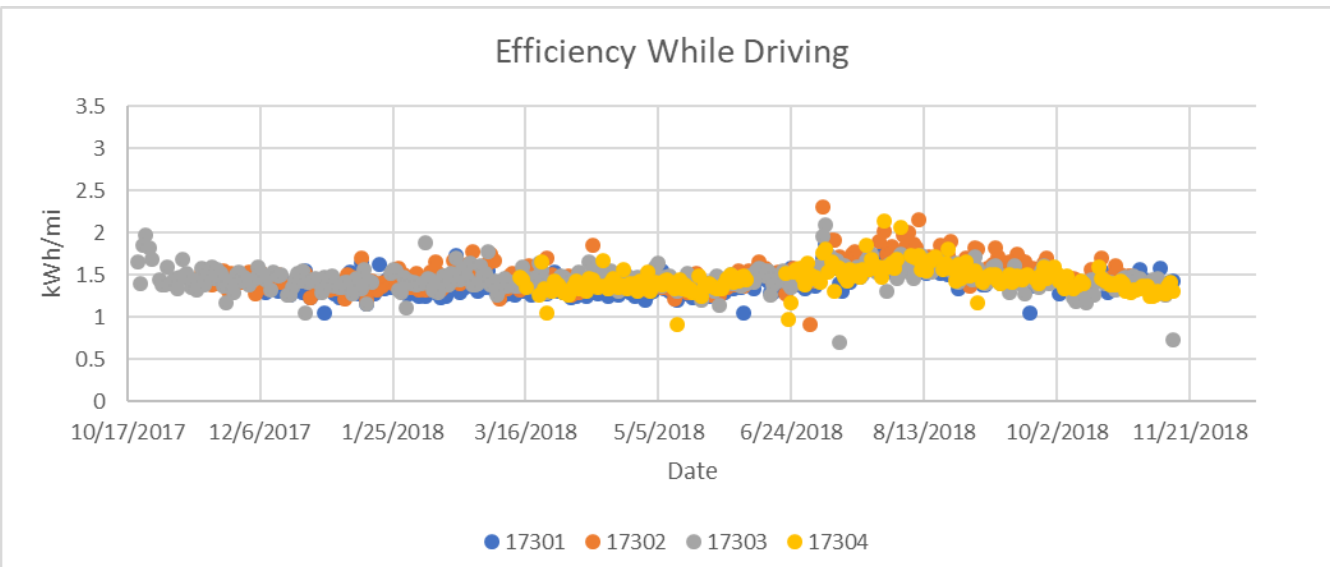
Source: Data from ViriCiti, analysis by CALSTART

Figure B-5: All Buses - Efficiency While Driving Before Removing Outliers (ViriCiti)



Source: Data from ViriCiti, analysis by CALSTART

Figure B-6: All Buses - Efficiency While Driving After Removing Outliers (ViriCiti)[29]



Source: Data from ViriCiti, analysis by CALSTART

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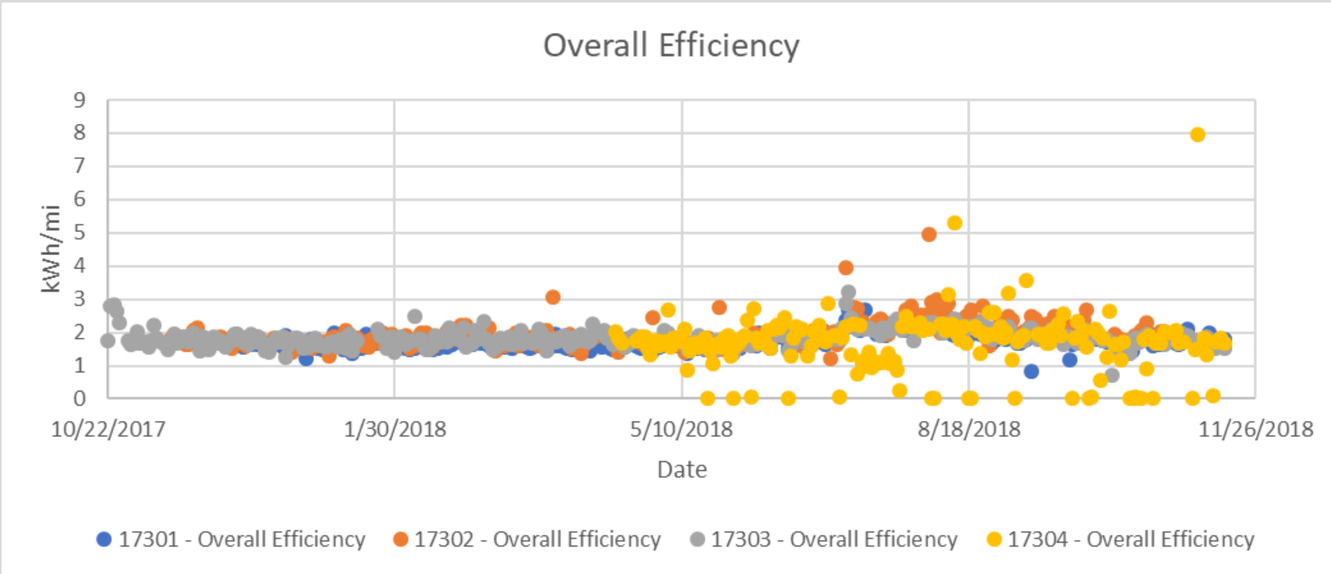
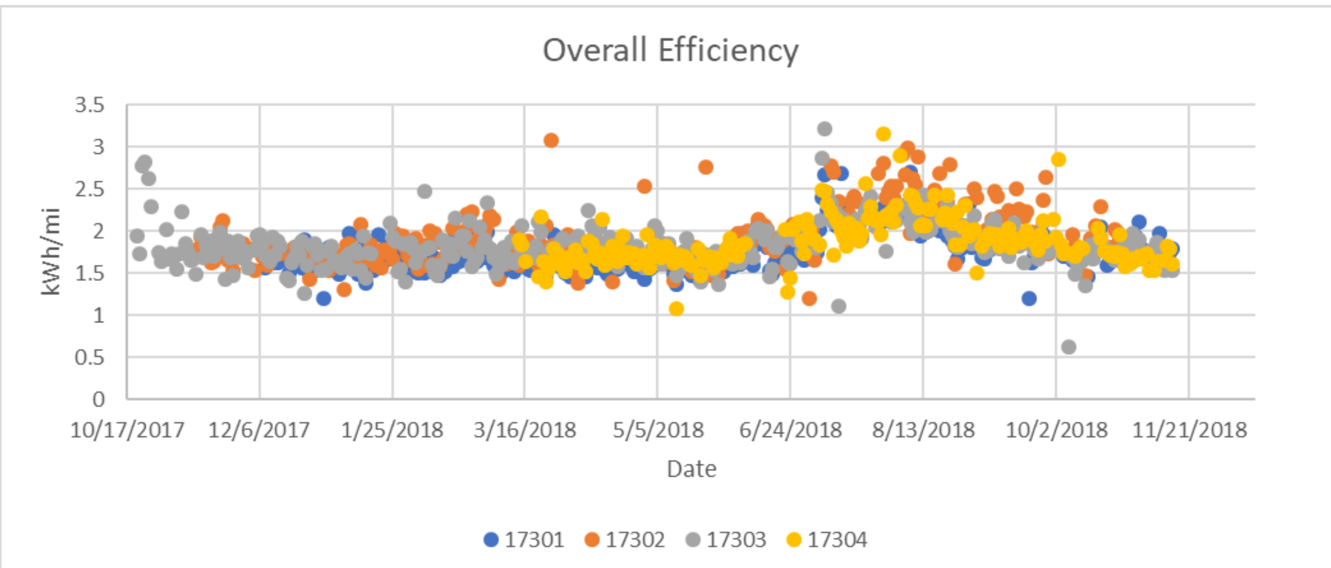
29 Data for Bus 17304 from June 08, 2018 through June 20, 2018 is omitted in this figure. These values were unusually low and out of sequence with the trend of the rest of the data. Upon inspection CALSTART discovered that ViriCiti reported incorrect values for Distance, leading to incorrect efficiency measurements. This was confirmed by checking LADOT-reported data for the same bus during the same time-frame. LADOT reported values that were consistent with the rest of the data.

Figure B-7: All Buses - Overall Efficiency Before Removing Outliers (ViriCiti)



Source: Data from ViriCiti, analysis by CALSTART

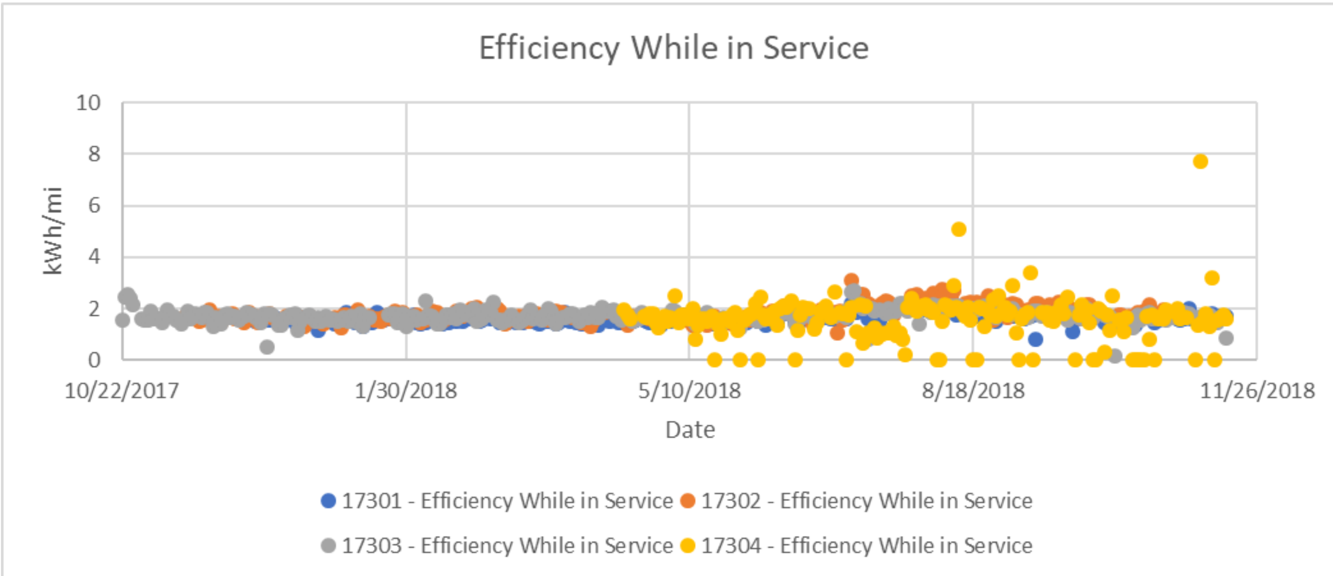
Figure B-8: All Buses - Overall Efficiency After Removing Outliers (ViriCiti)[30]



Source: Data from ViriCiti, analysis by CALSTART

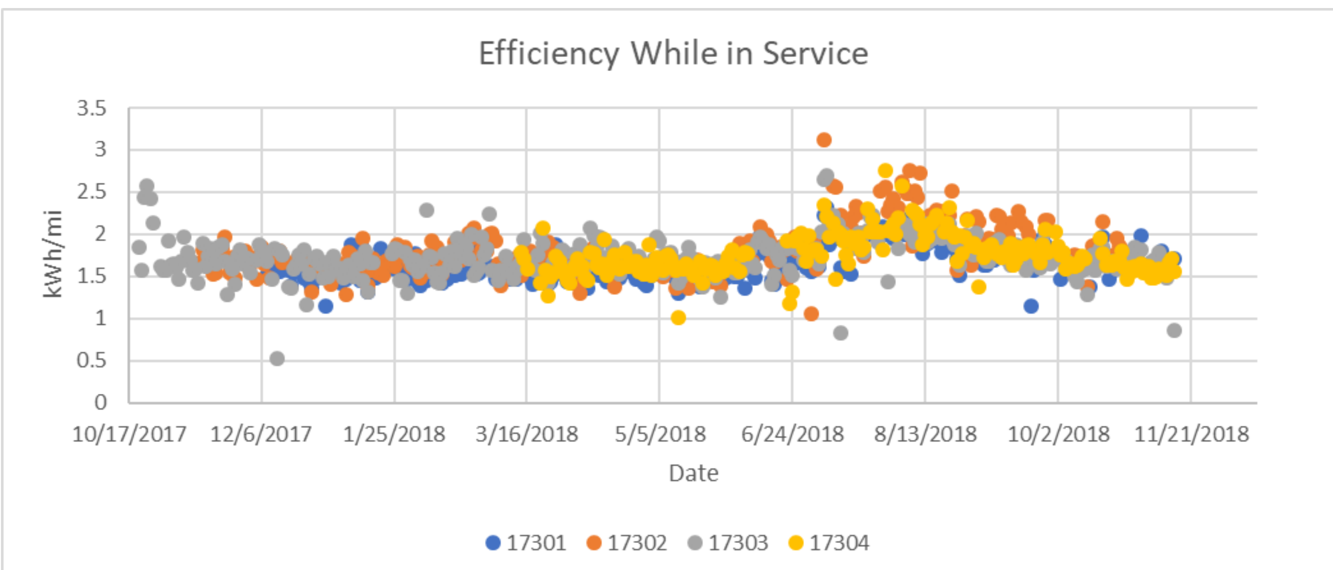
30 Data for Bus 17304 from June 08, 2018 through June 20, 2018 is omitted in this figure. These values were unusually low and out of sequence with the trend of the rest of the data. Upon inspection CALSTART discovered that ViriCiti reported incorrect values for Distance, leading to incorrect efficiency measurements. This was confirmed by checking LADOT-reported data for the same bus during the same time-frame. LADOT reported values that were consistent with the rest of the data.

Figure B-9: All Buses - Efficiency While in Service Before Removing Outliers (ViriCiti)



Source: Data from ViriCiti, analysis by CALSTART

Figure B-10: All Buses - Efficiency While in Service After Removing Outliers (ViriCiti)[31]



Source: Data from ViriCiti, analysis by CALSTART

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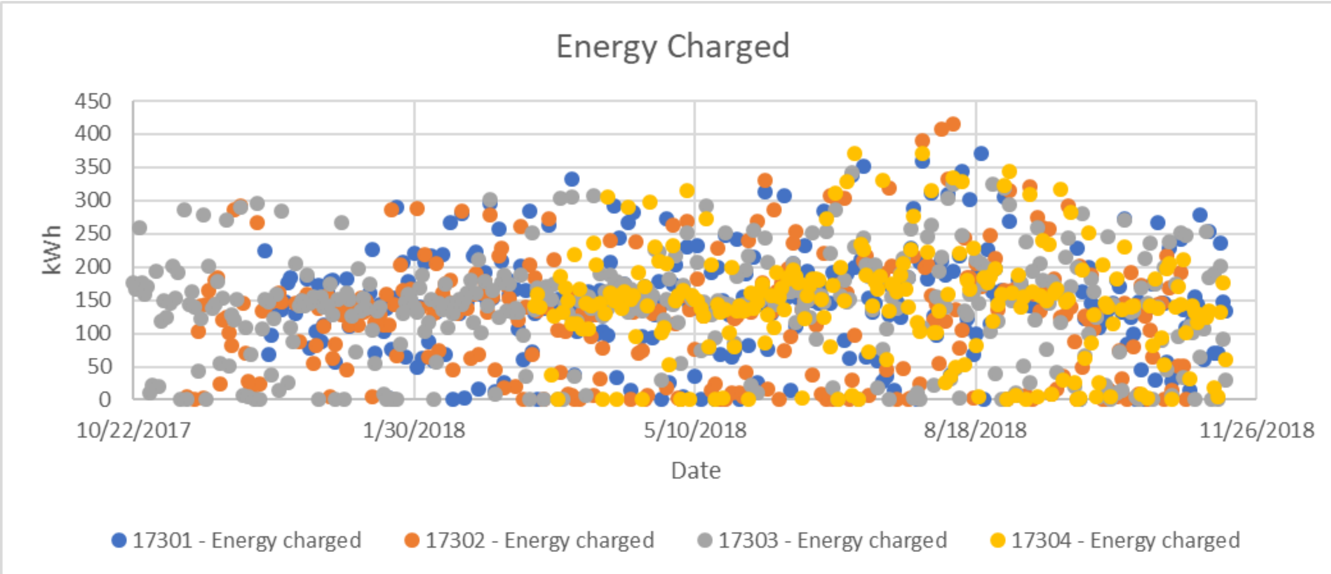
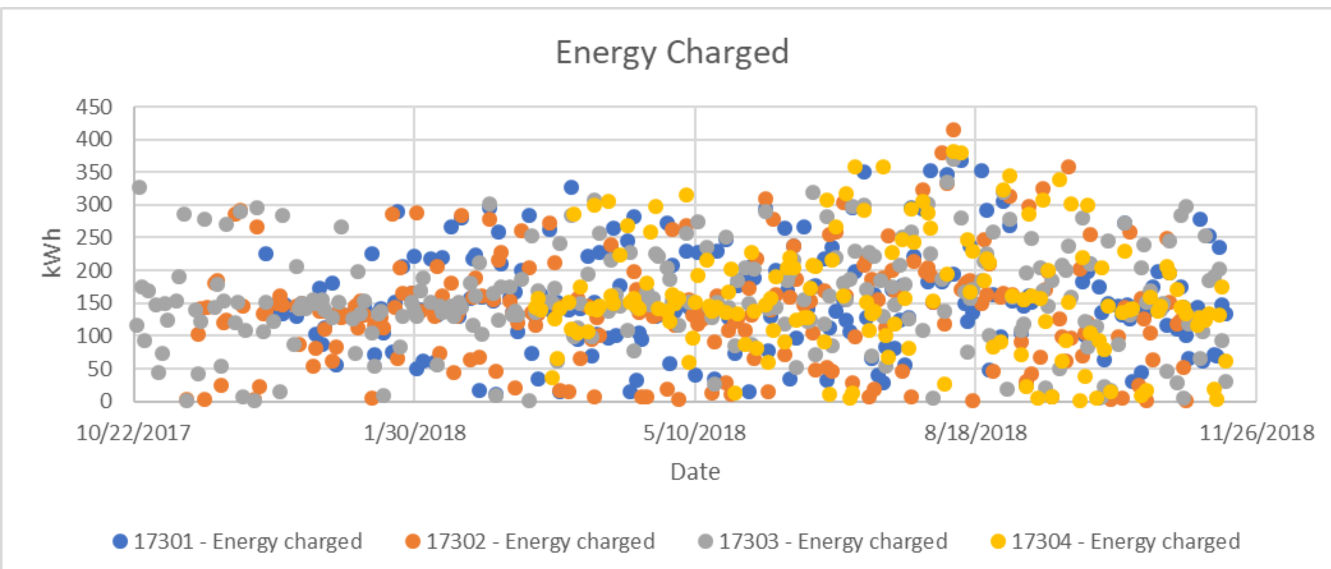
31 Data for Bus 17304 from June 08, 2018 through June 20, 2018 is omitted in this figure. These values were unusually low and out of sequence with the trend of the rest of the data. Upon inspection CALSTART discovered that ViriCiti reported incorrect values for Distance, leading to incorrect efficiency measurements. This was confirmed by checking LADOT-reported data for the same bus during the same time-frame. LADOT reported values that were consistent with the rest of the data.

Figure B-11: All Buses - Energy Charged Before Removing Outliers (ViriCiti)



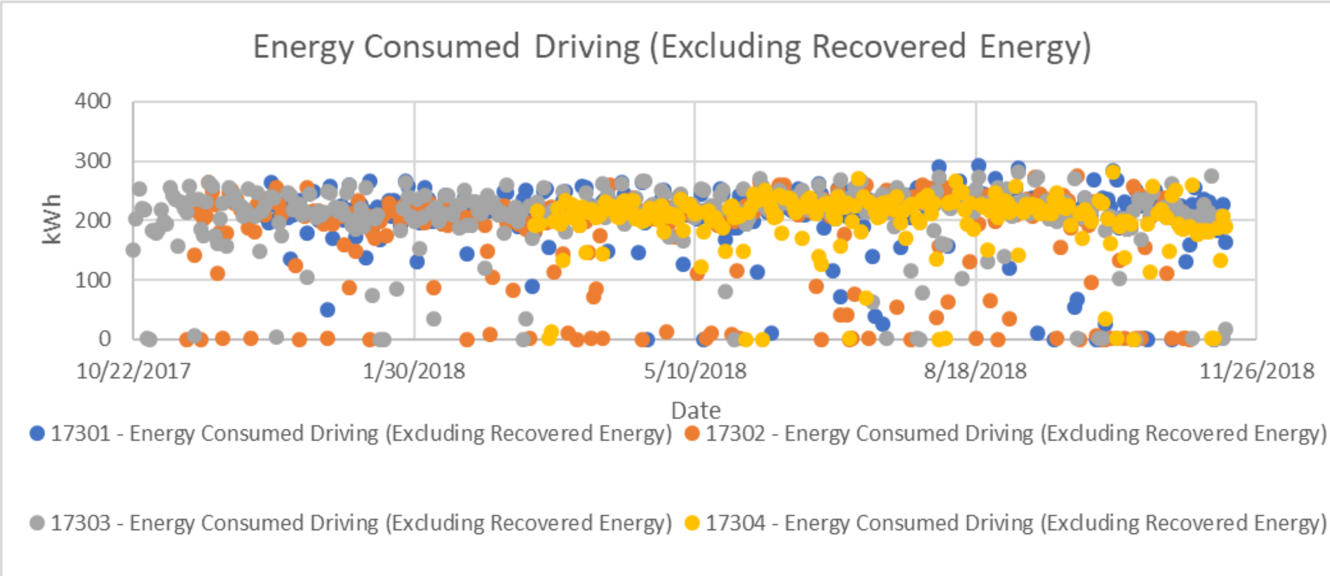
Source: Data from ViriCiti, analysis by CALSTART

Figure B-12: All Buses - Energy Charged After Removing Outliers (ViriCiti)



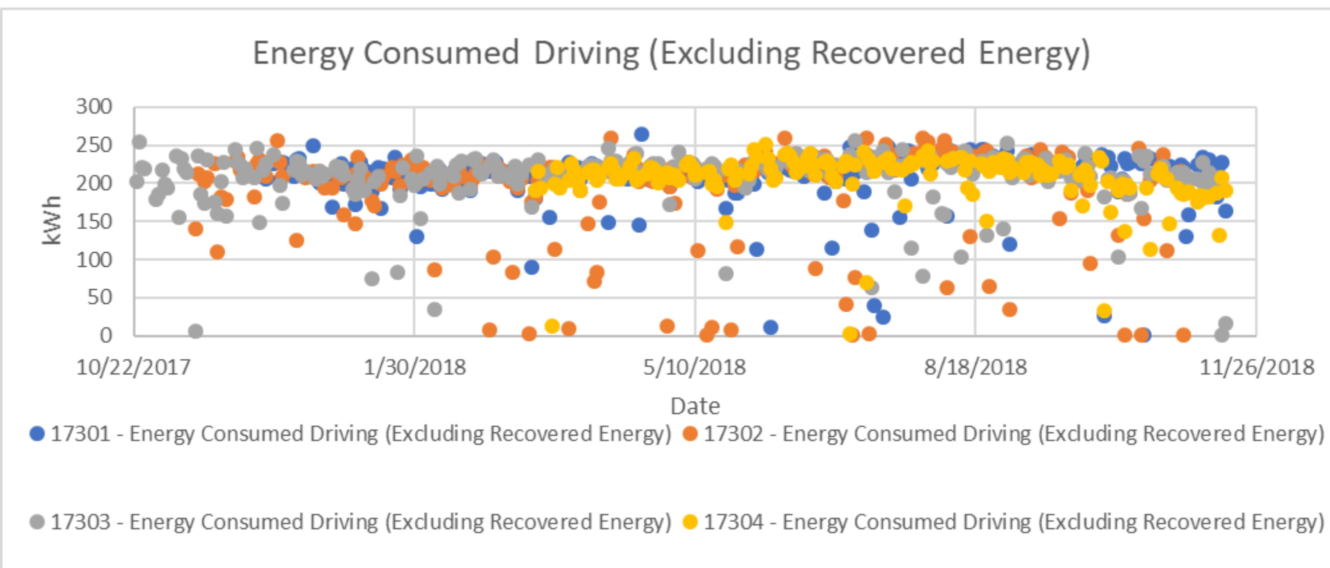
Source: Data from ViriCiti, analysis by CALSTART

Figure B-13: All Buses - Energy Consumed Driving (Excluding Recovered Energy) Before Removing Outliers (ViriCiti)



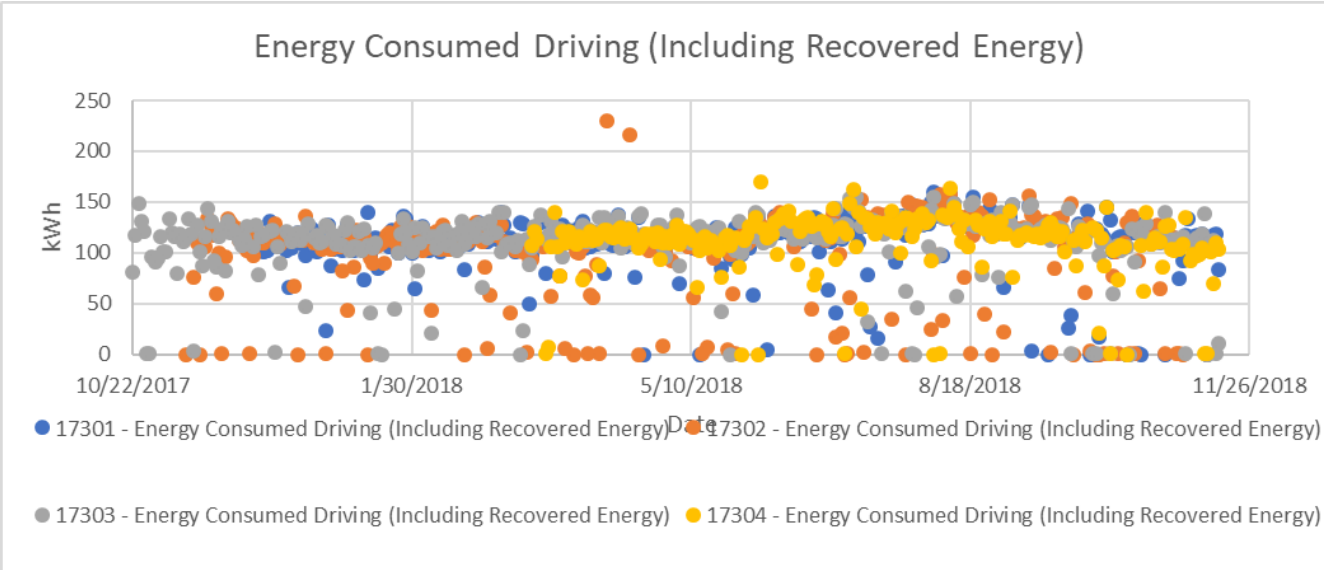
Source: Data from ViriCiti, analysis by CALSTART

Figure B-14: All Buses - Energy Consumed Driving (Excluding Recovered Energy) After Removing Outliers (ViriCiti)



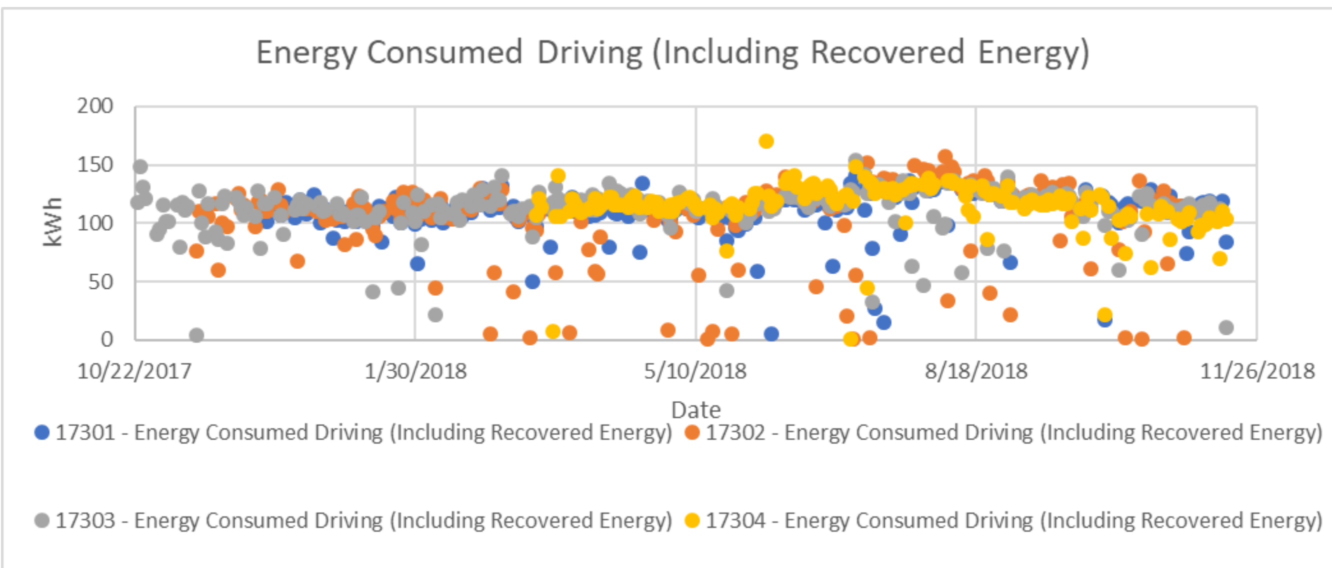
Source: Data from ViriCiti, analysis by CALSTART

Figure B-15: All Buses - Energy Consumed Driving (Including Recovered Energy) Before Removing Outliers (ViriCiti)



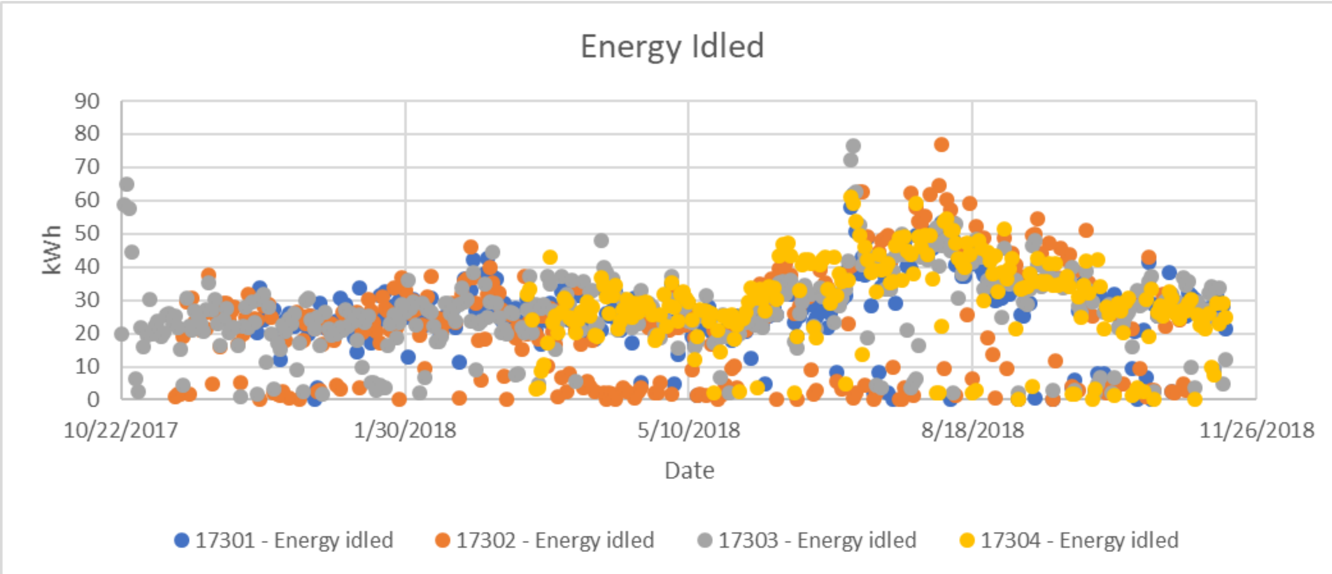
Source: Data from ViriCiti, analysis by CALSTART

Figure B-16: All Buses - Energy Consumed Driving (Including Recovered Energy) After Removing Outliers (ViriCiti)



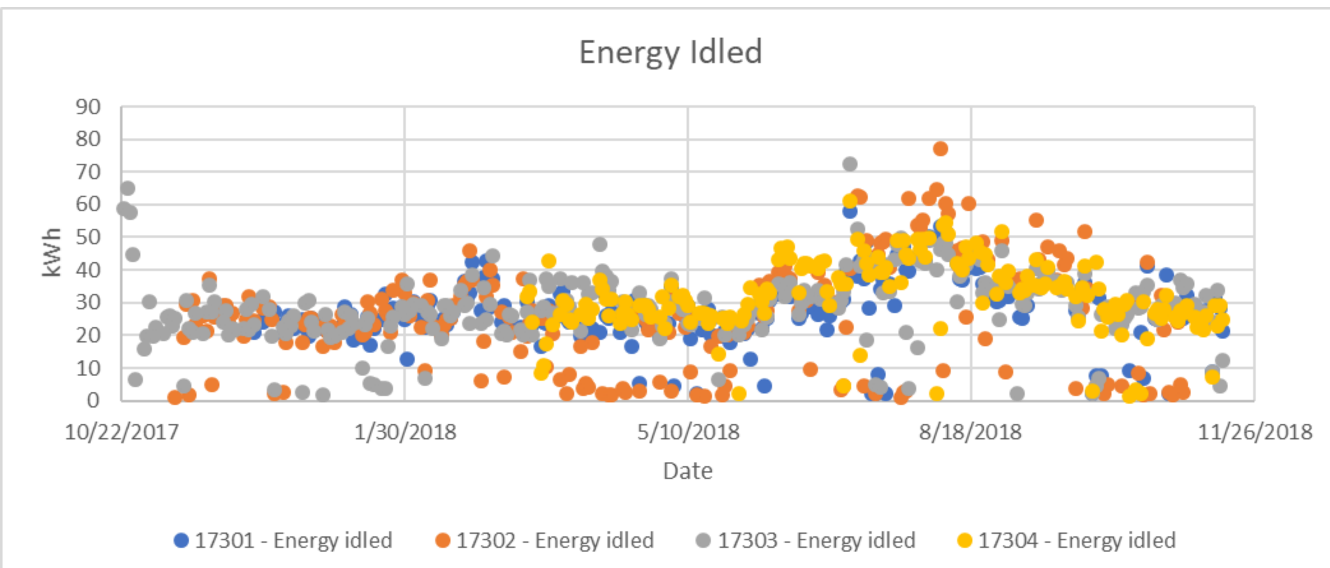
Source: Data from ViriCiti, analysis by CALSTART

Figure B-17: All Buses - Energy Idled Before Removing Outliers (ViriCiti)



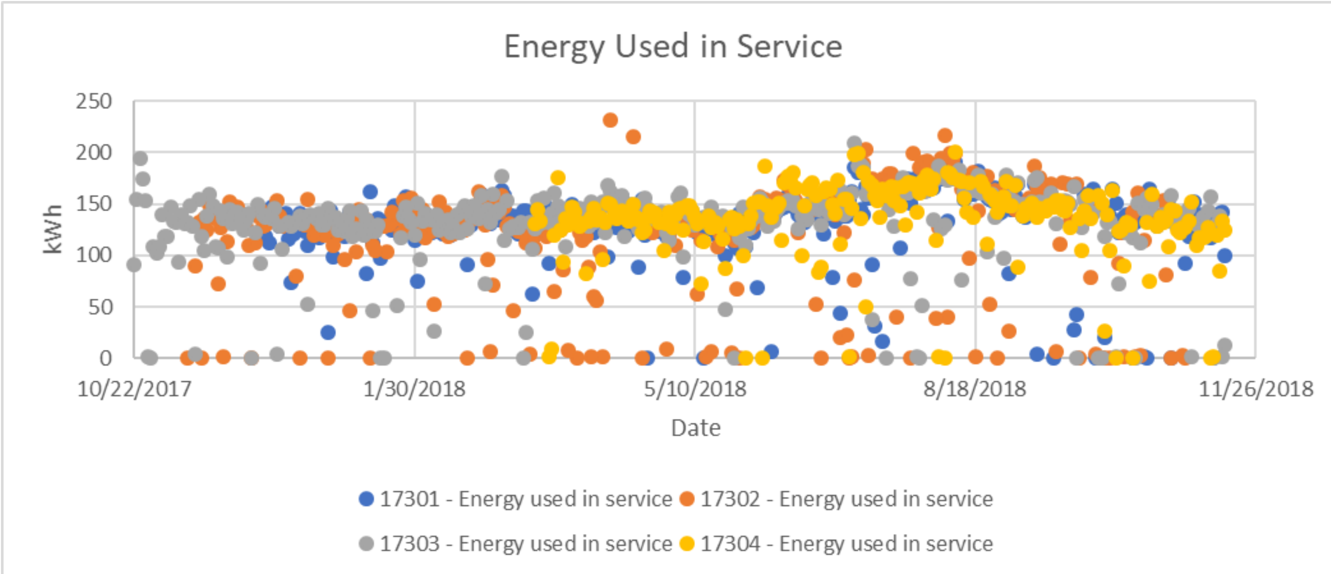
Source: Data from ViriCiti, analysis by CALSTART

Figure B-18: All Buses - Energy Idled After Removing Outliers (ViriCiti)



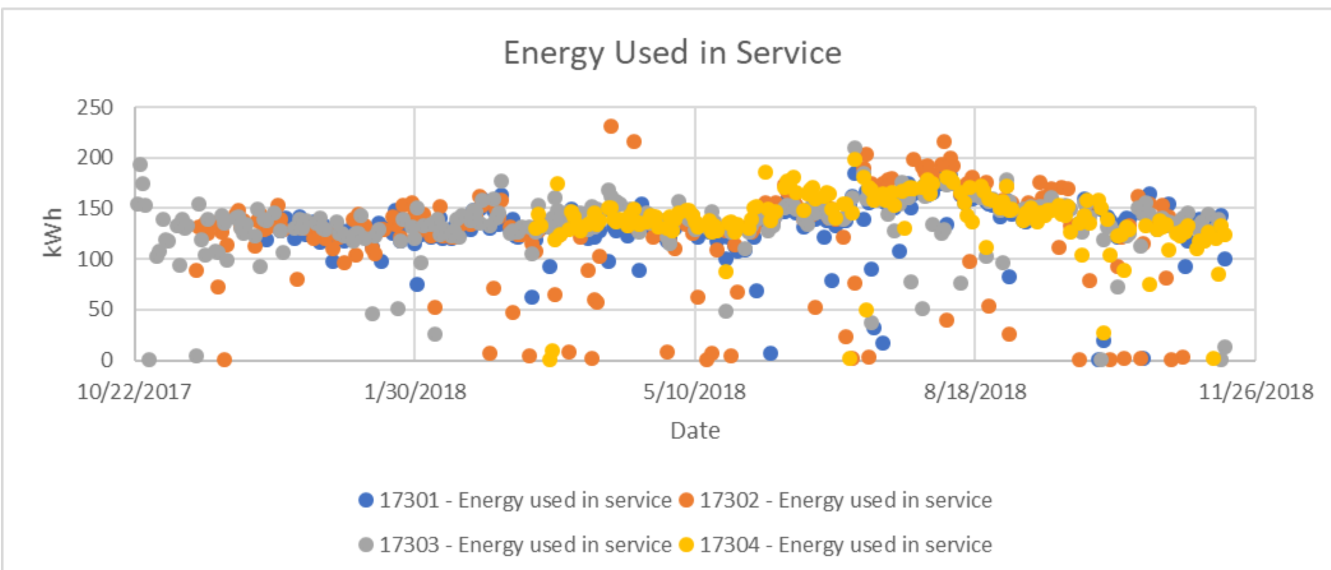
Source: Data from ViriCiti, analysis by CALSTART

Figure B-19: All Buses - Energy Used in Service Before Removing Outliers (ViriCiti)



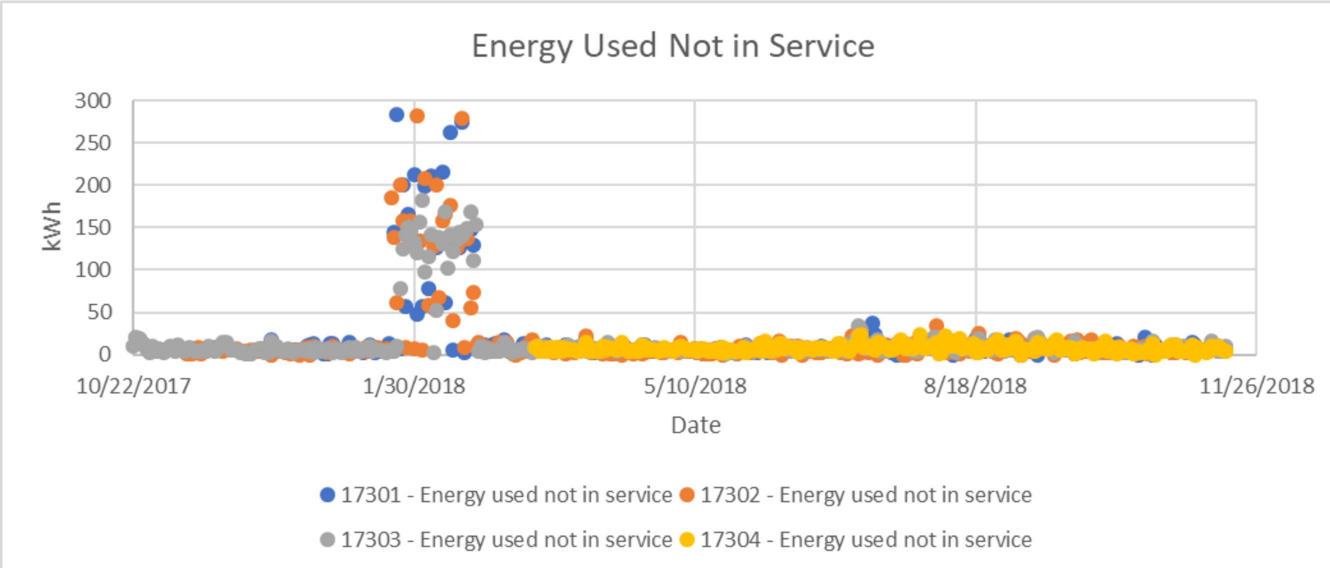
Source: Data from ViriCiti, analysis by CALSTART

Figure B-20: All Buses - Energy Used in Service After Removing Outliers (ViriCiti)



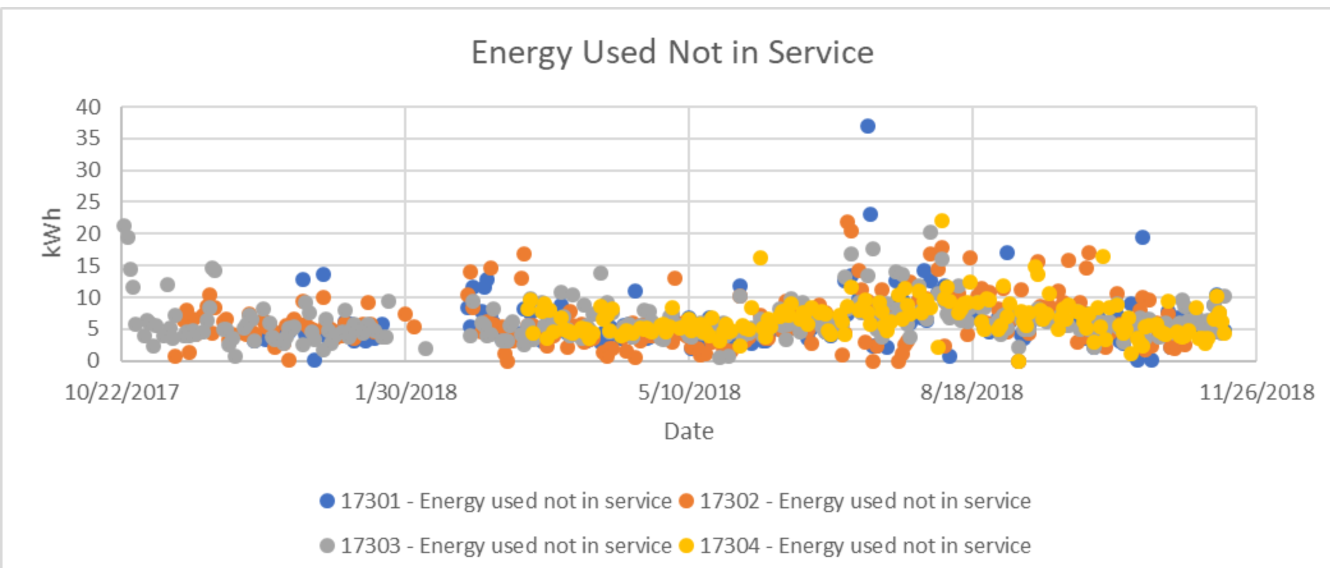
Source: Data from ViriCiti, analysis by CALSTART

Figure B-21: All Buses - Energy Used Not in Service Before Removing Outliers (ViriCiti)[32]



Source: Data from ViriCiti, analysis by CALSTART

Figure B-22: All Buses - Energy Used Not in Service After Removing Outliers (ViriCiti)



Source: Data from ViriCiti, analysis by CALSTART

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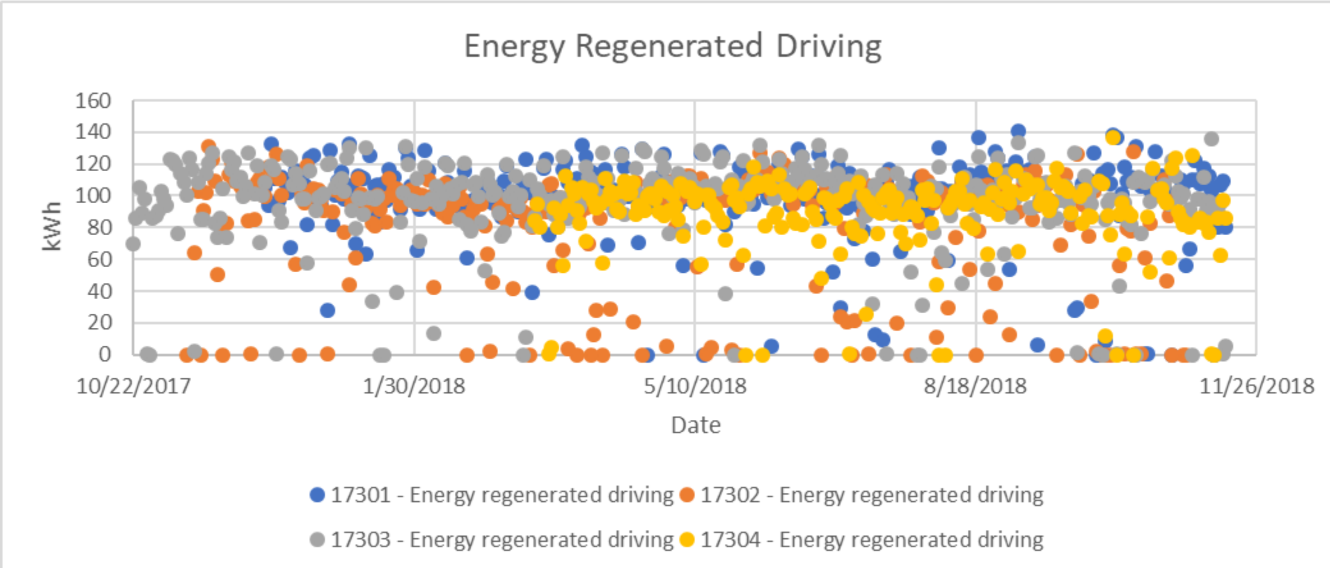
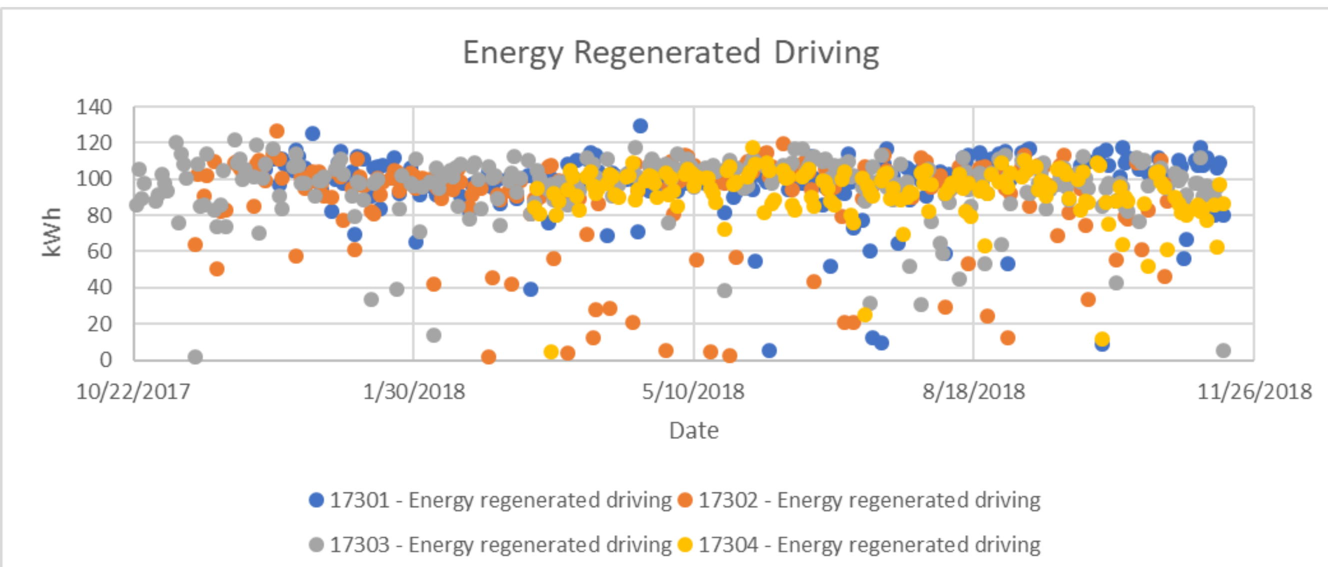
32 The grouping of data points that were removed as outliers in this figure were determined to be caused by an error in calculation from ViriCiti. Energy Used in Service and Energy Used Not in Service should sum to equal Energy Used. That validation equation holds for all data points except those shown in the grouping removed.

Figure B-23: All Buses - Energy Regenerated Driving Before Removing Outliers (ViriCiti)



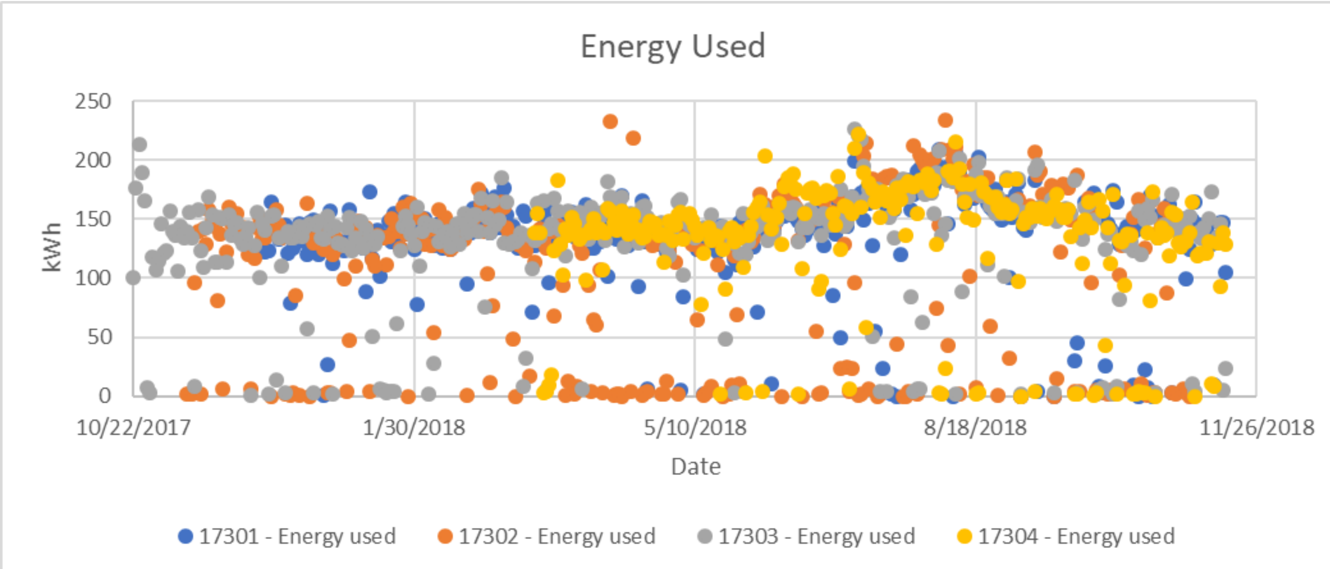
Source: Data from ViriCiti, analysis by CALSTART

Figure B-24: All Buses - Energy Regenerated Driving After Removing Outliers (ViriCiti)



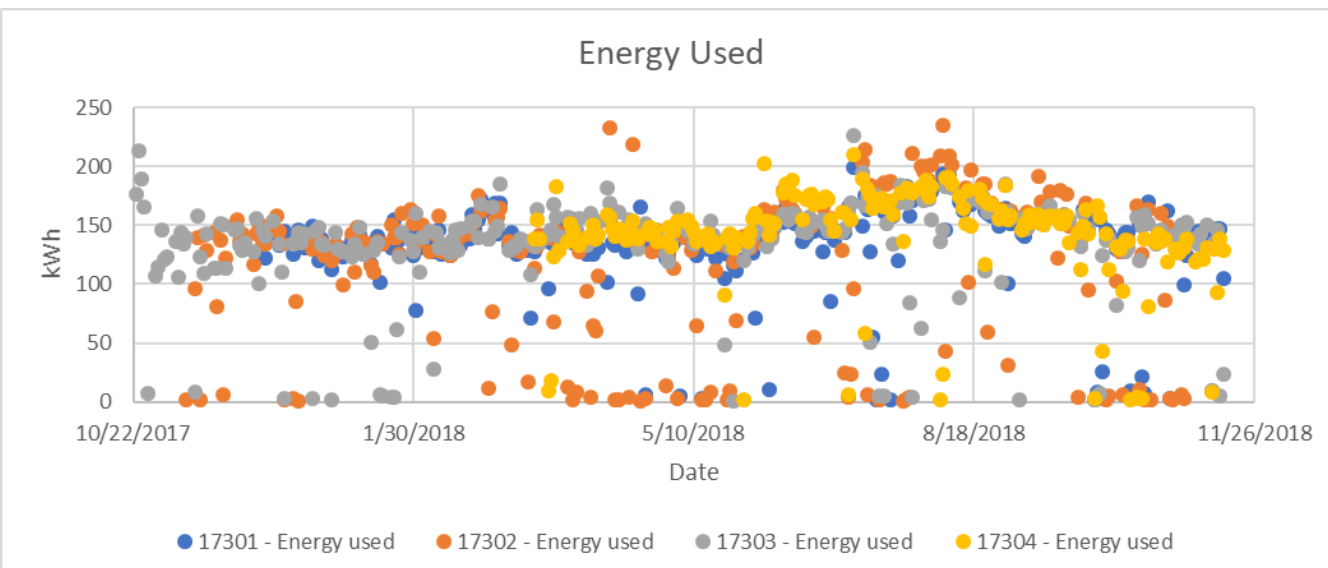
Source: Data from ViriCiti, analysis by CALSTART

Figure B-25: All Buses - Energy Used Before Removing Outliers (ViriCiti)



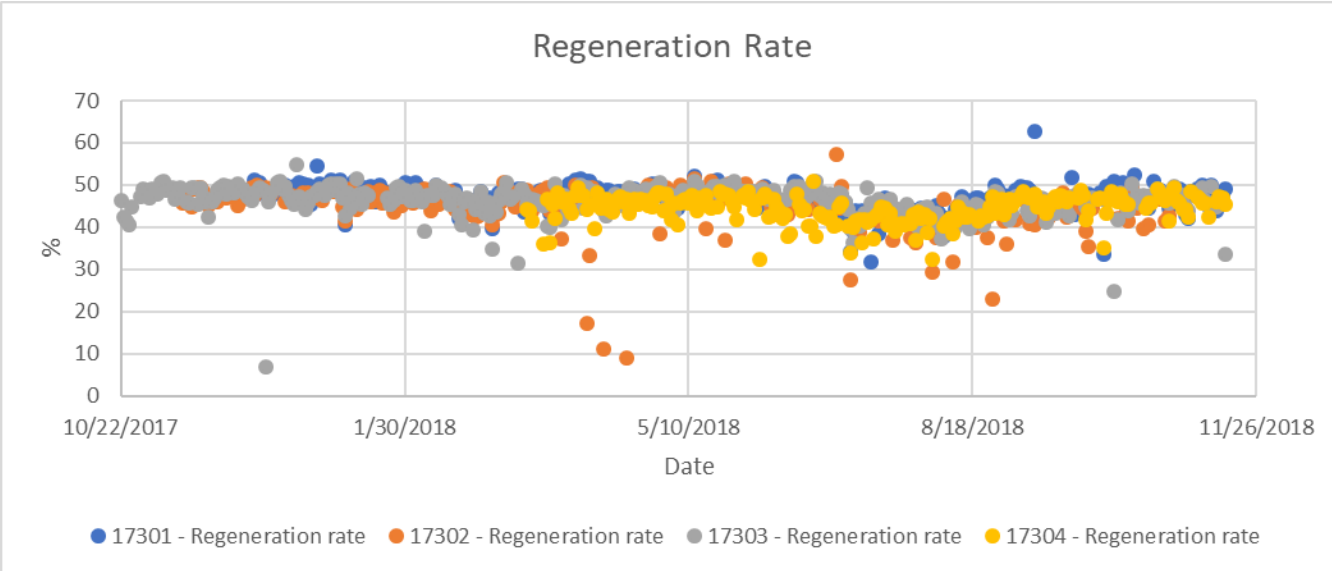
Source: Data from ViriCiti, analysis by CALSTART

Figure B-26: All Buses - Energy Used After Removing Outliers (ViriCiti)



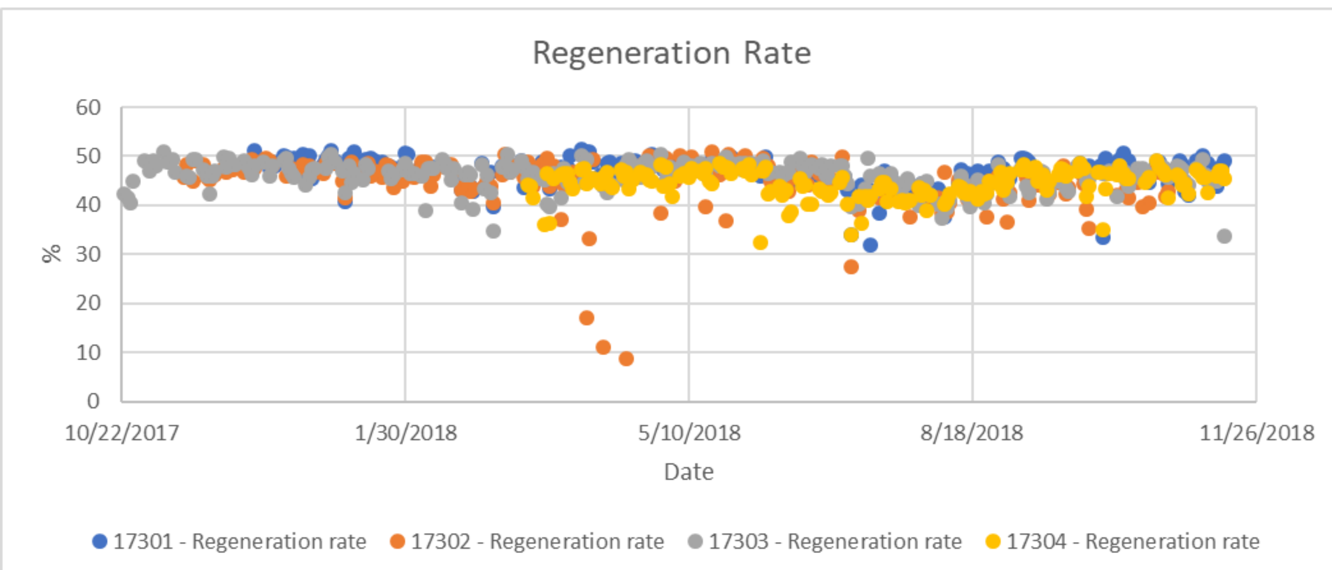
Source: Data from ViriCiti, analysis by CALSTART

Figure B-27: All Buses - Regeneration Rate Before Removing Outliers (ViriCiti)



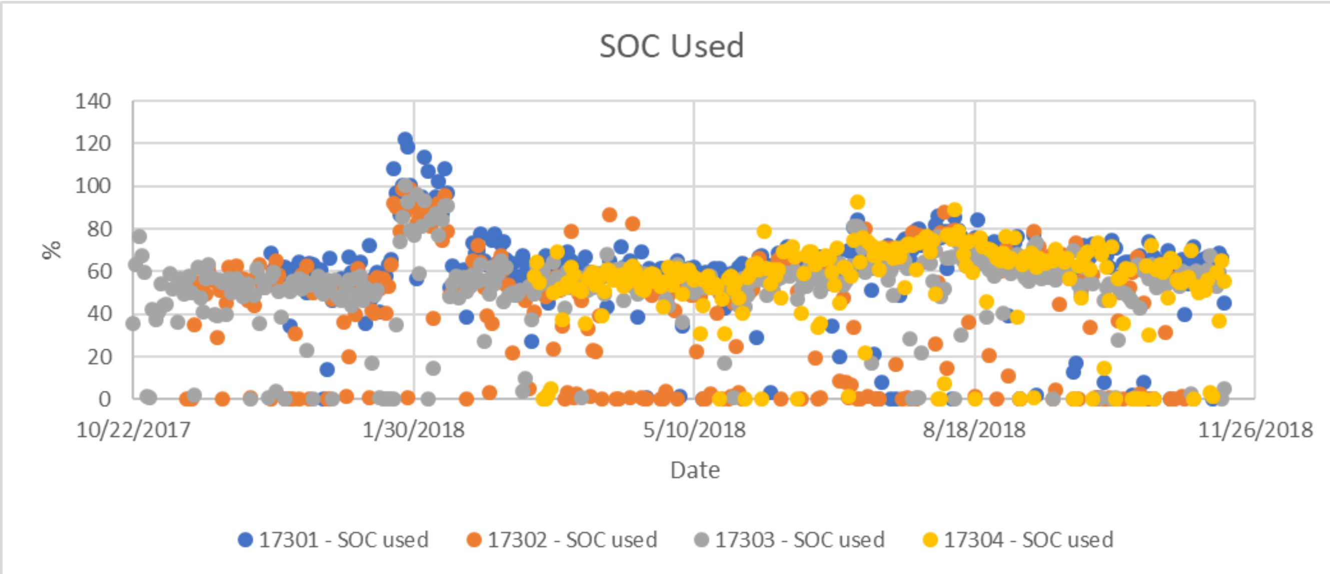
Source: Data from ViriCiti, analysis by CALSTART

Figure B-28: All Buses - Regeneration Rate After Removing Outliers (ViriCiti)



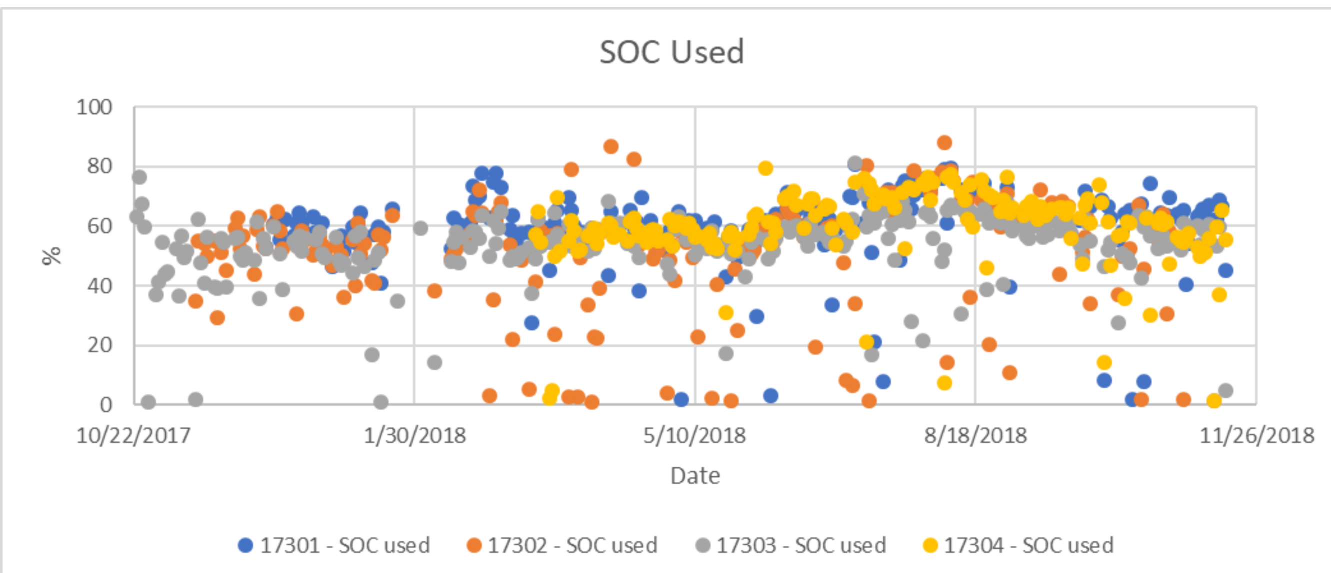
Source: Data from ViriCiti, analysis by CALSTART

Figure B-29: All Buses – State of Charge Used Before Removing Outliers (ViriCiti)



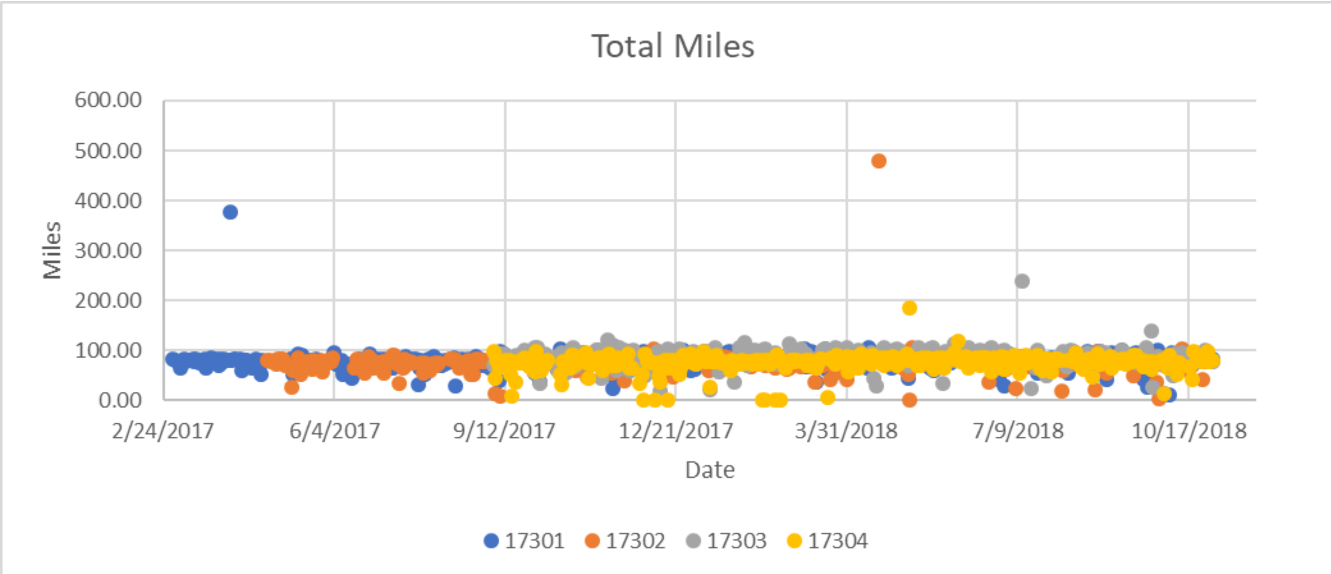
Source: Data from ViriCiti, analysis by CALSTART

Figure B-30: All Buses – State of Charge Used After Removing Outliers (ViriCiti)



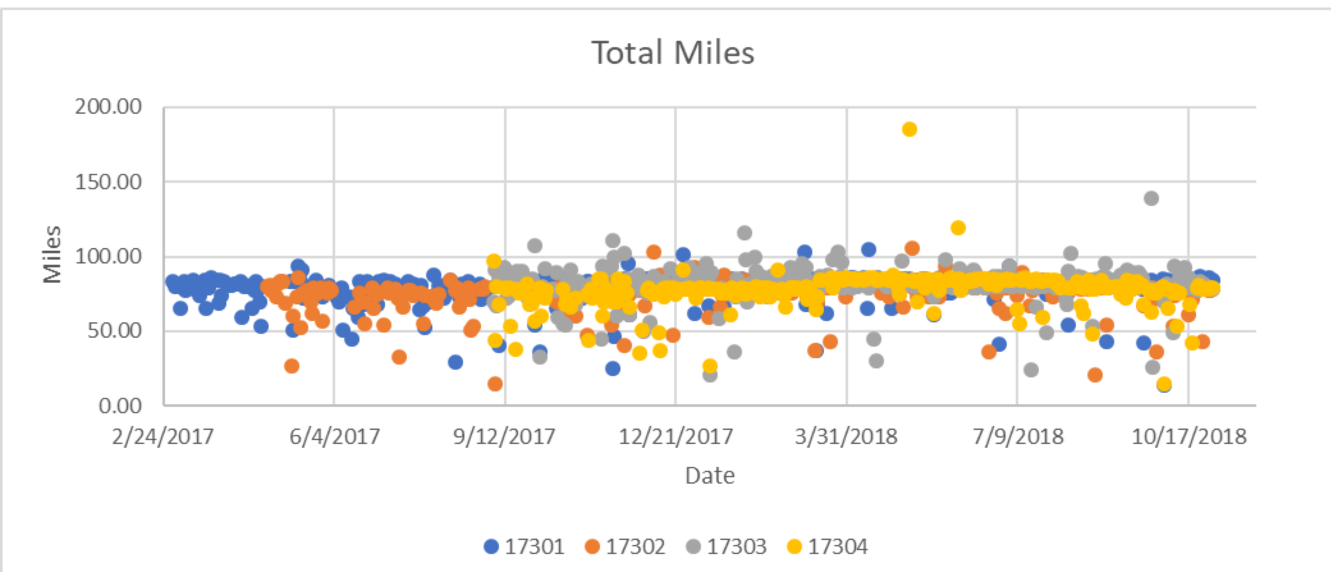
Source: Data from ViriCiti, analysis by CALSTART

Figure B-31: Total Miles Before Removing Outliers (LADOT)



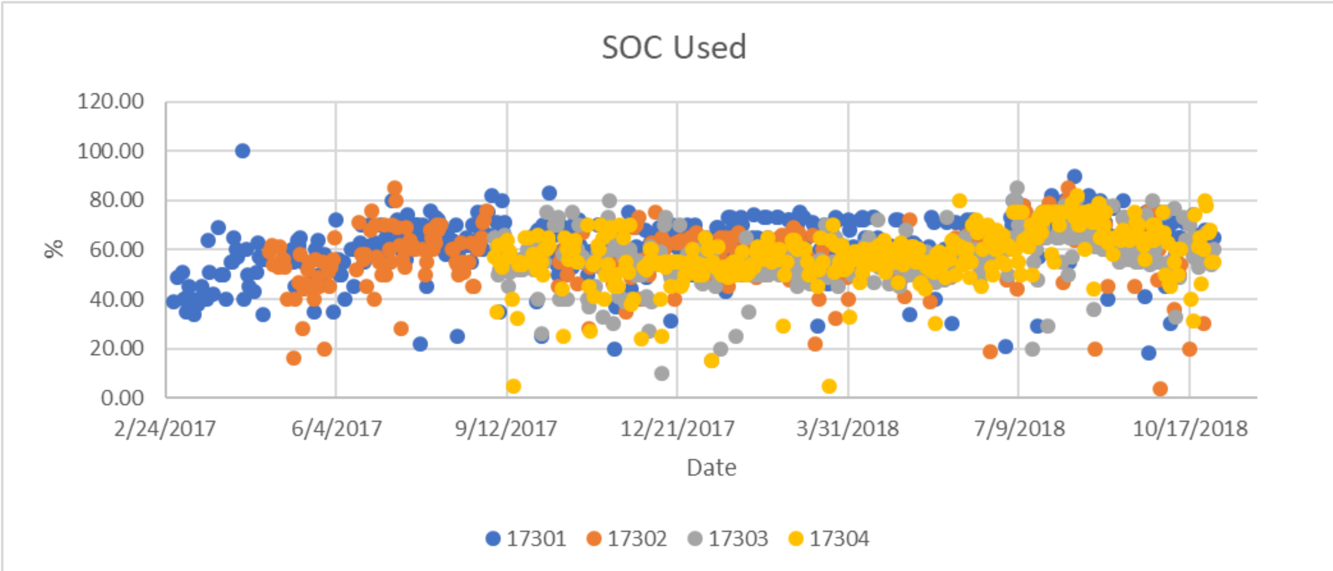
Source: Data from LADOT, analysis by CALSTART

Figure B-32: Total Miles After Removing Outliers (LADOT)



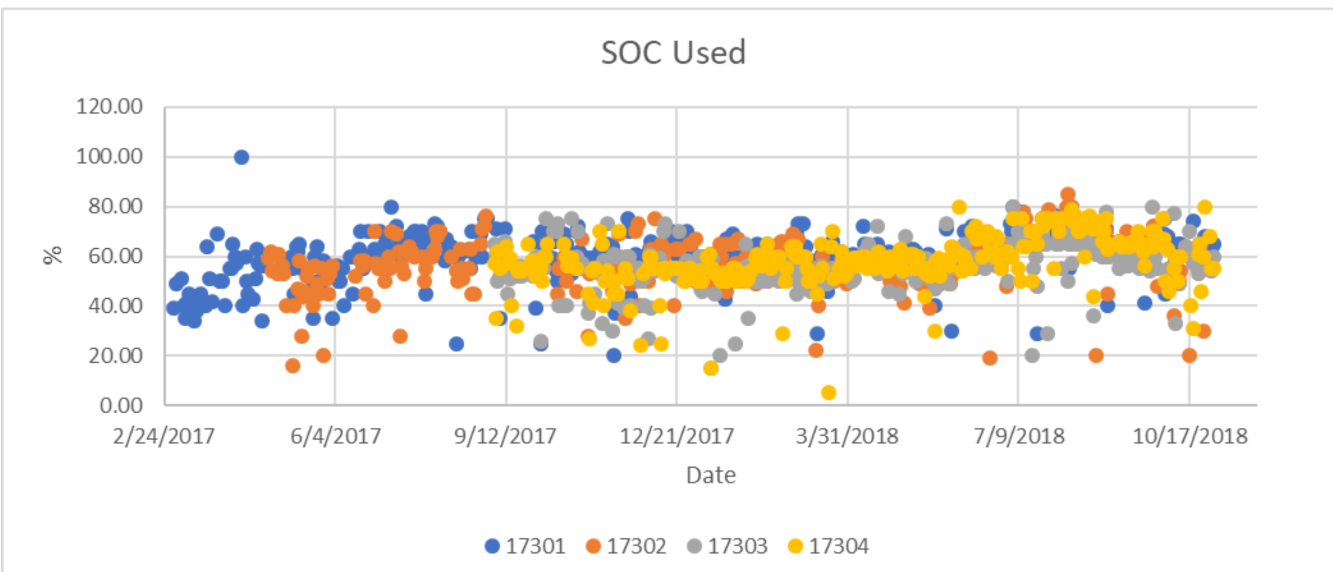
Source: Data from LADOT, analysis by CALSTART

Figure B-33: State of Charge Used Before Removing Outliers (LADOT)



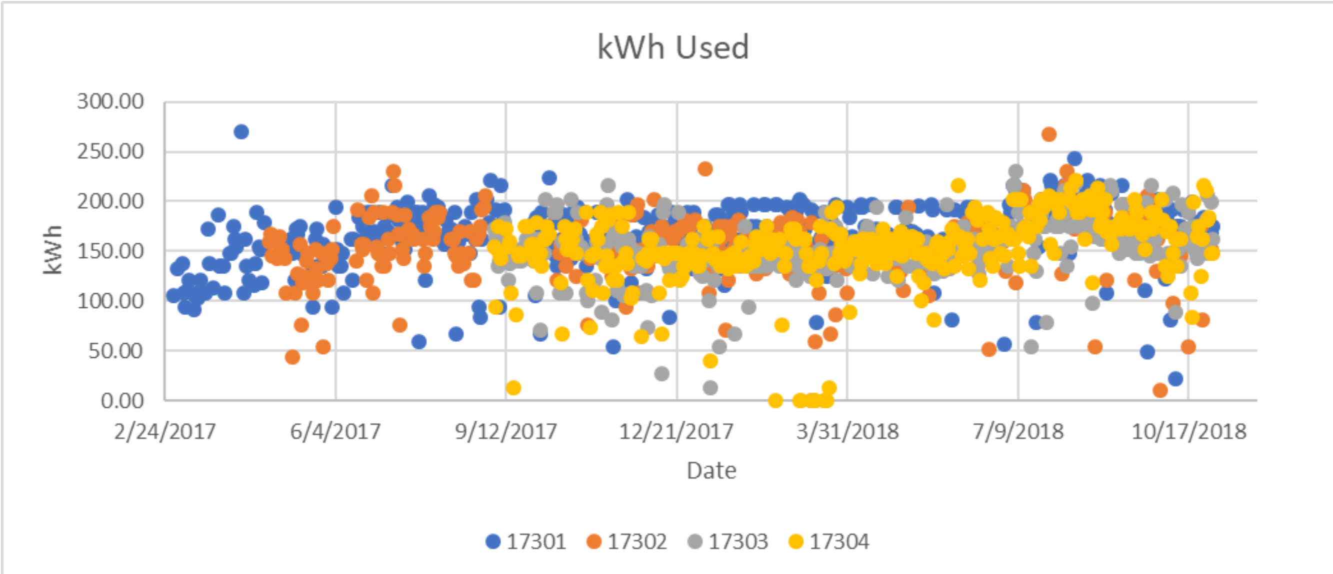
Source: Data from LADOT, analysis by CALSTART

Figure B-34: State of Charge Used After Removing Outliers (LADOT)



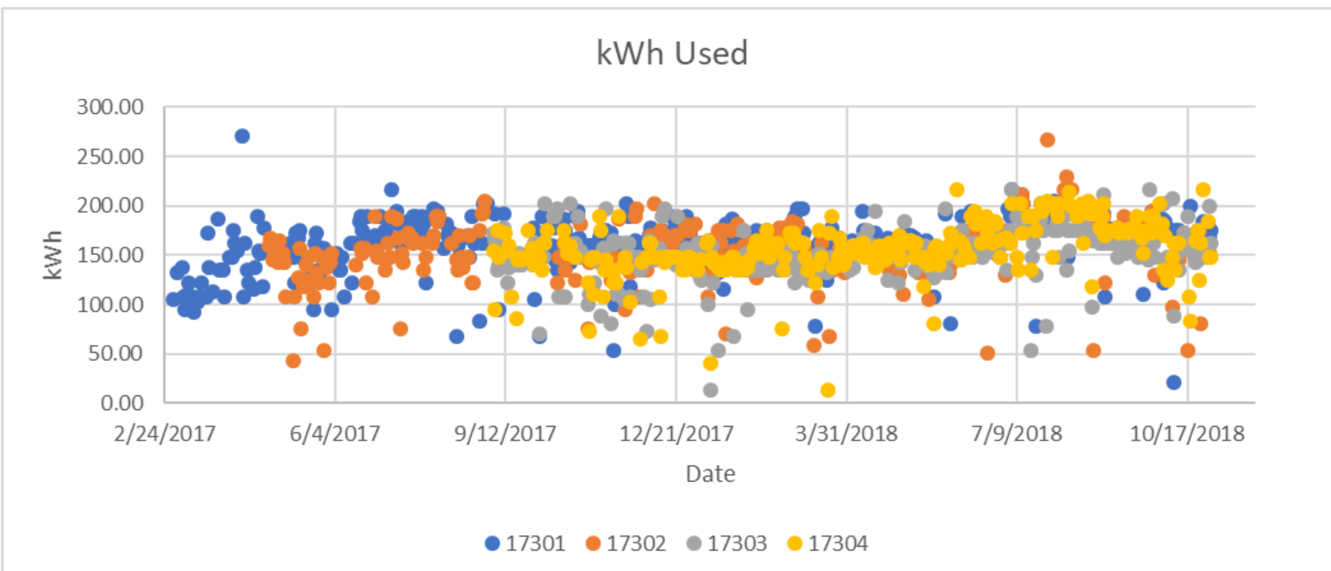
Source: Data from LADOT, analysis by CALSTART

Figure B-35: kWh Used Before Removing Outliers (LADOT)



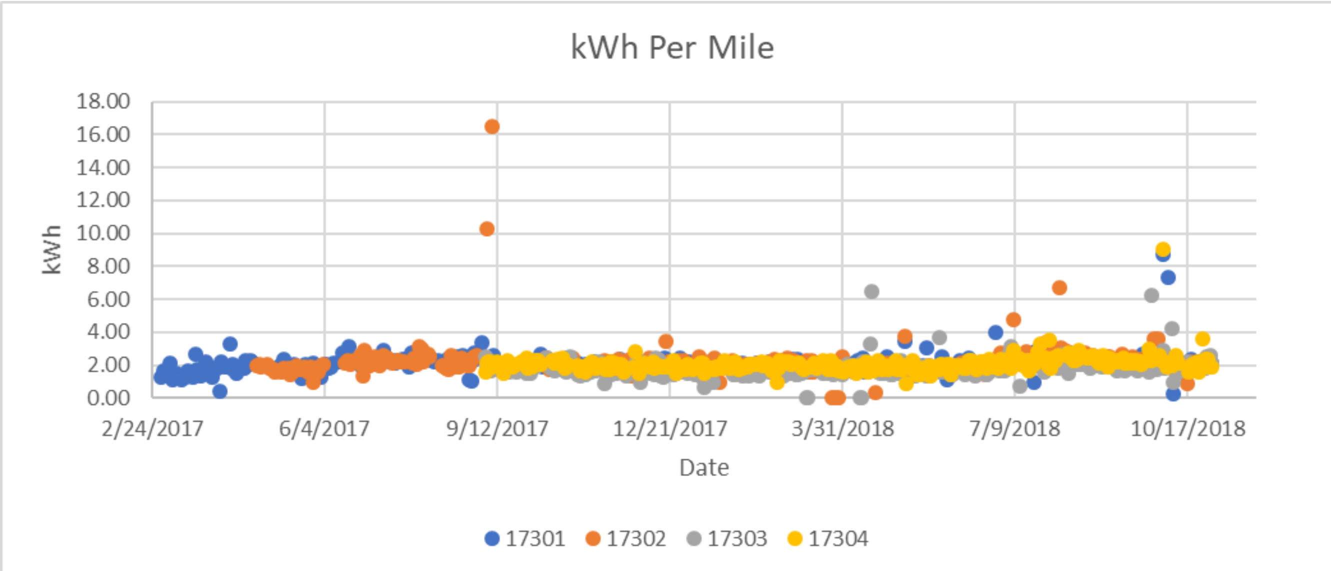
Source: Data from LADOT, analysis by CALSTART

Figure B-36: kWh Used After Removing Outliers (LADOT)



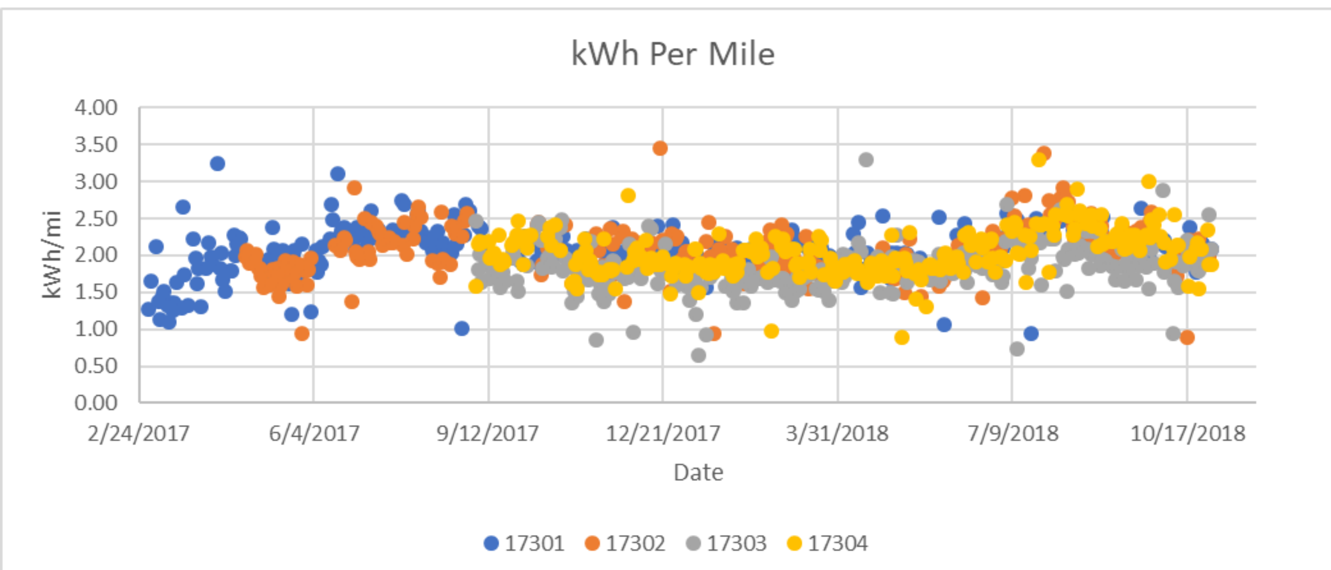
Source: Data from LADOT, analysis by CALSTART

Figure B-37: kWh Per Mile Before Removing Outliers (LADOT)



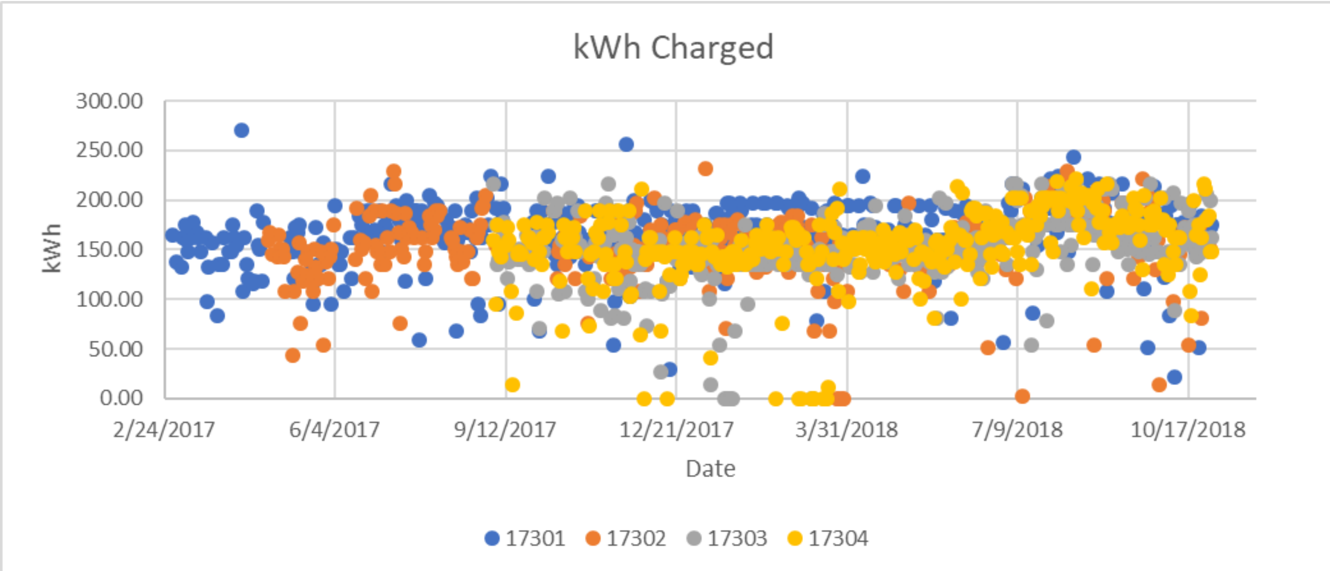
Source: Data from LADOT, analysis by CALSTART

Figure B-38: kWh Per Mile After Removing Outliers (LADOT)



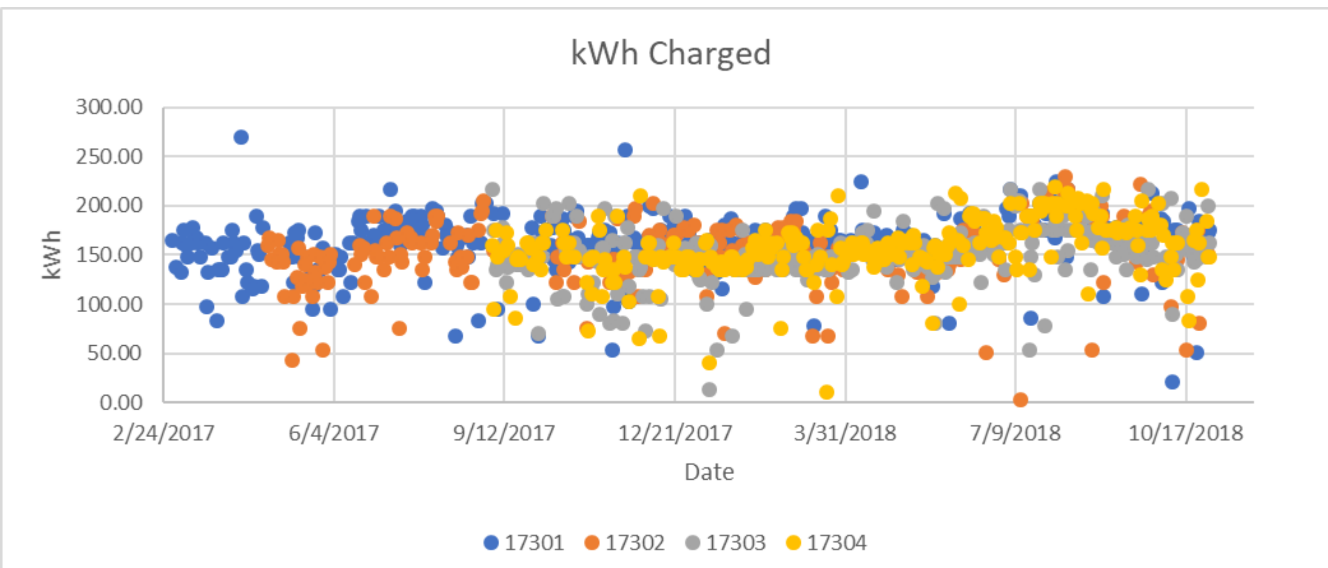
Source: Data from LADOT, analysis by CALSTART

Figure B-39: kWh Charged Before Removing Outliers (LADOT)



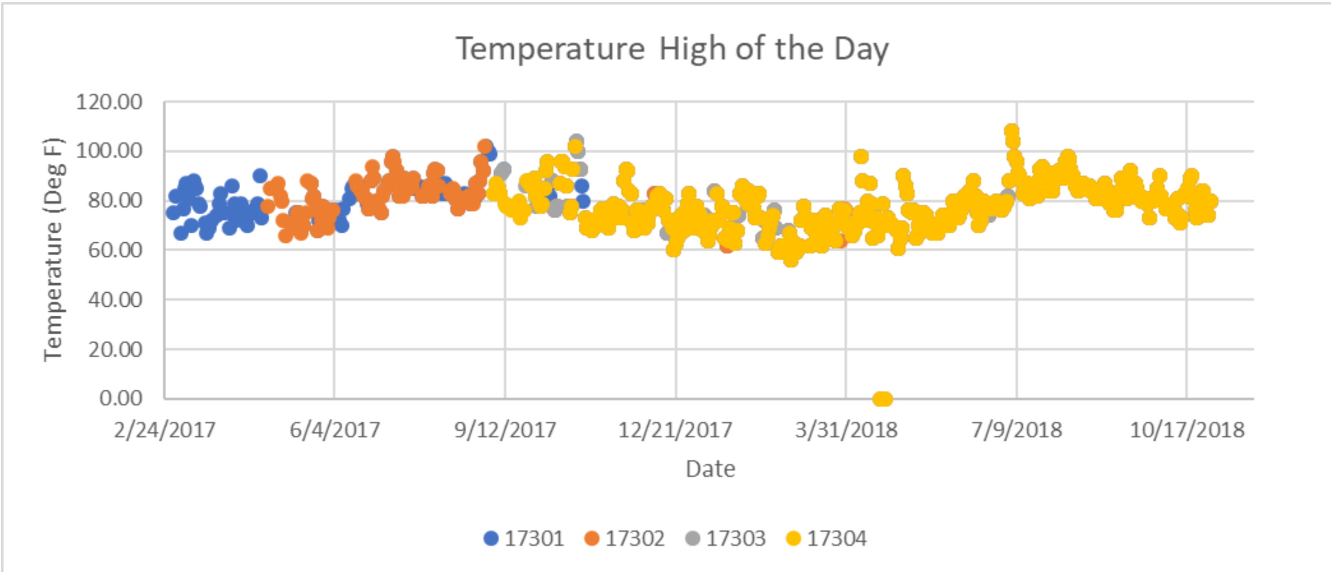
Source: Data from LADOT, analysis by CALSTART

Figure B-40: kWh Charged After Removing Outliers (LADOT)



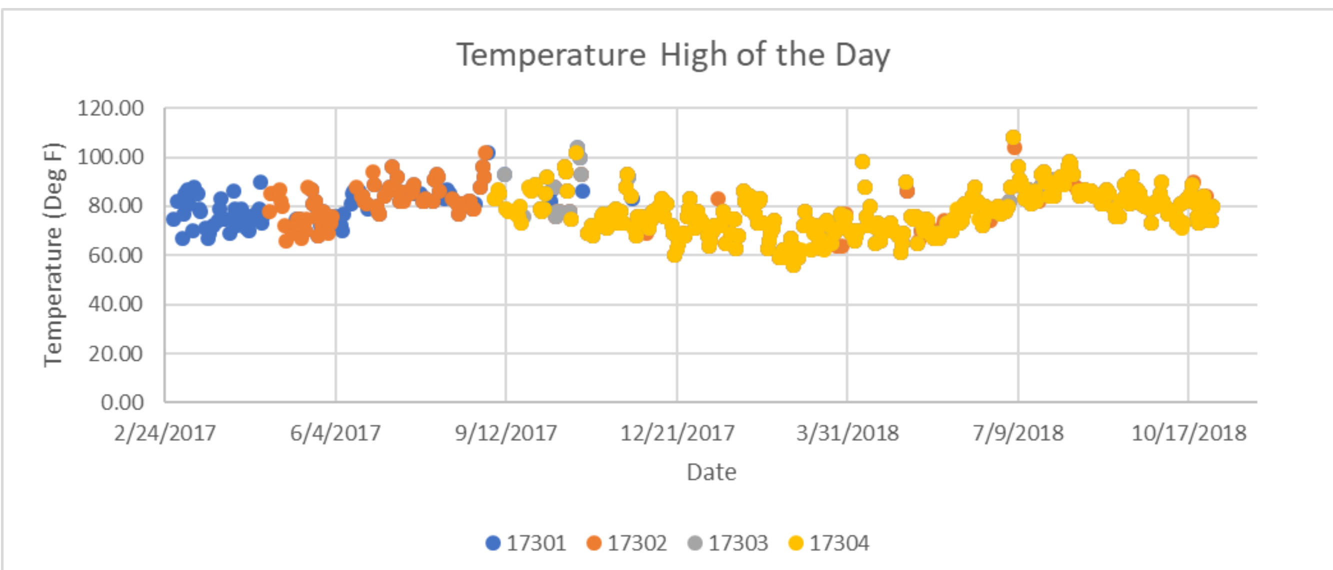
Source: Data from LADOT, analysis by CALSTART

Figure B-41: Temperature High of the Day Before Removing Outliers (LADOT)



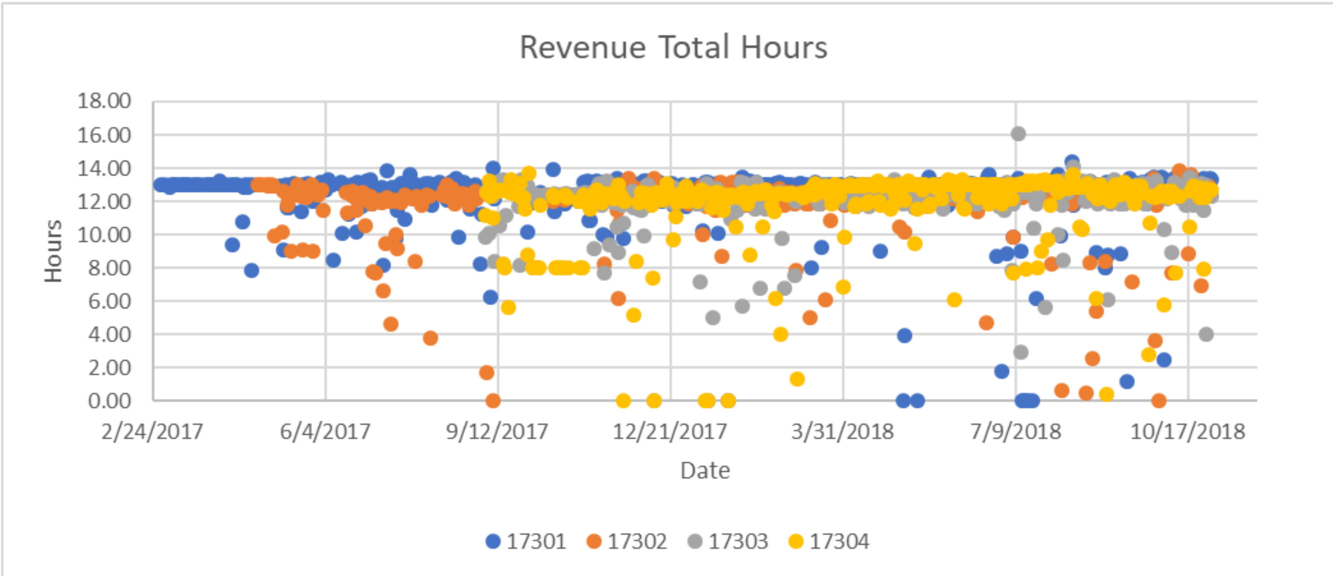
Source: Data from LADOT, analysis by CALSTART

Figure B-42: Temperature High of the Day After Removing Outliers (LADOT)



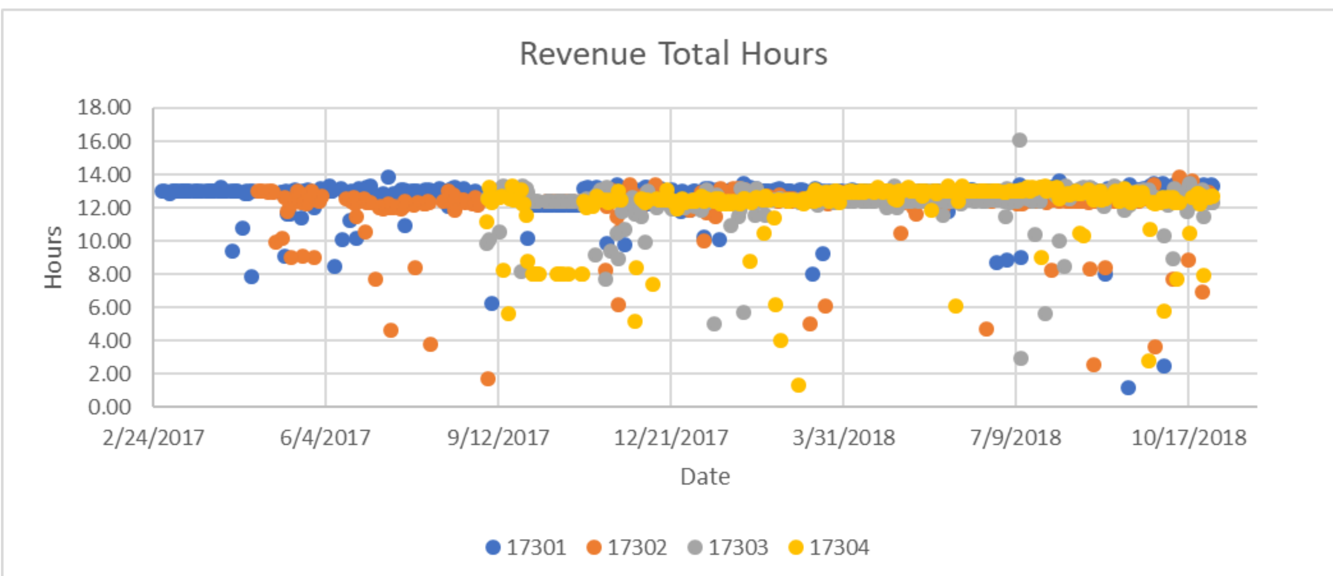
Source: Data from LADOT, analysis by CALSTART

Figure B-43: Revenue Total Hours Before Removing Outliers (LADOT)



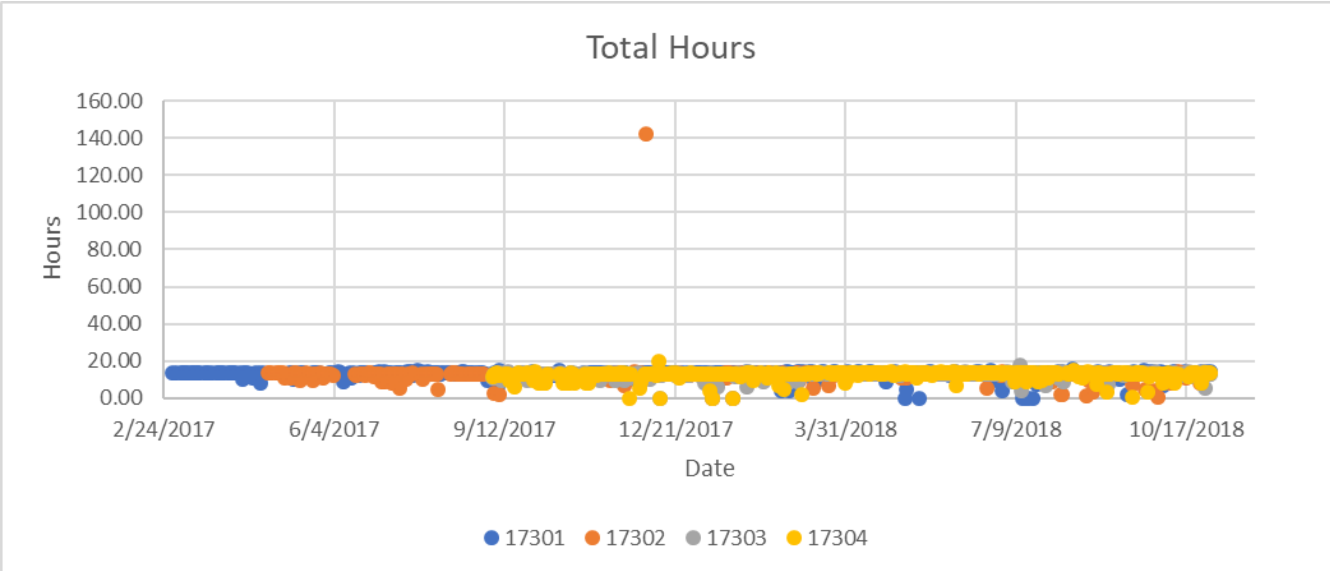
Source: Data from LADOT, analysis by CALSTART

Figure B-44: Revenue Total Hours After Removing Outliers (LADOT)



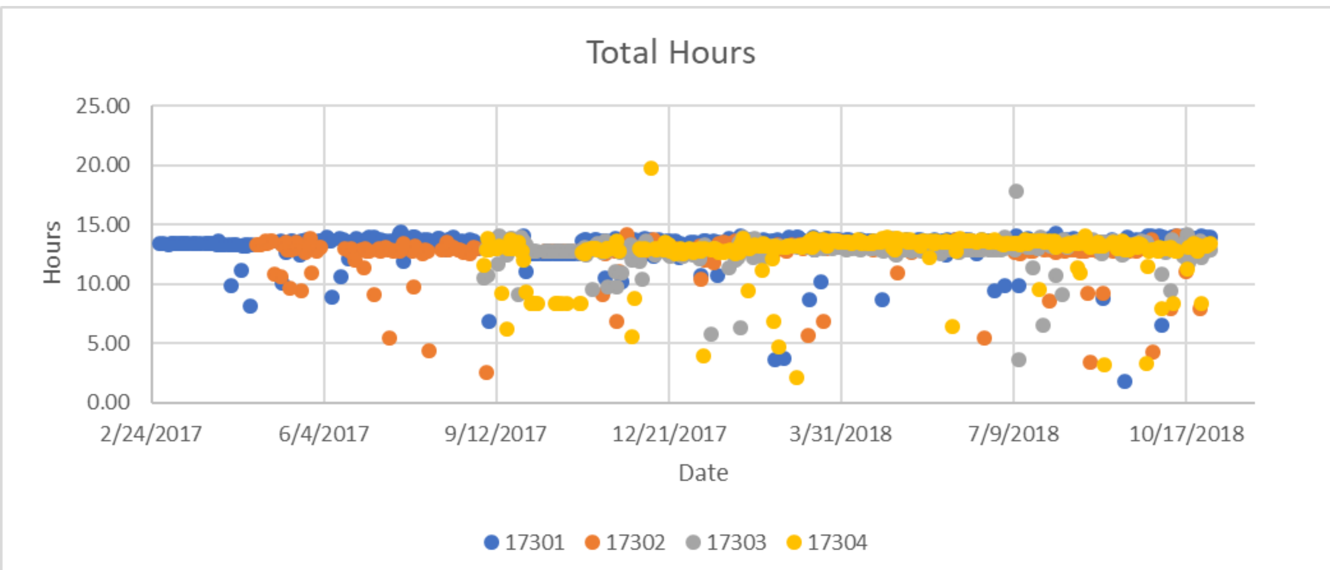
Source: Data from LADOT, analysis by CALSTART

Figure B-45: Total Hours Before Removing Outliers (LADOT)



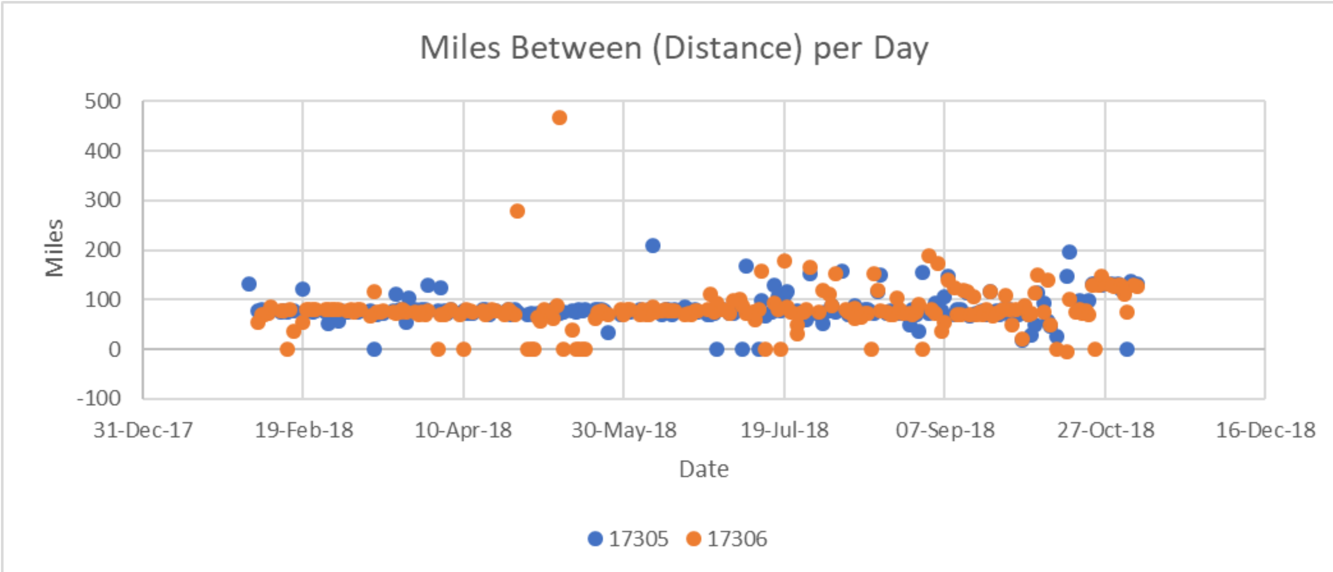
Source: Data from LADOT, analysis by CALSTART

Figure B-46: Total Hours After Removing Outliers (LADOT)



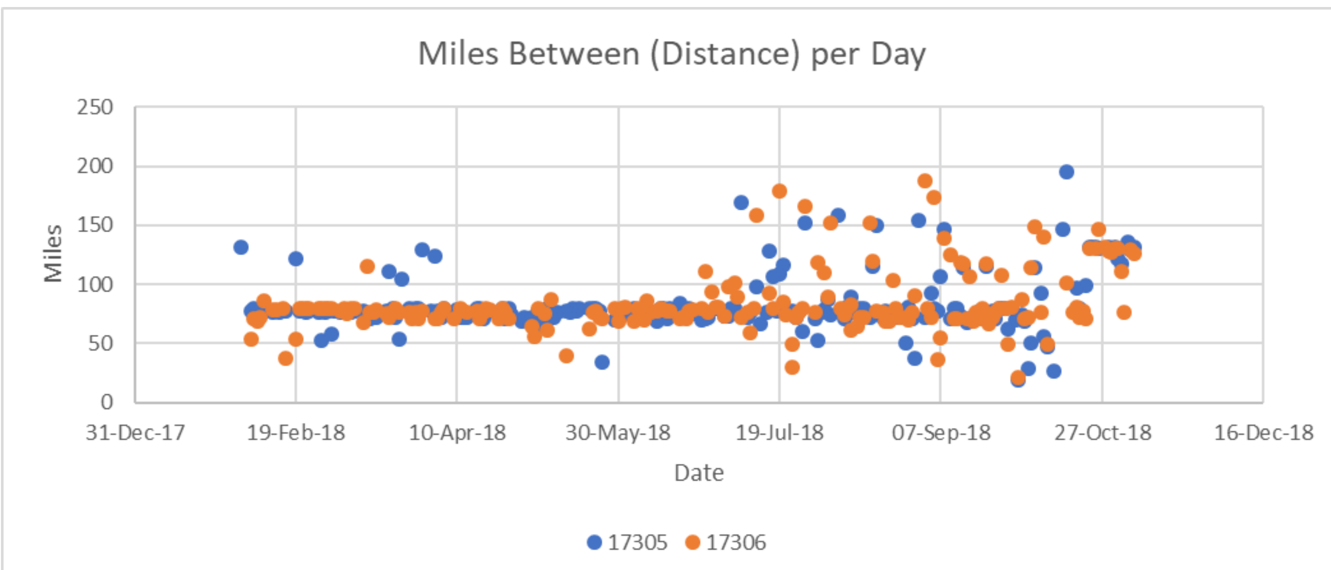
Source: Data from LADOT, analysis by CALSTART

Figure B-47: Miles Between (Distance) Before Removing Outliers (CNG)



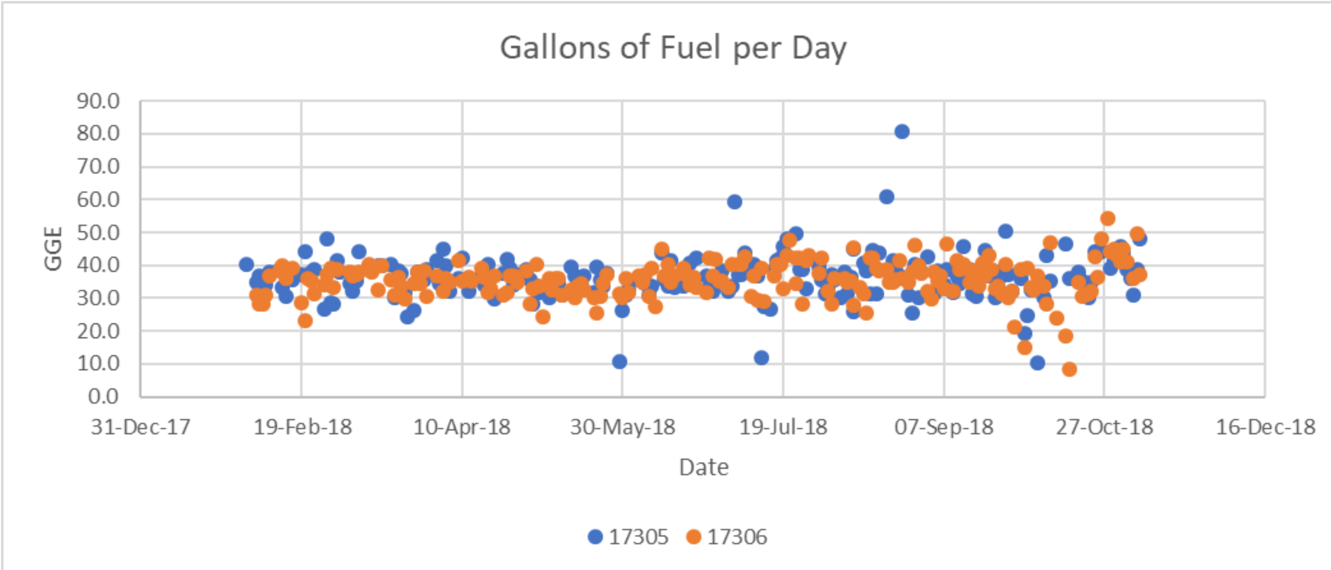
Source: Data from LADOT, analysis by CALSTART

Figure B-48: Miles Between (Distance) After Removing Outliers (CNG)



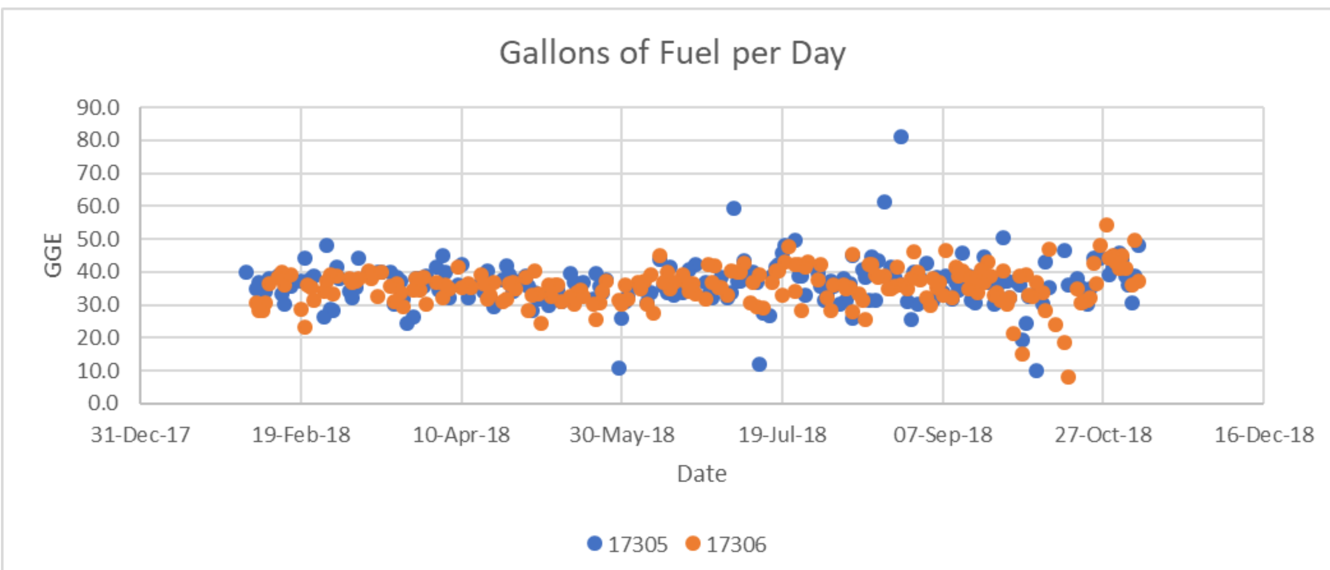
Source: Data from LADOT, analysis by CALSTART

Figure B-49: Gallons of Fuel per Day Before Removing Outliers (CNG)



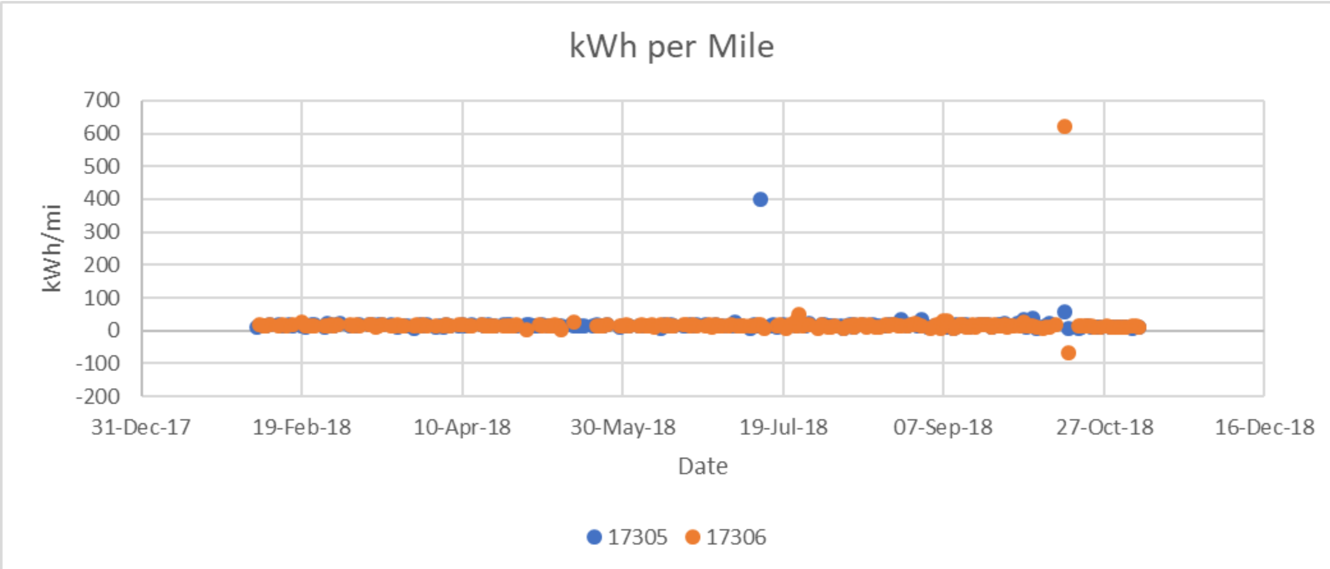
Source: Data from LADOT, analysis by CALSTART

Figure B-50: Gallons of Fuel per Day After Removing Outliers (CNG)



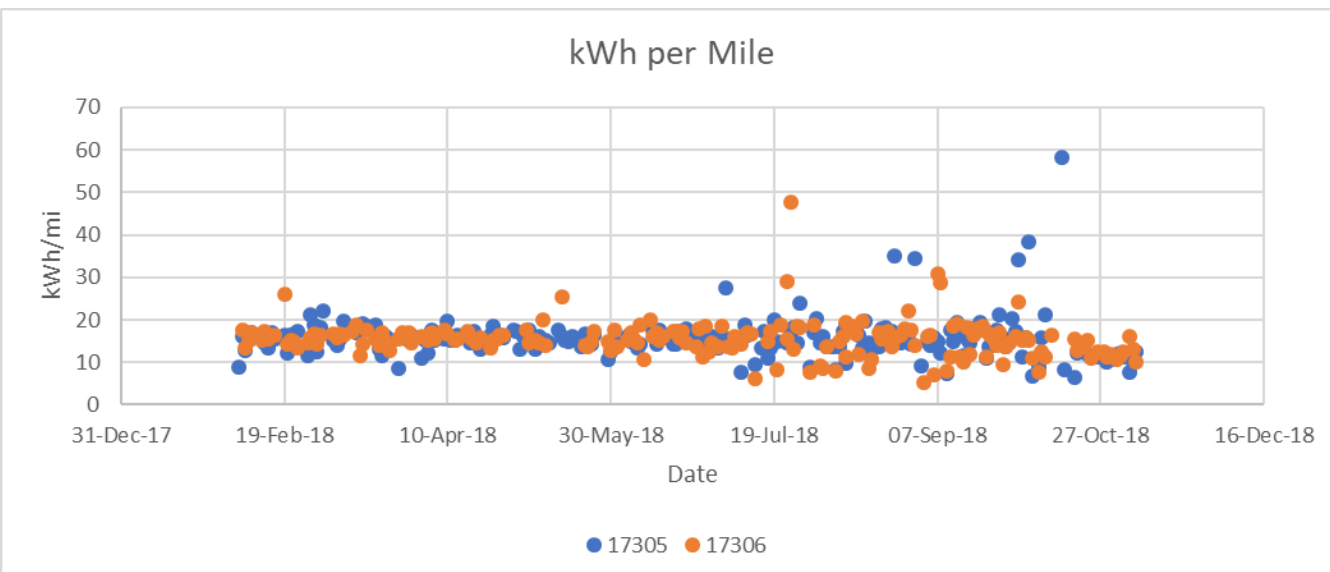
Source: Data from LADOT, analysis by CALSTART

Figure B-51: kWh per Mile Before Removing Outliers (CNG)



Source: Data from LADOT, analysis by CALSTART

Figure B-52: kWh per Mile After Removing Outliers (CNG)



Source: Data from LADOT, analysis by CALSTART

APPENDIX C: In-Use Emissions from a CNG Bus in Urban Downtown Service

CALSTART contracted with Engine, Fuel, and Emissions Engineering, Inc. to measure in-use pollutant emissions from a 32-foot El Dorado transit bus (model year 2015[33]) powered by a Cummins CNG engine with a three-way catalyst for emissions treatment. The vehicle tested is part of the LADOT DASH bus fleet that operates in downtown Los Angeles. Testing this bus provided a baseline level of emissions that was used to calculate the emissions savings provided by the adoption of zero-emission battery-electric buses operating on the same route. Exhaust emissions from the CNG bus were measured while the bus was operating in simulated passenger service, following the DASH A Downtown route.

Table C-1: Average Emissions and Fuel Consumption for the CNG Bus

	CO2	CO	NOx	Total Hydrocarbon	Particulate Matter	Fuel
Average grams per mi						
DASH Bus	3,396	13.5	0.81	3.11	0.010	1,229
EPA Standard[34]	-	72.56	0.93	6.09	0.050	-
Approximate grams per kWh						
DASH Bus	580.1	2.31	0.14	0.53	0.002	210
EPA Standard	-	15.51	0.20	1.3	0.010	-

Source: Engine, Fuel, and Emissions Engineering, Inc.

Mass emissions of carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOx), particulate matter and total hydrocarbons were measured during a series of tests over two days. Fuel consumption was calculated by carbon balance. The results are summarized in Table. Distance travelled was measured using GPS, but it was not possible to measure the actual work output from the engine. The values expressed in grams per kWh are therefore approximate, based on assumed brake-specific fuel consumption of 210 grams per kWh.

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33 While the CNG buses used for comparison in terms of performance and maintenance are model year 2017, the same as the electric buses, the bus used for emissions testing was model year 2015. This was the bus that LADOT made available for testing on August 23 and 24, 2017.

34 Data and conversion factors from: E. Cooper, and et al. "Exhaust Emissions of Transit Buses." Sustainable Urban Transportation Fuels and Vehicles. WRI, 2012. http://www.wrirosscities.org/sites/default/files/Exhaust-Emissions-Transit-Buses-EMBARQ.pdf.

APPENDIX D: Voice of Customer Commercialization Activities Report

LADOT/BYD Bus Demonstration Voice of the Customer – January 18, 2017

CALSTART compiled the list of invitees from fleets within the 88 cities of Los Angeles County who operate DASH-similar routes. After several rounds of invitation emails describing the project, event, and survey link, the following fleets were represented at the Voice of the Customer Commercialization Event: Anaheim Transportation Network, Los Angeles Department of Transportation, Antelope Valley Transit Authority, City of Downey, East Contra Costa County/Tri-Delt, City of Gardena, City of Lancaster, Los Angeles World Airport, City of Norwalk, Palos Verdes Peninsula Transit Authority, City of Pasadena, Sacramento County Airport, San Diego International Airport, City of Torrance, and the University of California Los Angeles. Regulators and other attendees included BYD Motors, California Air Resources Board, CALSTART, City of Los Angeles Department of Water & Power, and South Coast Air Quality Management District. Regulators were invited to the meeting to learn about the technology and learn about the needs of the fleet attendees. BYD Motors provided an end-user presentation on the technology, as well as a tutorial on charging infrastructure.

The Voice of the Customer Commercialization Event was held at Los Angeles International Airport from 10:00 AM to 2:00 PM at their administration building. As airport shuttles run routes similar to DASH buses, airport fleets were also included.

Figure D-1: The LADOT BYD Electric Bus Used for the Ride and Drive

Source: CALSTART

Figure D-2: Interior Shot of the LADOT BYD Electric Bus

Source: CALSTART

Key speakers included Fred Silver from CALSTART who discussed the overall program and provided an overview of electric buses; Samantha Bricker from Los Angeles World Airports who spoke on the Airport's sustainable transportation initiatives; Marvin Moon from LADWP who reviewed charging infrastructure; Corinne Ralph from Los Angeles Department of Transportation (LADOT) who talked about the BYD buses and LADOT's fleet goals; and Zachary Kahn from BYD who answered questions about BYD's technology. Three moderated panels allowed early adopters (University of California, Los Angeles Fleet & Transit, Antelope Valley Transit Authority, Los Angeles World Airports, and LADOT) to share their experiences, LADWP and BYD Motors to discuss Infrastructure Solutions, and CALSTART to update attendees on Available Funding.

Figure D-3: Fred Silver (CALSTART) Discussing Overall Bus Program (Top), Clinton Bench (UCLA Fleet & Transit) Sharing Early Adopter Experiences (Bottom)

Source: CALSTART

Figure D-4: Tom Brotherton (CALSTART) Presenting the HVIP

Source: CALSTART

Presentations were followed by lunch and a Ride & Drive where attendees could drive or ride the buses along a set route around the Airport. After the Ride & Drive, attendees were separated into a Fleet Focused Roundtable for fleet-affiliated attendees only and a Policy Roundtable with regulators to brainstorm how to share funding sources and address challenges for sustainable fleet vehicles.

The main takeaways from the roundtables were:

- Current existing training for electric vehicle maintenance is lacking; smaller fleets may not have the resources for an extensive maintenance crew.
- Training drivers to optimize EV range may be extensive.
- Fleets without external sustainability/alternate fuel requirements that are adopting EVs, such as Foothill Transit, will help shift attitudes toward electrification.
- There is apprehension toward suppliers due to companies that have gone out of business and the reliability of vehicles.
- Standardization of technology would help with solicitations by opening applicant pool based on requirements.
- Fleets should be aware that the cost of electrifying also includes any necessary infrastructure installation and construction/retrofitting. Utility companies need to be involved early to conduct feasibility studies, identify pricing/charging and funding available.

- Timing of funding can affect project planning
- Electrified fleets should share information, challenges, best practices to expand resources and support each other.

Pre- and Post-Event Surveys

The pre-VOC survey sent to invitees was designed to collect information on the fleets represented and the familiarity with all-electric transit buses. All attendees were encouraged to complete the survey; out of 57 attendees, 21 responses were received.

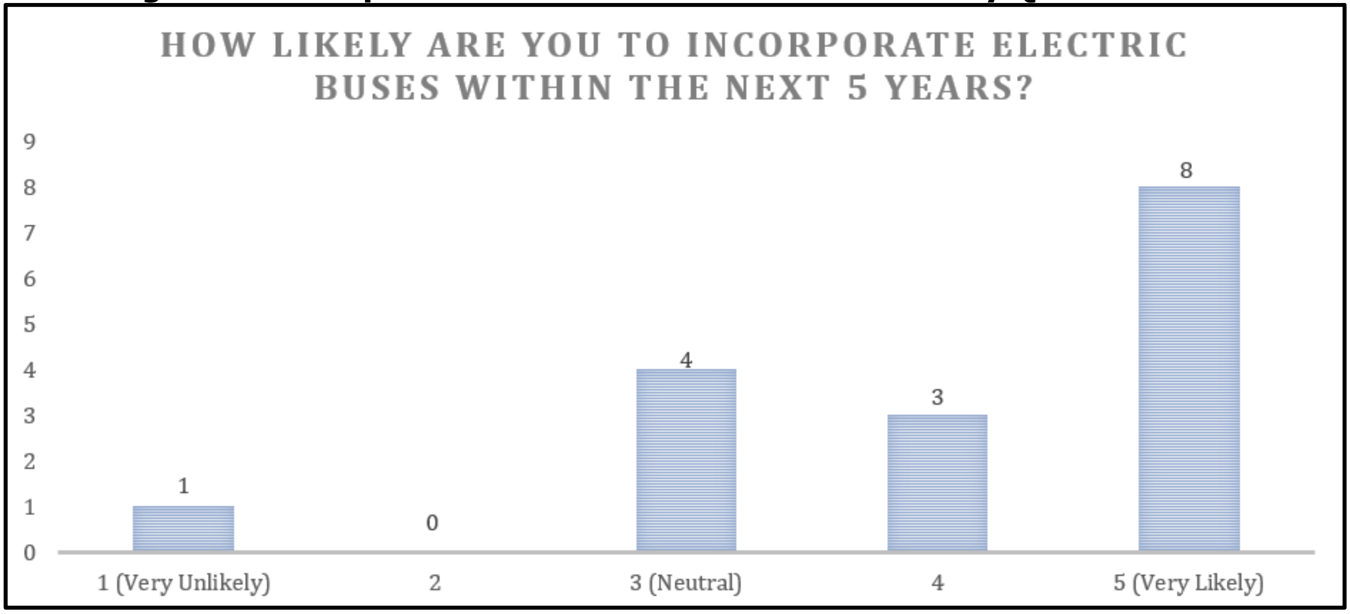
Fleet data collected include contact information, the total number of 30/35/40-foot transit buses in the fleet, average hours of bus operation, average mileage of buses per day, bus purchase arrangements, and alternative fuels currently used. Fleets were asked about their ranked valuation of 8 areas of bus purchasing: reliability, warranty/service/support, battery replacement costs, vehicle incremental costs, charging infrastructure costs, operational costs, range capability, and total cost of ownership. The survey recorded fleet interest in electric buses by likelihood of purchasing electric buses in the next 5 years and their initial opinions (strongly disagree to strongly agree) on electric bus performance, reliability, maintenance costs, and fuel costs as compared to conventional buses. The survey also asked users to identify out of a list what vehicle manufacturers were well-known.

Pre-Event Survey Results

Out of the 21 responses gathered, the following trends were observed:

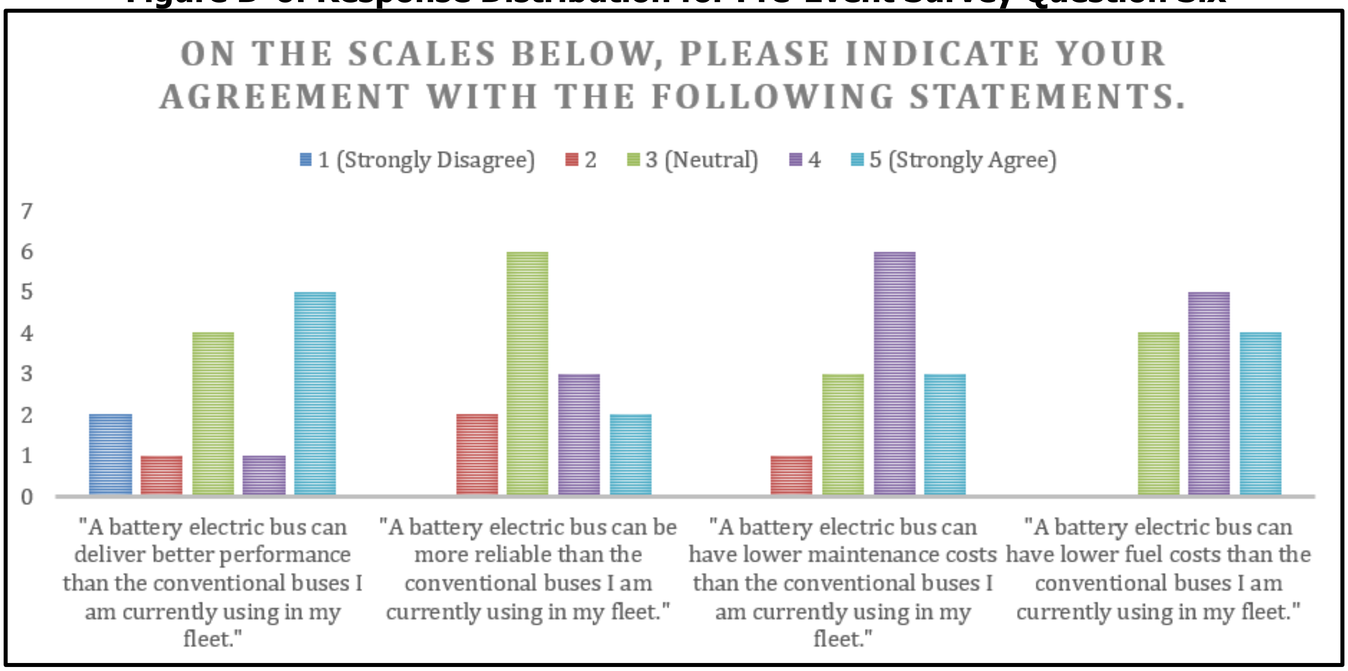
- Fleets were most concerned over bus reliability (61.11 percent of responses ranked Reliability as Highest Priority).
- Fleets were least concerned battery replacement and charging infrastructure costs.
- Prior to the Voice of the Customer Commercialization Event, most fleets were either neutral on purchasing electric buses or already interested in purchasing them within the next 5 years (only 15.79 percent of responses were "Very Unlikely" to incorporate electric buses within the next 5 years).
- Most fleets did not feel strongly about electric buses in comparison to conventional buses in relation to performance, reliability, and maintenance costs. However, most fleets thought that fuel costs with electric buses would be lower than conventional buses.

Figure D-5: Response Distribution for Pre-Event Survey Question Four



Source: CALSTART

Figure D-6: Response Distribution for Pre-Event Survey Question Six



Source: CALSTART

After the Voice of the Customer Commercialization Event, all attendees were sent a link to fill out a post-VOC survey that was meant to track any differences in all-electric bus perception following the event. CALSTART collected 12 responses.

The post-VOC survey asked attendees to rank the same 8 areas of bus purchasing, whether they were likely to purchase electric buses in the next five years, and their opinions on the same electric bus topics mentioned on the first survey. To focus specifically on the fleets represented at the event, the survey collected data on the average hours of daily operation, average mileage of buses per day, types of alternative fuels currently used, and awareness of vehicle manufacturers.

Post-Event Survey Results

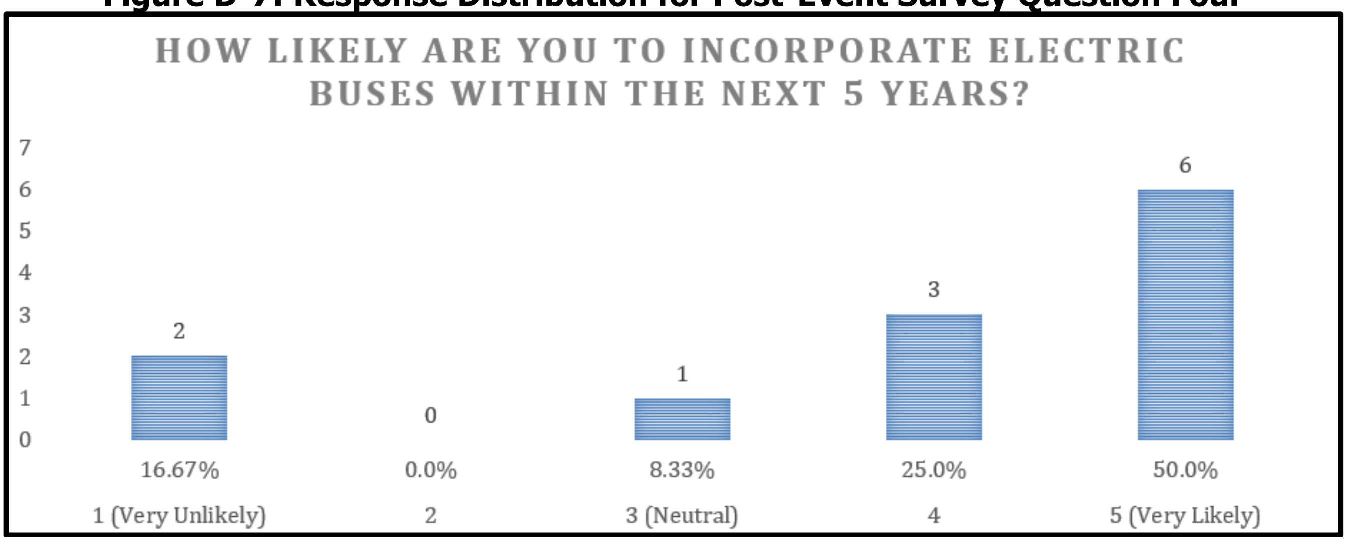
Out of the 12 responses gathered, the following trends were observed from the fleet attendees:

- Fleets were still most concerned over bus reliability but were also concerned over charging infrastructure costs and bus range.
- Half of the responses were Very Likely to purchase electric buses within the next 5 years (6 out of 12 responses marked "Very Likely").
- Most fleets still thought fuel costs would be reduced with electric buses, but more fleets thought maintenance costs would also be reduced.

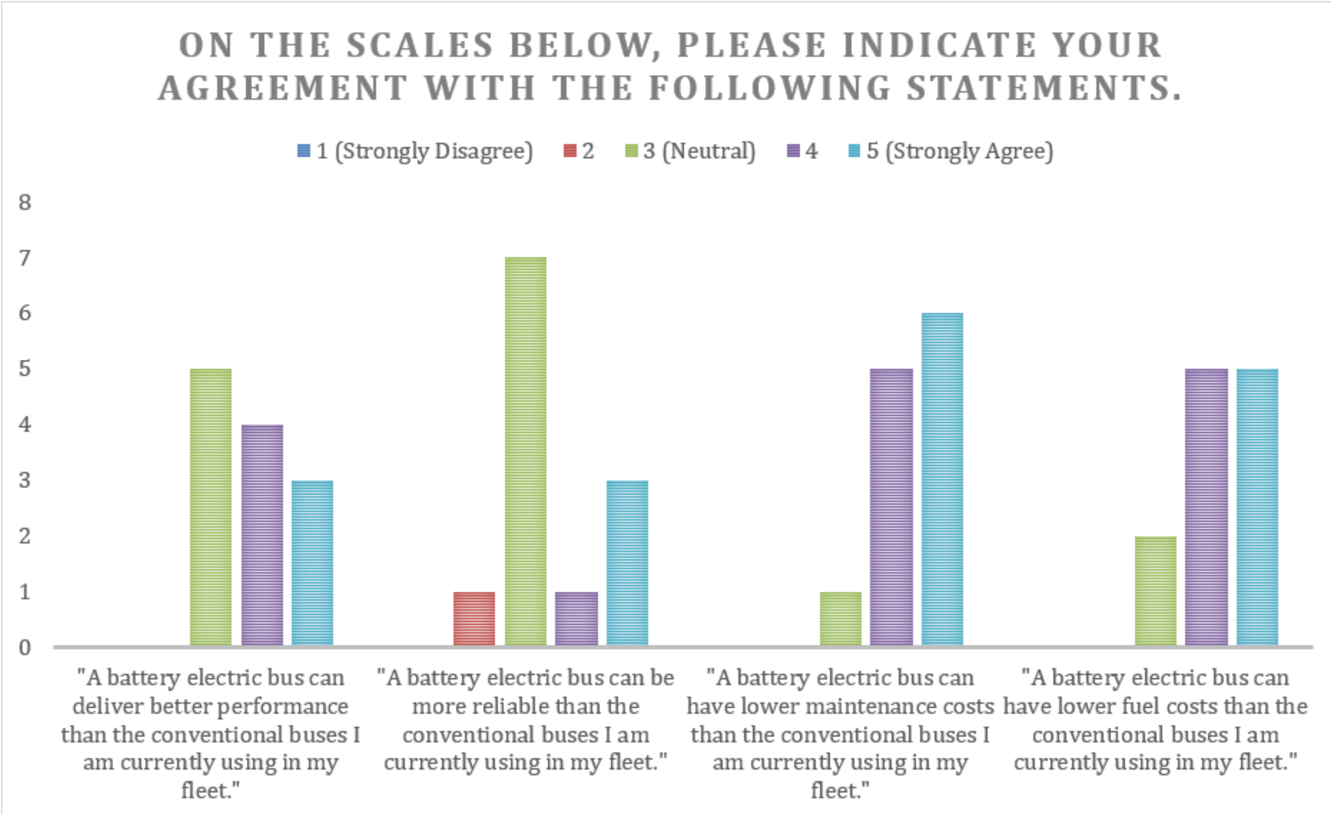
Transit fleets operating under DASH conditions (relatively short routes and limited hours of operations) were primarily concerned over bus reliability before and after the Voice of the Customer Commercialization Event, reflecting a valuation of non-stop vehicle operations regardless of fuel type. Many of the invited agencies reported that they were already interested in adding electric buses to their fleets. Due to the differences in response rates for the surveys before and after the event, it is difficult to determine whether the event managed to change the opinions of those who were neutral or unlikely to purchase electric buses.

The following graphs show the distribution of survey responses on select questions:

Figure D-7: Response Distribution for Post-Event Survey Question Four



Source: CALSTART



Source: CALSTART

Main Takeaways

After the Voice of the Customer Commercialization Event, the participating fleets seemed to have learned of more benefits and challenges of operating all-electric transit buses: responses after the Voice of the Customer Commercialization event showed that attendees not only knew that electric buses reduced fuel costs, but also reduced maintenance costs. On the other hand, another major concern in purchasing electric buses showed that the discussions on charging infrastructure and related costs did result in transit agencies become more aware of the additional costs of incorporating electric buses beyond the cost of the buses themselves.

Based on the Policy roundtable, regulators shared different funding opportunities that they felt were underutilized, indicating that fleets may not be aware of the different programs that could help them alleviate their concerns on operational costs of electric buses. As the transit agencies that were represented at the Voice of the Customer Commercialization event reported that the majority of participants were interested in purchasing electric buses within the next five years, increasing awareness of funding programs could help increase the volume of electric buses in transit fleets in California.

APPENDIX E:
Raw Data Samples

ViriCiti Raw Performance Data Sample

Table E-1: ViriCiti Raw Performance Data Sample

DateTime	Bus	Average Speed	Distance	Consumption driving	Consumption overall	Consumption in service	Energy charged	Energy consumed driving	Energy driven	Energy idled	Energy used in service	Energy used not in service	Energy regenerated driving	Energy used	Regeneration rate
12/8/2017 0:00	17301	11.7	78.6	1.3	1.6	1.5	225.1	206.5	101.0	21.1	118.7	3.2	105.5	122.1	51.1
12/9/2017 0:00	17301	13.1	71.6	1.4	1.7	1.6	69.3	196.7	102.6	20.2	112.8	10.0	94.1	122.9	47.8
12/10/2017 0:00	17301	15.6	96.6	1.4	1.7	1.5	98.1	263.8	130.8	33.7	146.5	17.8	133.0	164.5	50.4

Source: ViriCiti

LADOT Raw Performance Data Sample

Table E-2: LADOT Raw Performance Data Sample for Bus 17301

Date	Start Miles	End Miles	Total Miles	SOC Start	SOC End	SOC USED	kWh Used	kW/Mile	kW Charged	Temp High of Day	Start Time	End Time	Revenue Start Time	Revenue End Time	Revenue Total Hours	Total Hours	kW Charge Hours	kW Rate	Operation Rate	Electricity $/day
12/8/2017	17719	17798	79	90	27	63.00	170.1	2.15	197.1	78	6:48 AM	7:22 PM	6:59 AM	7:11 PM	12.2	12.57	197.1	$0.19	$72.85	$37.45
12/9/2017	17798	17869	71	100	44	56.00	151.2	2.13	148.5	83	9:43 AM	10:19 PM	10:15 AM	10:02 PM	11.78	12.6	148.5	$0.19	$72.85	$28.22
12/10/2017	17869	17966	97	99	30	69.00	186.3	1.92	189	82	9:10 AM	11:01 PM	10:00 AM	10:41 PM	12.68	13.85	189	$0.19	$72.85	$35.91

Source: LADOT

CNG Bus Raw Performance Data Sample

Table E-3: CNG Bus Raw Performance Data Sample

Date	Vehicle #	Mileage	Miles Between	Fuel Type	Gallons of Fuel
06-Nov-18	17305	18,650	131	Compressed Natural Gas	38.9
05-Nov-18	17305	18,521	129	Compressed Natural Gas	30.8
04-Nov-18	17305	18,385	136	Compressed Natural Gas	35.9

Source: LADOT

PMI Maintenance Cost Raw Data Sample

Table E-4: PMI Maintenance Raw Data Sample

Bus	Date Started	Date Completed	Labor	Parts	Tires	Warranty	Outside	Shop	Tax	Misc	Sublet Parts	Sublet Labor	Total
17301	10/4/2017	10/4/2017	$147.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$147.00
17301	9/8/2017	9/8/2017	$105.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$105.00
17301	8/14/2017	8/14/2017	$105.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$105.00

Source: LADOT

Work Order Maintenance Cost Raw Data Sample

Table E-5: work order Maintenance Cost Raw Data Sample

Bus	Date Started	Date Completed	Labor	Parts	Tires	Warranty	Outside	Shop	Tax	Misc	Sublet Parts	Sublet Labor	Total
17301	10/17/2017	10/17/2017	$21.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$21.00
17301	10/3/2017	10/3/2017	$21.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$21.00
17301	9/11/2017	9/11/2017	$10.50	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$10.50

Source: LADOT