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Characterization of battery electric transit bus energy consumption by temporal and speed variation

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ABSTRACT

De-carbonizing transport is an important strategy for combating climate change and reducing the health impacts of air pollutants. The transit bus sector is one of the highest potential categories to be electrified with Battery-Electric Buses (BEBs). The energy consumption and fueling patterns of BEBs, however, will be different from conventional technology buses, so research is needed to better understand these phenomena to make the BEB rollout successful. We have analyzed the BEB activity and charging data collected over a year from a transit fleet (consisting of 40-ft and 60-ft BEBs) undergoing complete electrification. The average energy consumption for 40-ft and 60-ft buses were 2.6 ± 0.3 kWh/mile and 3.6 ± 0.5 kWh/mile, respectively, over the year. The regenerative braking recovered a significant amount of energy spent and that accounts for 37.3% and 40.2% of the total average energy required for 40-ft and 60-ft bus operation, respectively. Bus speed has a significant effect on average energy consumption per mile; the higher speed resulted in less energy consumption for both types of buses. The variability of seasonal and intra-day energy consumption per mile can be attributed to increased use of air conditioner (A/C) and heater, which were controlled according to the ambient temperatures. This transit agency may incur 16.2 ± 2.1% (based on current fleet composition, energy tariffs) more energy costs in Summer compared to Winter, if no optimized operation is used. This effort provides reliable BEB energy consumption estimates that can be used for any transit fleet's energy efficiency objective.

1. Introduction

De-carbonizing transport is an important strategy to slow global warming and reduce the health impacts of air pollutants. Zero-emission vehicles, which are part of low carbon transportation, are replacing conventional technology (Gasoline, Diesel, CNG, LNG, etc.) vehicles quickly because of their energy efficiency, emission reduction benefits, and lower operating costs [1–6]. Studies show that electric vehicles could reduce transportation lifecycle GHG emissions (including car manufacturing, tailpipe, and fuel cycle emissions) by 50% compared to conventional vehicles [7,8]. The conventional technology heavy-duty vehicles emit 2952 g of CO_2e/km during operation versus 1091 g of CO_2e/km of a heavy-duty electric vehicle [9]. Even though the light-duty vehicle sector has led the new wave of turnover to zero-emission technology, heavy-duty vehicles have started catching up [6,10]. Realizing the positive impact of clean vehicles on air quality and fossil fuel imports, the adoption of heavy-duty zero-emission electric vehicles has been encouraged through incentive policies [10–12]. Despite the policies, most of the time the adoption rate falls short of goals, which can be attributed to technical and cost barriers [8,10], especially for heavy-duty vehicles.

Typical challenges that heavy-duty electric vehicles face include driving range limitations, lack of charging infrastructure, higher upfront cost, long charging time, and lack of electric vehicle service technicians

Abbreviations: A/C, Air Conditioning; AM, AM Peak hours (6 a.m.–9 AM); AVTA, Antelope Valley Transit Authority; BEB, Battery Electric Bus; CAN, Controller Area Network; CNG, Compressed Natural Gas; CO_2e, Carbon dioxide equivalent; ECU, Engine Control Unit; GHG, Green House Gas; GPS, Global Positioning System; kWh, Kilowatt Hour kWh/mileKilowatt Hour/Mile; LCT, Low Carbon Transportation; LNG, Liquified Natural Gas; MID, Mid-day hours (9 a.m.-3 PM); mph, Mile/Hour; NT, Night hours (6 p.m.–10 p.m. and 4 a.m.–6 AM); OEM, Original Engine Manufacturer; PM, PM Peak hours (3 p.m.–6 PM); SOC, State of Charge; VCU, Vehicle Control Unit; WAVE, Wireless Advanced Vehicle Electrification.

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[13,14]. Due to their unique duty cycle patterns reflective of their vocations, planning for sufficient charging infrastructure is also a challenge [8,13–15]. This limits the operational range and requires a significant upfront investment as well as detailed information on energy requirements for successful fleet electrification [14,16,17]. Therefore, having a reliable estimate of energy consumption for commercial vehicle operation would be a critical metric to evaluate the cost-effectiveness and to determine the charging infrastructure needs and hence the acceptance of electric vehicles [18,19]. Most heavy-duty fleet operators largely rely on the manufacturer's technical specifications for their operational planning and the total cost of ownership calculations due to the dearth of sufficient real-world energy consumption data [16,20,21]. Understanding energy consumption is important to estimate the electricity/fuel cost and charging/fueling needs, which affect the types and locations of charging/fueling infrastructure, e.g., whether to use depot charging or on-route charging [22,23]. Therefore, characterizing energy consumption rates for different types of heavy-duty operations using real-world data would be critical [20,22,24–27].

The transit bus sector has a high potential to be electrified because of its fixed route schedules and the service area's proximity to maintenance/charging infrastructure [16,23,28–30]. The main hurdle to increase the adoption rate of transit Battery Electric Buses (BEB), however, is providing confidence that their operational capabilities can meet the demands of local routes, and thus minimizing the financial risk for the operators [3,31]. The operation range of transit BEBs is a function of, mostly, externalities such as traffic, roadway (i.e. grade, rolling resistance of pavement, etc.), and meteorological conditions [20,22,24,32–36]. Besides, bus body-type and operating conditions like the state-of-charge of the battery, location of charging stations, bus speed and acceleration, passenger ridership, etc. And operators' driving style could influence BEB energy consumption [18,26,32,37–40].

Real-world operational characteristics based on large real-world datasets can provide important and practical insights to transit operators and zero-emission vehicle program management [6,29,31,41]. For example, average energy consumption by speed and state-of-charge (SOC) of the battery during a trip can provide necessary considerations on how to optimize transit bus operations such as dispatch scheduling, route selection, charging frequency, and others. Besides, understanding regenerative braking efficiency in energy recovery at various real-world operating conditions would be a critical factor for examining BEB operation ranges and their charging frequencies, which would significantly affect the average energy consumption of BEBs [2,12,20,25,26,37].

Understanding real-world energy consumption along with the operational behavior of transit BEBs will help to identify the barriers hindering faster adoption of BEBs, which will be beneficial to policymakers as well as transit operators [10–12]. The lessons learned from BEBs can be extended to other heavy-duty electric vehicles in designing vehicles for industry and developing governmental strategies such as incentive programs and air pollution and greenhouse gas controls.

In this study, a large activity dataset was collected for a whole year (i.e., 2019–2020) from ten buses where five 40-ft and five 60-ft BEBs were operating on relatively flat terrain and under typical desert climatic conditions. These extreme climatic conditions mean the summer average daily high-temperature ranges in 100 °F - 115 °F and the winter average daily low-temperature ranges in 15 °F - 40 °F. Their energy consumption rates were characterized per temporal and vehicle speed variations.

2. Methods and materials

Between January 2019 and March 2020, ten battery-electric buses were instrumented with vehicle activity data loggers. The BEBs are operated by the Antelope Valley Transportation Authority (AVTA), located in Lancaster, California. AVTA is one of the first few transit agencies in CA leapfrogging from diesel to zero-emission buses. Currently, AVTA operates 40-ft transit buses and 60-ft articulated transit buses with 324 kWh and 520 kWh batteries, respectively. The average age of 40-ft buses is 1.4 years and for 60-ft buses, it is 0.4 years and there is no observed battery degradation in the fleet during the data collection period. The data loggers were switched periodically among different sets of buses, every 3 months, to acquire data over a large cross-section of the fleet using a limited number of loggers, including both 40-ft and 60-ft BEBs. AVTA covers over 30 different routes in their region: six commuter routes that connect Lancaster with Los Angeles and Edwards Air Force Base, twenty-four local routes that provide service within the cities of Lancaster and Palmdale in Southern California. Currently, however, AVTA is not operating any BEBs on commuter routes due to associated operational challenges. The route map of AVTA service coverage is shown in Fig. 1 and it shows all the routes.

At the time of data collection, BEBs were running on transit routes travel on flat terrain (0% ± 2% road grade). The 40-ft buses were dispatched based on their availability and the 60-ft buses on high passenger demand routes. Ambient temperatures in this region vary significantly daily and seasonally; in summer, the average daily high-temperature ranges in 100 °F - 115 °F, and in winter the average daily low-temperature ranges in 15 °F - 40 °F. These high variabilities affect overall energy demand over the year due to increased energy demand from the air conditioner (a/c) or heater (Ma, Jiang et al., 2018). For this study, the data collected from 10 buses were used and each bus provided at least 45 days' worth of data.

Due to the extensive data collection effort, our study has more data samples and results that can capture more variability in BEB energy consumption. The worldwide deployment of BEBs has started in the past 5 years except in China, therefore, there are very limited studies available that focused on their real-world energy consumption [42]. For example, Pamula and Pamula [43] has studied energy consumption of 3942 trips of BEBs in Poland and suggested different locations for charging locations. However, these only trips covered fewer days over four seasons, which may not be enough to draw accurate estimations, therefore, they relied on machine learning approach for reliable predictions. In our current study we have collected energy consumption for more than 14,000 trips. In other study conducted by Ji et al. [42], the data sample size is 4360 trips which happened during 14 months of data collection period and they are collected from 31 buses. The ambient temperature during this data collection period were between −27 °C (−16.6 °F) and 35 °C (95 °F) which did not cover higher temperatures (i.e. 110 ° F – 115 °F) like our study. As part of our data collection, we have collected data for 14 months, for 10 buses at a time (for every quarter) and 28 different buses that include both 40-ft and 60-ft types. Chen et al. [44], used 2600 operating hours data to develop a machine learning based energy consumption model for BEBs, in which they selected 4 random weeks in each season in a year, and the data sample size is much smaller (less than 5200 trips) than our current study. Further, climatic conditions of their study area (Chattanooga, Tennesse) in a typical season are milder than the ambient conditions during our study period. These drastic temperature variabilities and larger data sample size would provide better reliable estimations and their relationship with different climatic and operational conditions can be better established.

Each BEB was instrumented with a data logger (HEM® data, Michigan U.S.A), which records 1-Hz Global Positioning System (GPS) location information and Vehicle Control Unit (VCU) parameters. The collected data were put through a quality assurance/quality control (QA/QC) process and erroneous data were eliminated. GPS location data were primarily used to calculate vehicle speed. If the GPS signal was lost, due to too few GPS satellites in range (4 or fewer), or noisy, occurring at very low speeds (less than 5 mph), and then the wheel speed provided by the VCU was used. When both GPS signals and wheel speed were not available, vehicle speed was imputed based on the immediate before and after reliable data points. For electricity consumption analysis, battery current (in amperes), battery voltage (in volts), and SOC of battery (in

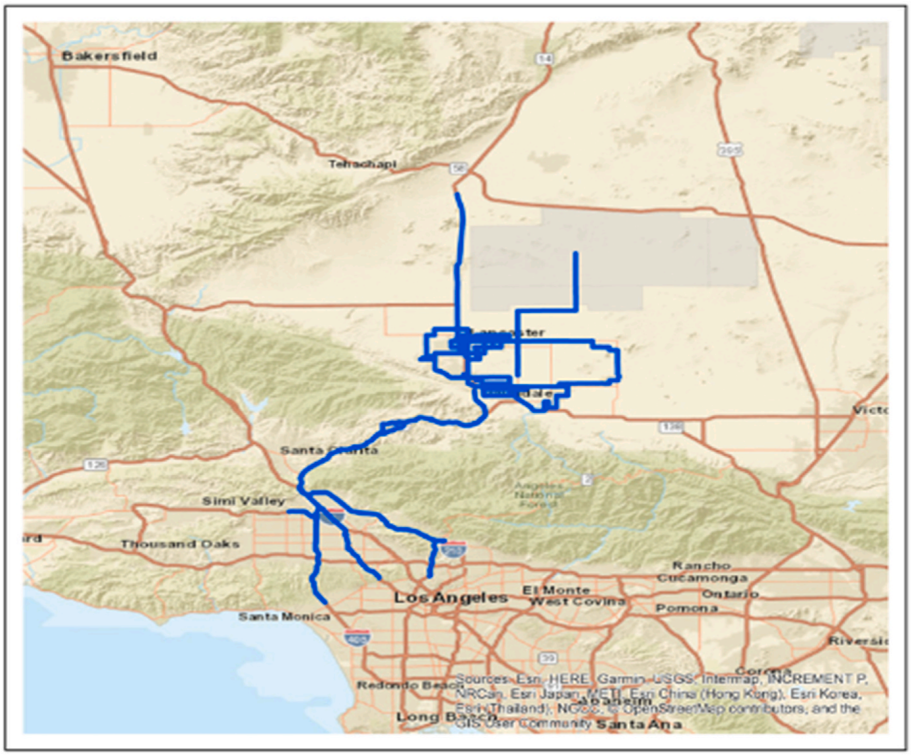

Fig. 1. Antelope Valley Transit Agency's transportation system map.

percent) were used. Note that electric vehicle VCU, which utilizes a Controller Area Network (CAN) standard developed by Original Engine Manufacturer (OEM), has not undergone the same standardization process as for internal combustion vehicle Engine Control Unit (ECU) data.

To extract trips from the daily BEB's continuous trajectory data, we developed and applied a path-matching algorithm on AVTA's route shapefile. This algorithm was implemented in Python 3.2 language using the most advanced spatial processing libraries like 'geopandas' [45]. Using the path-matching algorithm, the daily trajectory, which was a continuous time-stamped path, was broken into individual bus trips. Data were processed to identify charging and braking activities. If the direction of the current was negative (if it was flowing into the battery) while the BEB was decelerating, it was assumed to be regenerative braking for the BEBs analyzed in this study. The instantaneous power consumption in kW was calculated by multiplying instantaneous current by instantaneous voltage. To get energy consumption in kWh, the instantaneous power is integrated over time.

AVTA uses two types of charging infrastructure: wired and inductive. Wired charging can provide 60 kW (single plug-in) and 125 kW (tandem plug-in) options to both types of buses. To optimize BEB operations, AVTA has also built inductive-charging facilities at three different transit terminals in their service area [46]. The maximum charging capacity of the inductive charging system (Wireless Advanced Vehicle Electrification or WAVE) was 250 kW, and this high-power supply drastically reduces charging time for *en route* buses.

To distinguish battery charging events among regenerative braking, plug-in charging, or inductive charging, we used following parameters: the length of time, the negative current flowed into the battery, and the voltage during that event. Based on extensive data analysis, the negative sign for current data is observed only in two instances: (a) during brake usage—the reverse rotation of armature coil in the electric motor produces current because of electromagnetic induction [47], and (b) during the battery recharging event. From the AVTA's web resources we learned that their inductive/wireless chargers work at around 500 V and wired chargers work at 125 V [46]. Usually, braking happens for a very short span of time i.e. in the order of seconds, whereas we observed that the inductive charger is only used for less than 15 min because of schedule limitations and the wired charging typically happens longer than 20 min. During the preliminary analysis, these assumptions were verified against the charging locations' latitude/longitude information with BEB's GPS location data. After careful consideration, following conditions were developed to classify different charging events: If negative current flows for more than 60 s with a voltage higher than 500 V then it was assumed inductive charging; if the voltage was 110–150 V (voltage varies based on current) then it was assumed as wired charging; if negative current flows less than 60 s it was assumed as regenerative braking.

3. Results and discussion

3.1. Summary statistics of activity, energy use, and battery recharge

Table 1 provides the summary statistics of daily activity, energy consumption, and overnight depot charging (only wired charging is available at the depots during the time of data collection) timings. It was observed from the activity data that the 40-ft buses (with 324 kWh battery) operate at slightly lower speeds compared to 60-ft buses (with 520 kWh battery). On average, the 40-ft buses run with a daily average speed of 21.0 ± 2.8 mph compared to 26.9 ± 3.8 mph of 60-ft buses. The average energy consumption discrepancy between two bus types may be due to differences in deployed routes, vehicle weight, passenger load, and respective traffic conditions. The 60-ft BEB routes run higher travel demand corridors and longer per trip distances than the 40-ft buses based on the route schedule. Further, they provided direct services between major trip attraction points such as Antelope Valley Mall and Palmdale International Shopping Mall. It was also evident from the daily average miles traveled observation, i.e., 60-ft buses drive 87.2 miles/day versus 40-ft buses drive 101.9 miles/day. The 40-ft buses were operated for longer hours of 8.3 h/day for different routes in a typical day compared to 6.5 h/day of the 60-ft buses that run on the same high-demand routes in a typical day. It was also observed that statistically

Table 1
Summary statistics of BEBs of daily activity, energy consumption, and overnight depot (wired) charging.

Bus Number	Daily Average Activity			Daily Average Energy Use/ Battery Recharge	
	Speed (mph)	Distance (miles)	Operation (hours)	Energy consumption (kWh/mile)	Overnight Depot Wired Charging Time (hours)
Bus1-40ft	30.4 ± 3.1	188.9 ± 37.8	11.3 ± 1.5	2.6 ± 0.3	2.8 ± 0.3
Bus2-40ft	20.6 ± 2.5	61.0 ± 8.5	6.9 ± 0.5	2.6 ± 0.2	1.2 ± 0.1
Bus3-40ft	16.1 ± 2.3	50.8 ± 8.6	6.3 ± 0.9	2.7 ± 0.4	2.9 ± 0.4
Bus4-40ft	19.7 ± 3.9	97.8 ± 17.6	8.7 ± 1.1	2.5 ± 0.3	4.2 ± 0.6
Bus5-40ft	18.4 ± 2.1	110.9 ± 12.2	7.9 ± 1.3	2.6 ± 0.4	3.3 ± 0.5
Bus1-60ft	30.1 ± 2.4	74.4 ± 6.0	4.2 ± 0.4	3.6 ± 0.4	3.9 ± 0.5
Bus2-60ft	19.8 ± 2.9	79.8 ± 6.4	6.6 ± 1.4	3.4 ± 0.6	3.1 ± 0.3
Bus3-60ft	22.7 ± 4.8	104.3 ± 10.4	7.4 ± 1.3	3.9 ± 0.3	1.5± ± 0.2
Bus4-60ft	39.5 ± 6.3	90.5 ± 14.5	7.8 ± 1.1	3.5 ± 0.5	2.2 ± 0.3
Bus5-60ft	22.4 ± 2.7	86.8 ± 19.1	7.3 ± 1.1	3.5 ± 0.8	4.2 ± 0.5

insignificant difference in the variance of the daily speed of buses between weekdays and weekends (see in Table 2); however, the operating hours were 10–15% shorter during weekends. As daily speeds were the same, therefore, the energy consumptions per mile were similar.

Energy usage and related recharging behavior of BEBs were greatly influenced by their activity behavior. 40-ft buses have lower average speeds and correspondingly lower daily operating distances so that their daily energy consumption was in the range of 207.9 ± 33.6 kWh (excluding Bus1-40-ft) compared to 60-ft buses' average energy consumption of 320.8 ± 58.7 kWh. Even though the average charged energy of 207.9 and 320.8 kWh for 40-ft and 60-ft buses, respectively, were different, the average overnight (wired) charging times were almost equal to 2.9 h/day. In this analysis, the impact of passenger load was not considered since detailed passenger onboarding data were not available. This similar charging time is attributable to the type of wired charging each bus type received at the depot; 40-ft buses use a single 60 kW charger while 60-ft buses use a tandem 125 kW charger, which provides almost 2 times faster charging.

Real-world energy consumptions of 40-ft and 60-ft BEBs were higher than standard test results. U. S. Federal Transit Authority conducts tests for the bus models' safety, reliability, performance, fuel economy, and emissions based on a standardized testing procedure (Code of Federal Regulation Part 655 in Title 40), often referred to as "Altoona Testing" [48]. From the Altoona testing, for the make, model, and model years studied in this research, the average energy consumptions were 2.0 kWh/mile and 2.8 kWh/mile for 40-ft and 60-ft buses, respectively [49]. In the other parts of the world, the fleet average was around 2.25 ± 0.2 kWh/mile [42,43]. From the current analysis, the average energy consumptions for 40-ft and 60-ft buses were 2.6 ± 0.3 kWh/mile and 3.6 ± 0.5 kWh/mile, respectively. Altoona Testing uses Central Business District (Manhattan Driving Cycle) Fuel Economy and Arterial (Orange County Bus Cycle) Fuel Economy tests [49]. The average speeds for these tests are 6.8 mph and 12 mph, respectively and they are less than the real-world average speeds observed in this study: 21.0 ± 2.8 mph and 26.9 ± 3.8 mph for 40-ft and 60-ft buses, respectively. These average speeds might have caused some of the average energy consumption per mile discrepancy between Altoona tests and real-world operation. During these Fuel Economy tests, the Air Conditioning (A/C) system is turned off. Therefore, due to these differences in operating and weather conditions, the real-world observations were expected to be higher than Altoona Testing's reported energy consumption for the same bus model. Since AVTA also operated diesel buses at the of the BEB data collection, we instrumented some of them and collected their engine operation data. Based on their fule consumption data, the energy consumption of the 40-ft diesel was 8.9 ± 1.2 kWh/mile that was almost 3.5 times higher energy per mile than BEBs. The difference would be mainly due to high thermal, transmission, and engine losses in the diesel engine and transmission system [50].

3.2. Effect of vehicle speed and battery status of charge (SOC) on energy consumption

The speed of battery electric vehicles might have an impact on their energy consumption [21,30]. The speeds were binned (0.1–65 mph at 5 mph intervals) and the average energy consumption was calculated for each speed bin. Fig. 2(a) and (b) provide the average energy consumption by speed for 40-ft and 60-ft buses, respectively. BEBs traveling in the slowest speed bin of 0.1–5.0 mph consumed the highest energy consumption per mile among all speed bins. That was 11.9 ± 1.7 kWh/mile (40-ft bus) and 19.9 ± 2.58 kWh/mile (60-ft bus). This may be due to the energy spent on auxiliary load rather than propelling the bus while driving a short distance. Even though at low speeds (<20 mph) the electric motor's rpm is low, the torque required to overcome rolling resistance is substantial that may cause higher energy consumption per mile [51,52]. Further, long dwell time (speed less than 3 mph) at scheduled stops might contribute the highest energy consumption rate at the lowest speed bin. At 60–65 mph, the average energy consumptions per mile were 0.87 and 1.07 kWh/mile for 40-ft and 60-ft buses, respectively. This comparatively lower energy consumption per mile at a higher speed can be majorly attributed to the steady driving as well as the inertia of motion. The BEBs operate on arterials (a type of highway), even though they reach a maximum speed of 60 mph while accelerating, they spend less than 1% of the total trip time at that speed.

Table 2
Summary statistics of BEBs of daily activity for weekdays and weekends.

Bus Number	Daily Average Activity					
	Weekday			Weekend		
	Speed (mph)	Distance (miles)	Operation (hours)	Speed (mph)	Distance (miles)	Operation (hours)
Bus1-40ft	29.5 ± 3.0	187.9 ± 37.6	10.8 ± 1.4	31.0 ± 3.2	189.1 ± 37.8	11.4 ± 1.5
Bus2-40ft	19.6 ± 2.4	60.2 ± 8.4	6.4 ± 0.5	21.2 ± 2.6	61.2 ± 8.5	7.1 ± 0.5
Bus3-40ft	15.2 ± 2.2	50.4 ± 8.5	5.9 ± 0.8	16.7 ± 2.4	50.9 ± 8.6	6.4 ± 0.9
Bus4-40ft	19.0 ± 3.8	97.1 ± 17.5	8.1 ± 1.0	20.1 ± 4.0	98.0 ± 17.6	8.9 ± 1.1
Bus5-40ft	18.2 ± 2.1	109.7 ± 12.1	7.1 ± 1.2	18.5 ± 2.1	111.2 ± 12.2	8.1 ± 1.3
Bus1-60ft	29.7 ± 2.4	73.7 ± 5.9	3.7 ± 0.4	30.3 ± 2.4	74.6 ± 6.0	4.4 ± 0.4
Bus2-60ft	19.2 ± 2.8	78.7 ± 6.3	6.1 ± 1.3	20.2 ± 3.0	80.1 ± 6.4	6.7 ± 1.4
Bus3-60ft	22.2 ± 4.7	103.9 ± 10.4	7.2 ± 1.3	23.0 ± 4.9	104.4 ± 10.4	7.5 ± 1.3
Bus4-60ft	39.1 ± 6.2	89.1 ± 14.3	7.1 ± 1.0	39.8 ± 6.3	90.8 ± 14.6	8.0 ± 1.1
Bus5-60ft	22.1 ± 2.7	86.1 ± 18.9	7.1 ± 1.1	22.6 ± 2.7	87.0 ± 19.1	7.4 ± 1.1

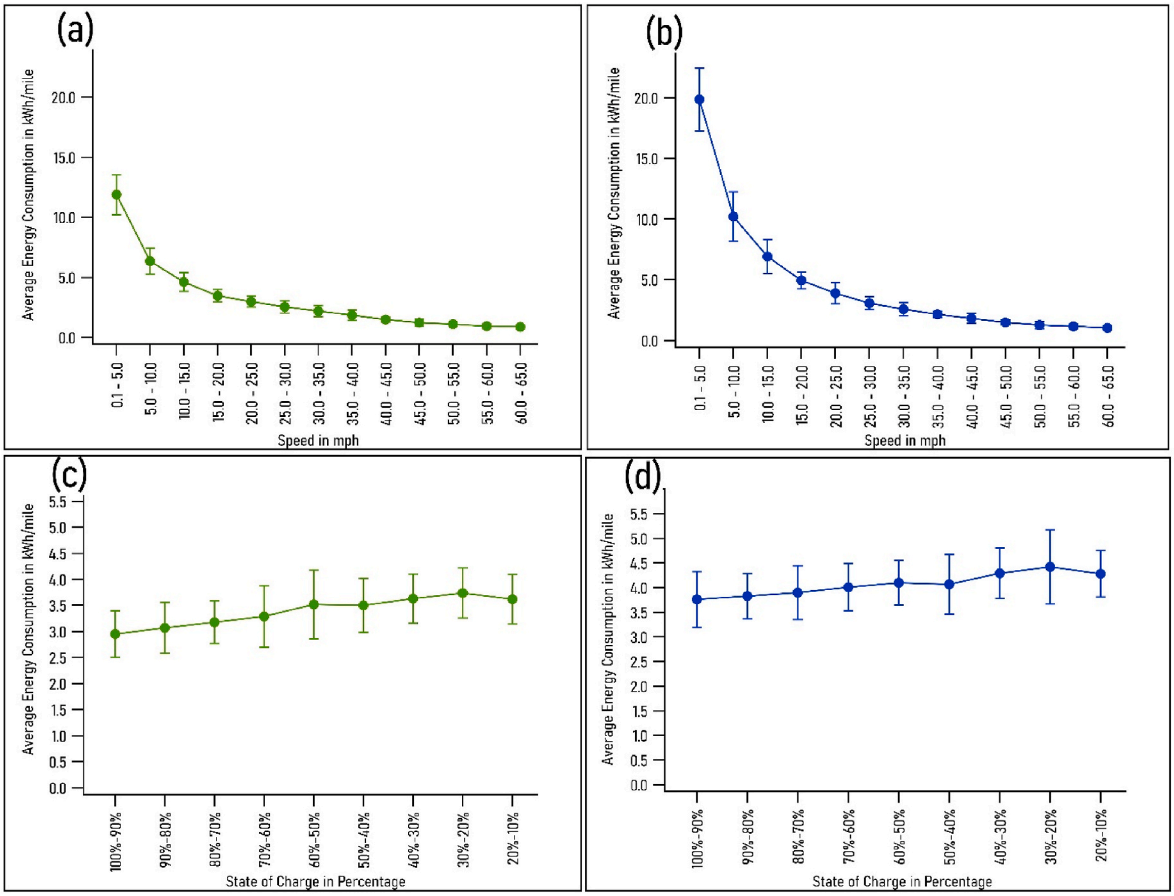

Fig. 2. (a) Average energy consumption in kWh/mile with the standard error by speed for 40-ft buses (b) Average energy consumption in kWh/mile with the standard error by speed for 60-ft buses (c) Average energy consumption in kWh/mile with the standard error by the state of charge (SOC) for 40-ft buses (d) Average energy consumption in kWh/mile with the standard error by the state of charge (SOC) for 60-ft buses.

It was observed that BEBs operating between 30 and 35 mph benefitted from the energy gained from regenerative braking at those speeds. After 35 mph, the energy gained from regenerative braking tapered off. This is due to engaging the frictional/hydraulic brakes at higher speeds to bring the bus to stop quickly as per safety requirements [53,54]. The 60-ft buses may have higher regenerative braking energy recovery (in kWh) at speeds greater than 35 mph compared to the 40-ft buses mainly due to higher motor power; two 150 kW and two 180 kW motors for 40-ft and 60-ft buses, respectively. Another reason for the overall better energy recovery of 60-ft buses may be their higher gross vehicle weight and related higher available kinetic energy; however, it may not be fully converted into electric energy due to motor power limitation. Also, the higher energy consumption rate at lower speed may be attributed to auxiliary energy demand per mile (including A/C and heater uses and mechanical operation of doors, etc.) and not fully optimized regenerative braking at lower speeds, which will be discussed later.

Driving at high speed at 35 mph and above can significantly reduce energy consumption per mile (i.e., less than 1.8 kWh/mile for 40-ft and less than 2.6 kWh/mile for 60-ft buses), but it may not be practical for transit fleets because transit operators always need to follow scheduled timings and to be operated in urban traffic. However, energy consumption can be optimized by improving driving behavior. Driving behavior can be improved with driver education for maintaining constant high speed throughout the trip and minimizing aggressive deceleration at a lower speed than 35 mph to maximize energy recovery during regenerative braking events [53]. AVTA has implemented a driver education program, however, during the data collection period, the program was continuing. Since it was not fully implemented; we did not take the impact of improved driving behavior into the present analysis, which we intend to do in our future work.

Studies have reported that the battery efficiency varies by SOC and in turn that could affect vehicle energy consumption [55]; Hossain, Hannan et al., 2020). We characterized BEB energy consumption by battery SOC and found a general trend of lower energy consumption per mile at high levels of SOC. Fig. 2(c) and (d) present energy consumption per mile by SOC for 40-ft and 60-ft buses, respectively. At the low SOC (20%–30%), the energy consumption was 3.71 and 4.42 kWh/mile, which were 26% and 17% higher than 2.95 and 3.76 kWh/mile at the high SOC (90%–100%) for 40-ft and 60-ft buses, respectively. The discharge voltage of Lithium-Ion batteries gradually reduces when SOC is between 100% and 10% and drastically thereafter [55]. To provide the required energy for the electrical motor, more charge/current must be withdrawn from the battery for the corresponding drop in discharge voltage. This causes continuously increasing energy consumption per mile between the state of charges of 100% and 0% [55]. We observed the energy consumption per mile does not change when SOC is around 50%, which can be attributed to battery recharge, i.e., the slight increase in battery SOC through recharge between trips might have improved the energy consumption per mile since it happens for both types of buses. However, the energy consumption per mile was slightly reduced for SOC of 10%–20% for both types of buses. This discrepancy can be because of driver intervention—from the data, it looks like when SOC drops to less than 20%, drivers tend to increase vehicle speeds thus decreasing energy consumption per mile and those are mostly deadhead miles (i.e., miles traveled not on passenger service). It was observed from the trip data when SOC was less than 20%, the average speed was 30 mph and above, which might have reduced energy consumption per mile during those instances. Based on current data, the 40-ft buses were plugged in for overnight charging with starting SOC of 62.4% on average and the 60-ft buses were at 80.3% of starting SOC until they are 100% charged. The optimal SOC percentage to recharge would greatly influence the overall energy cost of the fleet and affect the optimal operation of transit services.

3.3. Effect of regenerative braking on energy consumption

The low energy consumption values at a higher speed may be partly due to the higher efficiency of the regenerative braking as discussed earlier. Fig. 3 provides the speed-specific motive energy consumption (positive battery current × battery voltage) and regenerative braking energy recovery (negative battery current × battery voltage), each in kWh/mile. The regenerative braking energy recovery for 40-ft BEBs has started from 1.3 kWh/mile (at speed 0.5 mph) to 2.9 kWh/mile (at speed 20 mph) and hardly changes until the driving speed was 35 mph (Fig. 3(a)). For speeds higher than 35 mph, the regenerative braking energy recovery showed a slight decrease compared to previous speeds but plateaued thereafter. The 60-ft BEBs also experience a similar pattern in regenerative braking energy recovery, i.e., 2.6 kWh/mile to 4.5 kWh/mile (Fig. 3(b)). This was similar to other studies that have found the optimum speed for regenerative braking energy recovery efficiency of light-duty vehicles [53,54]. The 60-ft buses may have higher regenerative braking energy recovery compared to the 40-ft buses. As discussed earlier, this may be due to the higher motor power of 60-ft buses, which implies higher recuperated energy for the same speed compared to 40-ft buses. As presented in Fig. 3(a) and (b), average energy recovered per mile were 1.88 and 3.12 kWh/mi for 40-ft and 60-ft buses, which

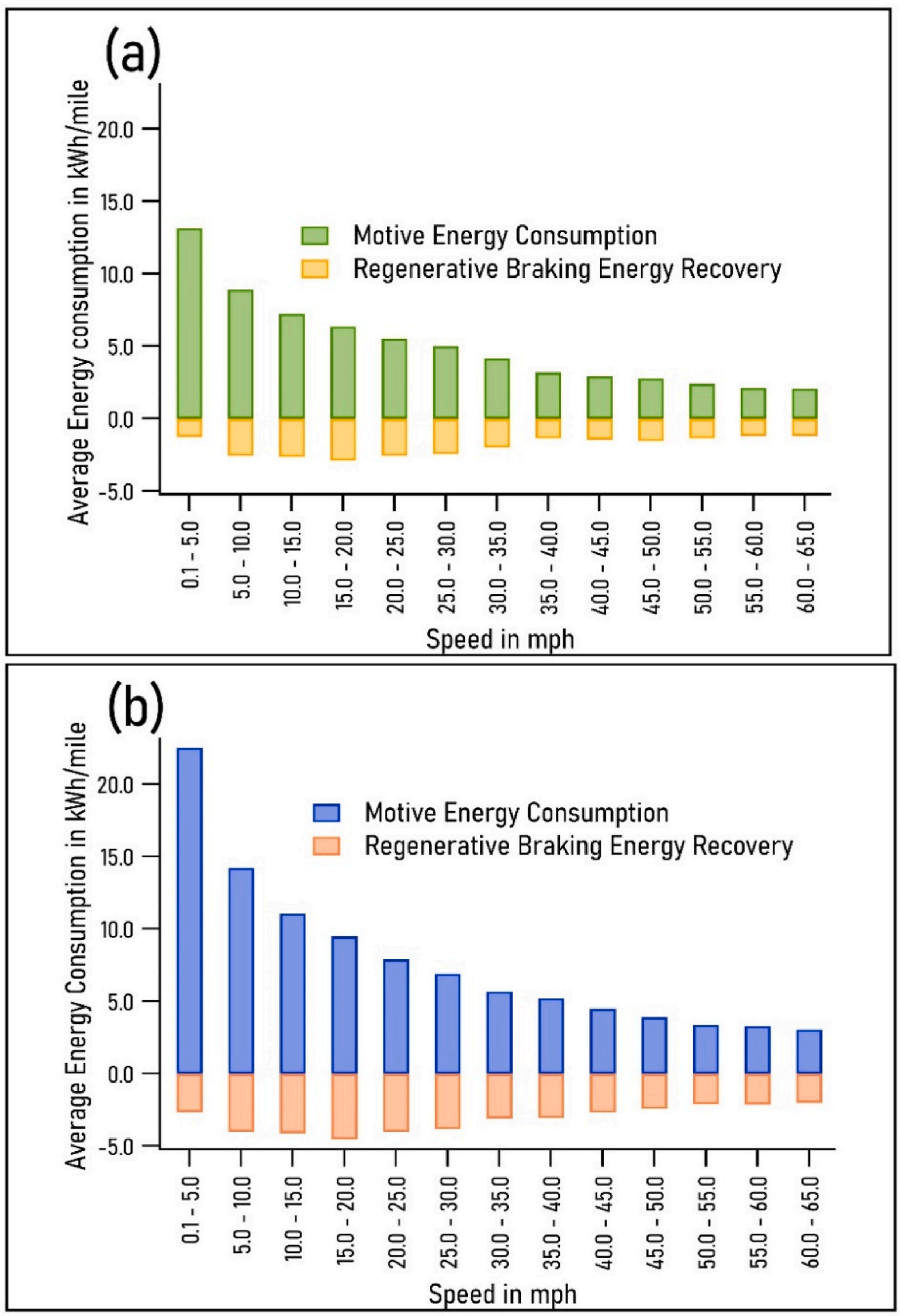

Fig. 3. (a) Speed based average motive energy consumption and regenerative braking energy recovery in kWh/mile for 40-ft buses (b) Speed based average motive energy consumption and regenerative braking energy recovery in kWh/mile for 60-ft buses.

account for 37.1% and 40.2% of average BEB energy consumption per mile, respectively. Based on current literature from electric and hybrid vehicle data, the regenerative braking efficiency of the passenger cars and medium-duty trucks are 18–50% and 20–45%, respectively [54,56].

3.4. Time of day and seasonal variability in energy consumption

In optimizing BEB operations and their charging frequency during a typical day, understanding intra-day variation in energy consumption would be important. We characterized the time of day (TOD) energy consumption and compared the variability winter and summer. Four different time periods were defined in a typical day: AM (6 a.m.–9 AM), MID (9 a.m.-3 PM), PM (3 p.m.–6 PM), and NT (6 p.m.–10 p.m. and 4 a.m.–6 AM). AM and PM time periods were considered as peak commute hours and MID and NT time periods were considered as non-peak hours based on traffic congestion. This time of day classification was often used for travel demand modeling to characterize traffic congestion (Mario 2016). Fig. 4(a) and (b) present the comparison of energy consumption of four different time periods for 40-ft and 60-ft buses during a typical winter day, respectively. For 40-ft BEBs, the energy consumptions for AM and NT time periods were similar i.e., 2.7 ± 0.4 kWh/mile and 2.8 ± 0.4 kWh/mile respectively. Average speed is a surrogate for

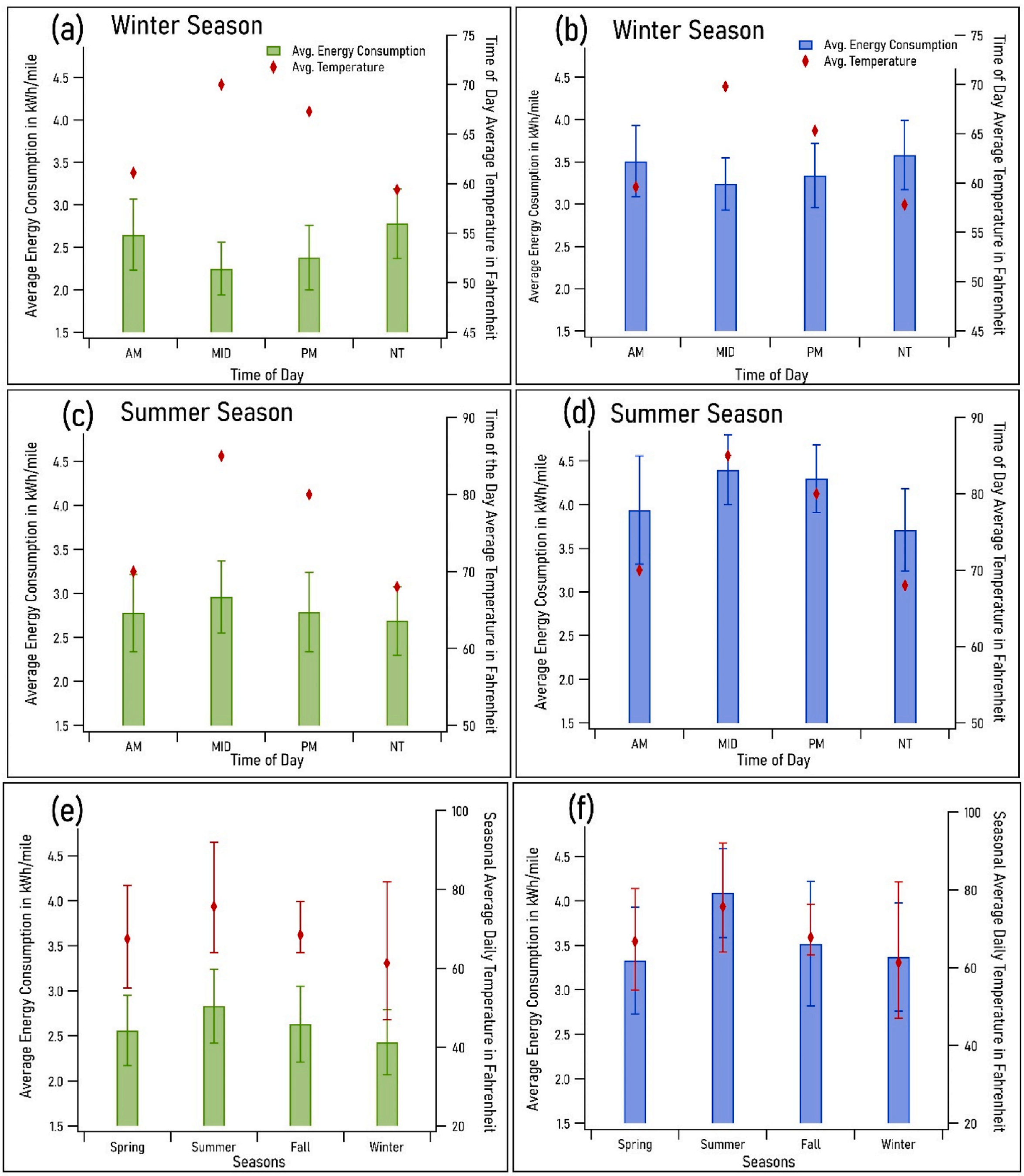

Fig. 4. (a) Time of day average energy consumption per mile for 40-ft buses in kWh/mile with the standard error during a typical winter day. (b) Time of day average energy consumption per mile for 60-ft buses in kWh/mile with the standard error during a typical winter day. (c) Time of day average energy consumption per mile for 40-ft buses in kWh/mile with the standard error during a typical summer day. (d) Time of day average energy consumption per mile for 60-ft buses in kWh/mile with the standard error during a typical summer day. (e) Seasonal average energy consumption in kWh/mile with standard errors for 40-ft buses. (f) Seasonal average energy consumption in kWh/mile with standard errors for 60-ft buses.

traffic congestion and the TOD-based energy consumption provides an insight into the impact of traffic congestion on energy consumption. For the analysis period, the average speeds of AM, MID, PM, and NT time periods are 19.7 mph, 22.1 mph, 20.1 mph, and 23.0 mph, respectively. Based on average speeds, the traffic conditions hardly change during a typical day on routes where 40-ft BEBs were deployed. Therefore, the TOD average energy consumption was not impacted by the traffic conditions. On the routes where 60-ft buses were deployed, the average speeds for AM, MID, PM, and NT time periods were 25.7 mph, 27.7 mph, 26.1 mph, and 28.2 mph, respectively. For these 60-ft bus routes, the TOD specific average speeds did not vary significantly among time periods, however, they were overall higher compared to the 40-ft bus routes because they were operated on major arterials. The TOD-specific average energy consumption of different time periods for 60-ft buses varies between 3.2 $\pm$ 0.3 kWh/mile and 3.6 $\pm$ 0.4 kWh/mile. Since vehicle speeds did not vary significantly among time periods, we could expect that the level of traffic congestion would not significantly influence the intra-day energy consumption of BEBs in this study. Rather, the temperature change of a day could be a predominant factor that explains the variability in energy consumption during different time periods in a typical day because of the use of A/C or heaters. Again, as discussed earlier, the temperature changes, related to A/C and heater use might cause the difference between real-world and testing conditions. Fig. 4(a) and (b) provide the average TOD energy consumption per mile against the average TOD temperatures in Fahrenheit for 40-ft and 60-ft BEBs. Based on the ambient temperature, drivers adjust the BEB cabin temperature, which exerts a load on the A/C or heater. When the temperature ranged from 58.1 °F to 60.3 °F during AM and NT time periods, the energy consumption tends to be higher than PM and MID time periods with the temperature of 65.1 °F–70.2 °F range. It is expected that the BEB operation during the lower temperatures led to the use of heaters, which would result in higher energy consumption as heaters consume more energy than A/C. Slightly warmer ambient temperature (above 66 °F) might have reduced heater load on overall energy consumption causing 18% and 10% less energy consumption for 40-ft buses and 60-ft buses, respectively. Fig. 4(c) and (d) present the TOD energy consumption per mile during a typical summer day and they were plotted against the average TOD temperatures in Fahrenheit for 40-ft and 60-ft BEBs, respectively. When the temperature was 80.4 °F–85.2 °F during MID and PM time periods, the energy consumption tends to be higher than AM and NT time periods with a temperature range of 68.1 °F–70.2 °F. As discussed above when the ambient temperature rises, to make the cabin cooler the drivers might have adjusted the A/C target temperature, which adds additional load on the battery. Since the average temperature for AM and NT time periods is above 66 °F, the heater load is not as significant as the A/C load. The differences between daytime (PM and MID) energy consumption/mile and rest of the day (AM and NT) energy consumption/mile were 9% and 13% for 40-ft buses and 60-ft buses, respectively.

To establish the effect of ambient temperature on overall BEB energy consumption, a seasonal analysis was conducted. Fig. 4(e) and (f) show seasonal variability in average energy consumption for 40-ft and 60-ft buses, respectively. Seasonal average daily temperatures in Fahrenheit were also presented in the same plots. For reference, the averages of minimum and maximum temperatures of seasons were also used in the plots. On average, 40-ft buses consume 2.6 $\pm$ 0.4 kWh/mile in spring, 2.8 $\pm$ 0.4 kWh/mile in summer, 2.6 $\pm$ 0.4 in fall, and 2.4 $\pm$ 0.4 kWh/mile in winter. The 60-ft buses consume 3.3 $\pm$ 0.6 kWh/mile during spring, 4.1 $\pm$ 0.7 kWh/mile during summer, 3.5 $\pm$ 0.6 kWh/mile during fall, 3.4 $\pm$ 0.6 kWh/mile during winter. The reason for the increase in energy consumption per mile between spring and summer can be attributed to the corresponding average daily temperature increase i.e., 67.5 °F–76.2 °F. When the average daily temperature decreased from 76.2 °F to 68.1 °F, between summer and fall, the average energy consumptions decreased 8% for 40-ft buses and 15% for 60-ft buses. A decrease in average energy consumption between fall and winter was observed for both bus types when average daily temperatures changed from 68.1 °F to 61.3 °F. This decrease was not expected because we hypothesized an increase in energy consumption at a lower temperature due to additional energy demand for cabin heating. It is unknown that if the buses used heaters at cold ambient temperature. The heater use was not available from the VCU data. Based on a general discussion with fleet managers and drivers who were undergoing an education program at the time of data collection, we speculate that the heaters were not used throughout the day in the winter but would have been used during AM and NT time periods. We also speculate that the frequency of heater use varies widely depending on days and drivers. These can be partly explained with wider ranges of the standard error of energy consumption in winter than in the other seasons.

3.5. Charging behavior analysis of BEBs

Fig. 5(a) and (b) show the battery charging frequencies of 40-ft and 60-ft buses, respectively, by TOD. The 40-ft buses with a smaller battery capacity (i.e., 324 kWh) are charged more frequently (0.8 $\pm$ 0.1 times/day) via a wired charging station during the late evening 6 p.m.-10 p.m. The charging frequency was calculated as the total number of charging occurrences during the data collection period are divided by the number of data collection days. The frequency/day is further divided into four time periods (i.e., AM, PM, MID, and NT) based on the time when battery charging started. However, the 60-ft buses are charged from wired charging stations equally during mid-day (9 a.m.- 3 p.m.) and late evening (6 p.m.–10 p.m.). Using the path-matching data, we found that the 60-ft buses were getting the wired charging from the depot, where a sufficient number of charging stations were available during the day. The same 60-ft buses, usually, were getting inductive charging frequently during mid-day (1.2 $\pm$ 0.1 times/day) and late evening (0.9 $\pm$ 0.1 times/day). Based on the current operating schedule of 60-ft buses, there were enough time gaps (also referred to as headway) for charging between consecutive trips. The 40-ft buses get wired charging frequently (0.25 $\pm$ 0.0 to 0.66 $\pm$ 0.1 times/day) at *en route* transit terminals, where buses were temporarily parked. Overall, the frequency of inductive charging of 40-ft buses (1.5 $\pm$ 0.2 times/day) was higher than 60-ft buses (1.2 $\pm$ 0.1 times/day). We observed lower charging frequencies for both wired and inductive (i.e., 0.0–0.25 times/day) charging of both types of BEBs during the PM period, which would have been resulted in increased bus volumes to meet high commuter demand. Thus, they had charged in-service buses more frequently during late evening hours (6 p.m.–10 p.m.) and late mid-day (1 p.m.–3 p.m.). Even though the late-night charging costs were cheaper, the recharging could have been spread throughout the day to optimize usage of charging points at different charging locations to optimize the operational efficiency [16,29], to reduce overall fleet-level energy costs by maintaining a high level of SOC [21,41], and to increase battery life by charging at mid- or high-level SOC [29,30].

Fig. 5(c) and (d) show charging durations for 40-ft and 60-ft buses, respectively. For inductive charging, 60-ft buses were charged longer (35.9 $\pm$ 2.5 min/day) than 40-ft buses (11.0 $\pm$ 1.0 min/day). For wired charging, 60-ft buses were charged longer (78.6 min/day) than 40-ft buses (35.7 min/day). The significant difference in the average daily charging times between two buses is mainly attributed to the routes they are deployed and their respective schedules. Charging durations for both bus types also varied by time of the day. During MID and NT periods charging durations were 2–10 times shorter than busy commute periods, AM and PM. As described earlier, the differences in charging durations were attributed to the increase of in-serve bus volume to meet the peak hour commute demands. It was evident that the average TOD charging durations were directly correlated with the charging frequency for both types of buses. During the time of this study, AVTA was still in the process of developing additional charging infrastructure at *en route* transit hubs. After the construction of these new charging infrastructure facilities, it is anticipated that the buses might improve the charging

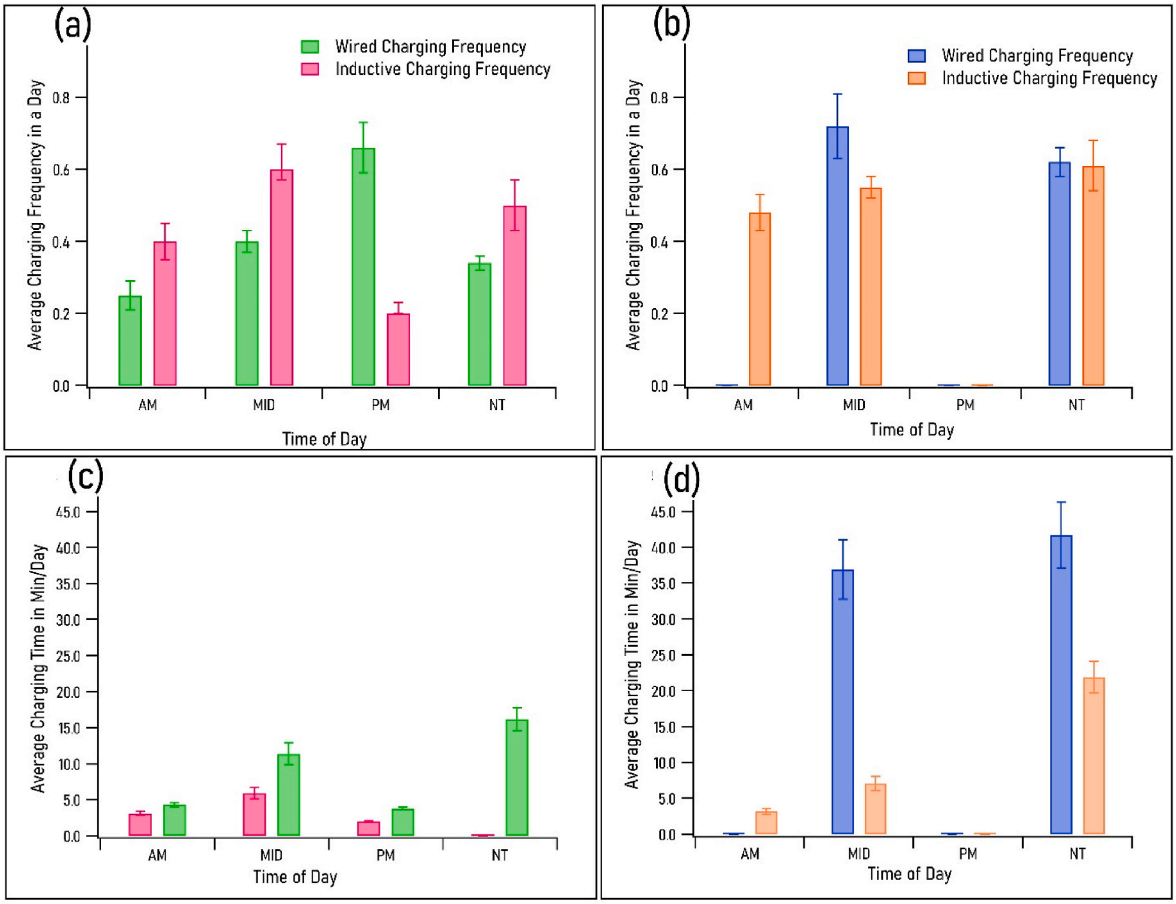

Fig. 5. (a) Time of day average charging frequency for 40-ft buses in times/day with the standard error during the data collection period. (b) Time of day average charging frequency for 60-ft buses in times/day with the standard error during the data collection period. (c) Time of day average charging time for 40-ft buses in minutes in a day with the standard error during the data collection period. (d) Time of day average charging time for 60-ft buses in minutes in a day with the standard error during the data collection period.

frequencies and charging times for both types of buses.

4. Conclusions and implications of research findings

This study examined the transit bus energy consumption and charging behavior using battery-electric bus data collected over 14 months. Compared to other studies, we have collected more data samples for the maximum possible number of trips during data collection period and those covers more routes (using two types of BEBs i.e. 40-ft and 60-ft) during all seasons in a typical year [42–44]. On average, the 40-ft buses run with a daily average speed of 21.0 ± 2.8 mph compared to 26.9 ± 3.8 mph of 60-ft buses. The average energy consumptions for 40-ft and 60-ft buses were 2.6 ± 0.3 kWh/mile and 3.6 ± 0.5 kWh/mile, respectively, over the year. In the same fleet, the 40-ft diesel and diesel-hybrid buses consume 8.9 ± 1.2 kWh/mile and 9.5 ± 1.4 kWh/mile, respectively, during the same data collection period. The conventional technology buses consume almost 3.5 times higher energy per mile than BEBs and the differences are mainly due to high thermal, transmission, and engine losses in the former type of buses. Both 40-ft and 60-ft BEBs consume less energy when they ran at high speed, greater than 35 mph. The energy consumption for the lowest speed, less than 5 mph was the highest for both 40-ft and 60-ft buses, 11.9 ± 1.7 and 19.9 ± 2.6 kWh/mile, respectively.

This may be due to continuous auxiliary power demand and lower braking energy recovery while the buses were moving short distances at creeping lower speeds. This combined effect causes higher energy consumption per mile at low speed. Since 37.1%–40.2% of total BEB energy consumed were from regenerative braking, maximizing energy recovery from regenerative braking events will reduce the energy consumption significantly by maintaining relatively high speed and avoiding hard deceleration that can be imparted to drivers through training programs. It was observed that the battery SOC affects energy consumption. The energy consumption gradually increases with SOC of 100% down to 20%. Therefore, transit operators must plan their BEB recharging schedules within this range of SOC without affecting the operating schedules. In addition to prioritizing driver education for energy savings, transit operators should also focus on optimizing the BEB operations through a real-time scheduling system. The variability of seasonal and intra-day energy consumption per mile can be attributed to the increased use of air conditioners (A/C) and heaters, which were adjusted based on the ambient temperatures.

Since BEB energy consumption changes daily and seasonally, it might have repercussions on the overall fleet's energy costs and operations. We have conducted an aggregate BEB operational cost analysis to demonstrate the use of findings from current study. The latest local energy tariff data for large industrial/commercial entities indicates the off-peak (9 p.m.–4 p.m.) Summer energy rates ($0.16/kWh) are a bit expensive compared to winter rates ($0.15/kWh) during same periods. The on-peak (4 p.m.–9 p.m.) rates are also similar for Summer and Winter seasons i.e. $0.23/kWh and $0.22/kWh respectively ("SCE-EV Rates," 2021). Assuming the same average daily operational mileage among seasons, on average the Summer operation may cost $0.05 ± 0.01/mile than the Winter operation. However, these extra cost of operation can be offset through frequent WAVE charging between trips as higher SOC can improve up to 15% (based on battery size or bus type). Further, as on-peak energy rates are 30% expensive the wired (depot) charging can be totally avoided through improved optimization or even constructing/utilizing a new WAVE charging location. More energy cost reductions during Summer season can be achieved through training the drivers with the improved bus operational techniques such as reducing auxiliary load and better brake operation during trips. Overall, based on the results from this study, the transit agency can incur $16.2 \pm 2.1\%$ (based on current fleet composition of 40-ft and 60-ft buses) more energy costs in Summer compared to Winter for this study area. Despite these cost analysis may not be completely relevant for other cities because the terrain, climatic, congestion conditions, and energy tariffs can be different, the potential aggregated energy costs/savings can be estimated using our findings.

This could be a factor for transit operators in their operational planning for different operation hours of a day and seasons. While in service, 40-ft buses were charged more frequently may be due to their longer operation hours than 60-ft buses. Even though the late-night charging costs were cheaper, to optimize the operations and overall fleet-level energy costs, the recharging can be spread out throughout the day to optimize the usage of charging points at different charging locations. Importantly, some of the findings from this study can be used while quantifying the benefits from BEBs as part of CARB's Low Carbon Transportation (LCT) investments and California Climate Investments (CCI) programs.

Even though the operational and charging characteristics of BEBs were extensively studied in this work, there are few limitations that are contextual. As described in methods and materials section, the terrain of the study area is flat and that restricts to collect data required to understand the impact of grade on average energy consumption. The study area is located in a smaller city (less busier compared to other major cities in California), therefore, the routes are less congested. In few data samples, we observed divergent average energy consumption values whenever the speed falls (that means congested)below daily averages, therefore, the estimates in this study cannot be applied when calculating energy costs for busy routes in larger cities. Finally, the climatic conditions in our study area are much different than rest of the California and United States. In other colder parts of World/USA, the average energy consumption per unit distance in Winter might be much different than the estimates made in this study because increased use of heater.

CRediT author statement

Harikishan Perugu: Conceptualization, Methodology, Data Collection, Validation, Data Curation, Writing-Original Draft, Writing-Review &Editing, Visualization **Sonya Collier**: Data Collection, Writing-Review &Editing. **Yi Tan**: Data Collection, Writing-Review &Editing. **Seungju Yoon**: Conceptualization, Methodology, Supervision, Writing-Review &Editing. **Jorn Herner**: Supervision, Writing-Review &Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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