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Comparison Analysis of Charging System Designs for Battery Electric Bus

FINAL REPORT

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Submitted by:

Hao Wang, PhD
Professor

Laura Soares
Graduate Research Assistant

Department of Civil and Environmental Engineering,
Rutgers, The State University of New Jersey
Piscataway, NJ 08854

External Project Manager

Warren J. Berry, New Jersey Transit

In cooperation with

Rutgers, The State University of New Jersey
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16. Abstract

Battery electric buses (BEBs) face the challenge of having a shorter range compared to diesel-powered buses. This research aims to compare different charging system designs of BEBs considering economic and environmental impacts. Case study was conducted for the potential BEB fleet based on Wayne Garage of NJ Transit having long and interstate routes. First, this study modeled power consumption for BEB trips using field operation data collected in Camden, NJ. The model was then applied to GTFS schedule data to simulate and estimate power consumption of BEB. The charging system to maintain transit service level in a hypothetical worst-case scenario was designed for four scenarios: 1) increasing fleet size, 2) opportunity charging with fast plug-in charger, 3) opportunity charging with Inductive Power Transfer (IPT), and 4) opportunity charging with pantograph charger. Life Cycle Cost Analysis (LCCA) was performed to calculate the initial investment and cumulative net present value for each scenario. Then, Life Cycle Assessment (LCA) was performed to evaluate cumulative energy demand and global warming impacts. The overall results show that the fast plug-in opportunity charging is the most cost-effective and environment friendly solution.

17. Key Words Charging system; Opportunity charging; Life cycle cost analysis; Life cycle assessment	18. Distribution Statement		
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Table of Contents

INTRODUCTION

In New Jersey, the state legislature passed the Global Warming Response Act (GWRA), in which the Department of Environmental Protection (DEP), in collaboration with other state agencies, is responsible for presenting recommendations to reduce emissions by 80% from 2006 levels by 2050 (Barr et al. 2020). The act plans to achieve 100% clean energy by (1) replacing internal combustion vehicles with electric vehicles, (2) using electricity as the source for space and water heaters in residential and commercial buildings, and (3) replacing fossil fuels in the electricity generation sector with renewable energy sources. NJ Transit, the public transportation agency of New Jersey, is transitioning to zero emission buses (ZEB) to support the state's emission goals. By 2032, 100% of purchased buses by NJ Transit must be zero-emission (NJ Transit 2020).

Several state agencies are implementing battery electric buses (BEBs) to comply their fleet with emission reduction plans. However, the migration of diesel-fueled buses to BEBs can be challenging since the electric vehicle has a lower range, and additional costs may be required overcoming this barrier. The transportation agency's choice of charging strategy for BEBs is crucial for designing a cost-effective and efficient operation. In general, BEBs charging operation follows two approaches: overnight charging and/or opportunity charging. The different charging methods have different costs and impacts the bus charging patterns. In the case of opportunity charging, where BEBs are charged during the day, high power is necessary due to the limited available charging time, whereas BEBs charged at night can take advantage of lower power rates. Conversely, charging the entire BEB fleet at night would lead to a significant cumulative power demand and induce demand charge. It is needed to determine the charger types and charging strategies to reduce the charging system cost.

LCCA serves as an effective decision-making tool for evaluating different BEB charging options, analyzing the tradeoffs between lower initial investments and long-term savings, identifying the most cost-effective system, and determining the payback time for the system (Soares and Wang 2021). Lajunen (2018) conducted life-cycle cost analysis for fleet operation of electric city buses considering overnight, end station, and opportunity charging. The results indicated that the end of station charging has a lower cost than the other charging options. The study developed a comprehensive simulation tool to evaluate bus energy consumption in different conditions. The bus energy consumption was simulated using a simplified model of the electric bus powertrain and no field data was used for the development or verification of the model. Wang et al. (2023) develop a collaborative optimization model for the life-cycle cost of BEB system, considering both overnight and opportunity charging methods. Opportunity charging presented a higher life-cycle cost than that for overnight charging. However, it considered only conductive charger for opportunity charging. On the other hand, inductive charging can be a good option for opportunity charging for BEB since it does not require the driver to leave the bus and manipulate the device, increasing safety, and saving time. Bi et al. (2017) performed life-cycle assessment and life-cycle cost analysis to compare the life cycle performance of plug-in charging versus wireless charging for an electric bus system. The results show that although wireless charging has the highest infrastructure cost, it has the lowest cost per bus-kilometer among plug-in charging, diesel, and hybrid bus systems. Nonetheless, the cost of wireless charger considered in the analysis significantly deviates from real-world commercial values.

Initiatives and polices to migrate public transit buses to BEBs seek to mitigate environmental impacts. The fundamental principle of ZEBs is to eliminate tailpipe emissions; however, to fully understand the environmental impact reduction, life-cycle assessment (LCA) need be performed. Ellingsen et al. (2022) performed a cradle-to-grave life cycle assessment of a hypothetical case study consisting of seven BEBs with differing battery technologies, battery sizes, and charging solutions. These included wireless opportunity charging, pantograph charging at end-stations, and plug-in charging at the depot overnight. The study is comprehensive and includes various charging solutions for BEB; however, it compares these scenarios without conducting an initial analysis of real-world public transit operations. Such an analysis could provide realistic numbers for the required number of chargers and BEBs for each solution. Munoz et al. (2019) conducted LCA to evaluate environmental and economic impacts of deploying alternative urban bus powertrain technologies in the south coast air basin The analysis for BEB considers two scenarios: short-ranged buses with wireless opportunity charging and long-ranged buses charged once a day with plug-in chargers. The study is very valuable since it uses the real-world requirements for the analysis. Nevertheless, it would be interesting to see the results for other charging solutions such as pantograph and opportunity charging using plug-in chargers.

In response to the research gaps, this study attempts to advance BEBs charging strategies cost and environmental analysis by using the real-world data. Since BEBs have lower driving range than that for diesel-fueled buses, adapting these new buses can be challenging. The solutions of increasing BEB fleet size and opportunity charging are analyzed and compared in a comprehensive way.

OBJECTIVE AND SCOPE

This research aims to compare different charging system designs of BEBs considering economic and environmental impacts. Case study was conducted for the potential BEB fleet based on Wayne Garage of NJ Transit having long and interstate routes. Four scenarios are analyzed to overcome the BEBs short range while maintaining the agency's service level objective (SLO) adding more BEBs to the fleet, installing fast plug-in chargers, installing IPT chargers, and installing pantograph chargers. Life Cycle Cost Analysis (LCCA) was performed to calculate the initial investment and cumulative net present value for each scenario. Life Cycle Assessment (LCA) was performed to evaluate cumulative energy demand and global warming impacts. Figure 1 illustrates the flowchart of analysis methodology.

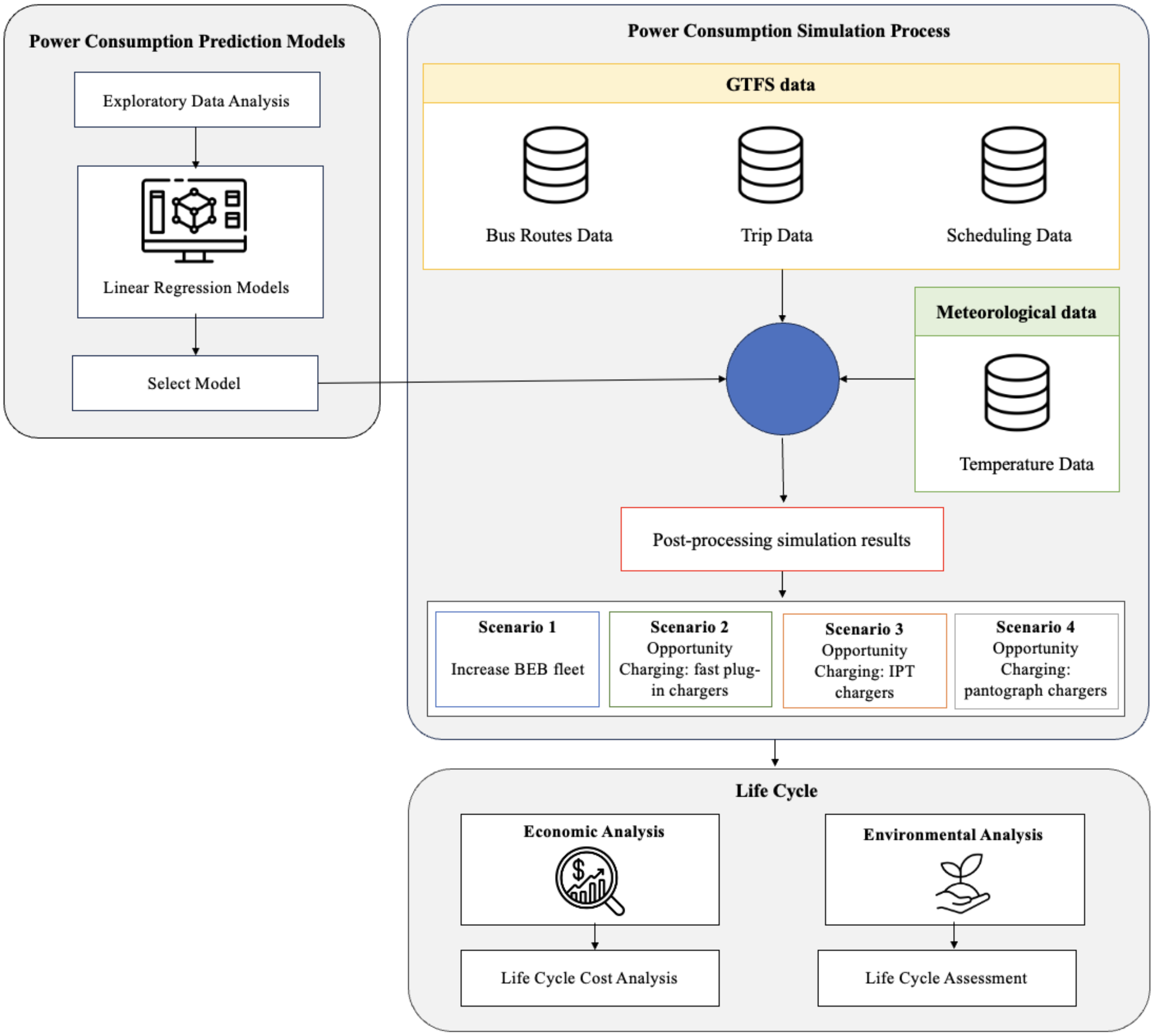


Figure 1 Methodology Flowchart

BEB POWER CONSUMPTION MODEL

Exploratory Data Analysis and Data Transformation

NJ Transit deployed three New Flyer BEBs in Camden in 2022 for a pilot project, and the buses are equipped with Connect 360. The in-vehicle sensors reported the following data from November 2022 to August 2023: energy consumption (kWh/mile), power consumption (kW), ambient temperature (F), and average speed (mph). This research assumes that BEBs similar to these in the pilot project would be used to replace the fleet of the Wayne Garage operation. Consequently, it is necessary to understand the factors influencing the energy consumption of BEBs and develop a predictive model.

Before creating a predictive model, it is instructive to understand the nature of the underlying data. Figure 2 shows the density plots of energy consumption and power consumption for BEBs along with ambient temperature and speed. Both appear to follow a log-normal distribution, as evidenced by the density plots of their natural-log transforms. It also shows scatterplots of the relationship between the covariate candidates (ambient temperature and average speed), energy consumptions, and the log-transformations of the consumptions.

While the transformation yielded excellent results for power consumption, demonstrating a satisfactory approximation of the normal distribution, a slight left skewness persists in the case of energy consumption. The scatterplot graphs show that as the temperature increases from its lowest observation to around 70 ℉, there is a downward trend in power and energy consumption; however, after this the consumptions begins to increase again. It appears there is a parabolic relationship between temperature and the dependent variables, and therefore a squared transformation is considered in the regression models. Furthermore, there is a noticeable positive, linear trend in power consumption with respect to the average speed. The relationship between average speed and energy consumption is less clear, with the scatterplot indicating that perhaps a log-log relationship is most suitable.

Regression Models

Based on the observations from the exploratory data analysis, several statistical models were developed and evaluated. The linear regression models examined various explicit linear relationships between the dependent variables (power consumption and energy consumption) and the covariates (temperature and speed), thereby allowing the assessment of specific hypotheses concerning the relationships between the variables. To choose amongst these models, this paper chose the adjusted-R2 as the selection criterion, since it represents the percentage of variance in the dependent variable explained by the regression while also penalizing complexity.

Different regression models were considered, including each individual dependent variable and their natural logarithm. The final model yielded the highest R^2 of any regression model while still satisfying the assumption requirements for linear regression. The estimated equation is shown in Equation (1). This model suggests that, on average, the power consumption will decrease parabolically as temperature increases towards 75 ℉, at which point the power consumption will begin increasing quadratically. For speed, an increase of 1 mph in the average speed of a bus during a trip increases the power consumption by 1.16 kW, on average.

$$\widehat{Power\ Consumption} = 54.1 - 1.5 * T + 0.01 * T^2 + 1.16 * v \quad (1)$$

Where, T is ambient temperature, and v is speed.

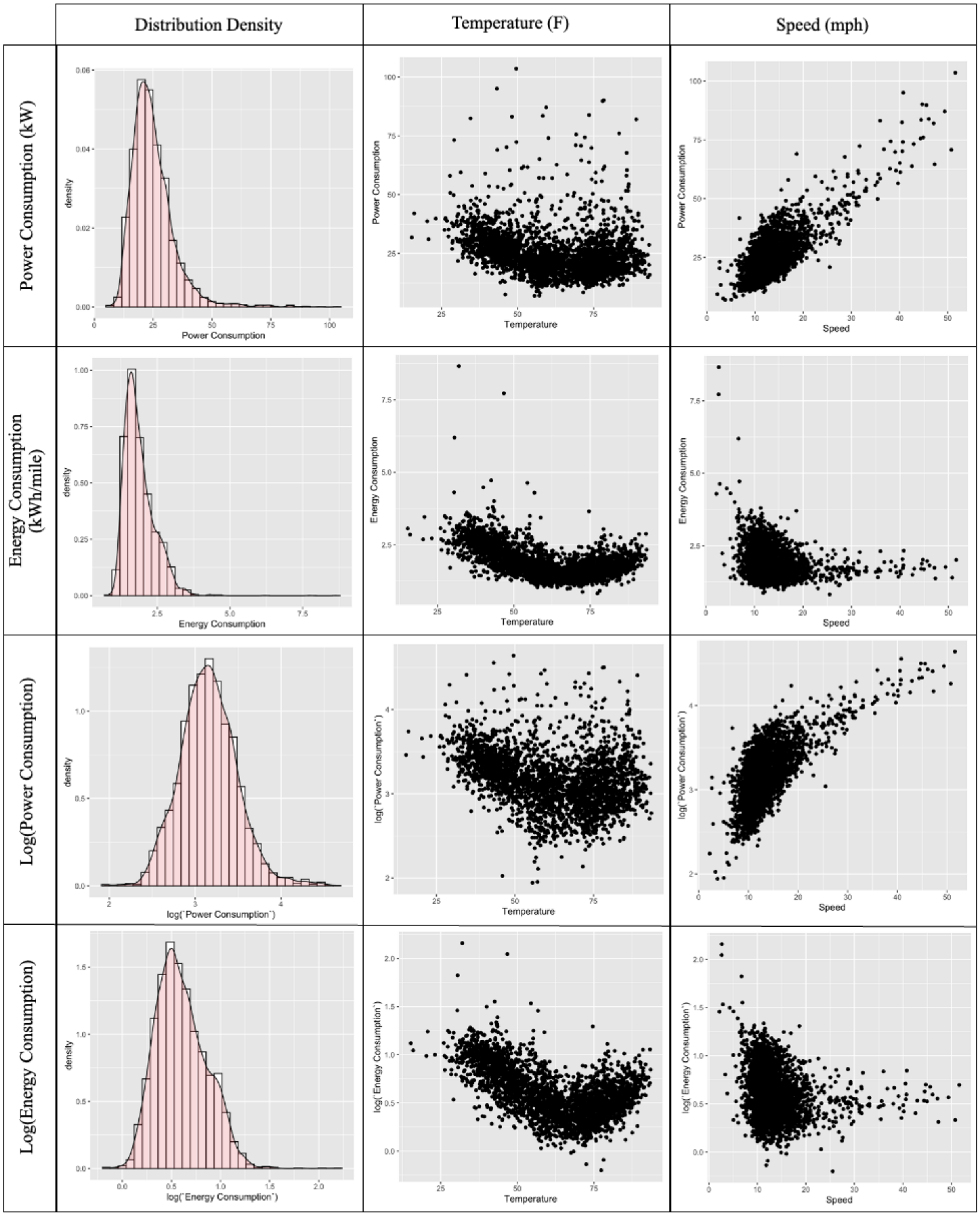


Figure 2 Dependent variables distribution, their transformation and relationship with the covariant

BEB CHARGING SYSTEM DESIGN

Analysis of GTFS Data

Case study was conducted for the NJ Transit Wayne Garage using Global Transit Feed Specification (GTFS) Open Standard schedule data from NJ Transit. A GTFS feed contains static transit information in text files provided by a transit organization. The files from the GTFS Feed describe the following aspects of transit information: routes, trips, stops, blocks, and service days. The most basic of these aspects is a stop, which identifies a location such as a bus stop, station, boarding area, or generic node in the transit graph. A sequence of two or more stops that occur at a specific time is a trip, a group of which defines a route when displayed to riders as a single service. A similar concept is that of a block, which consists of a single trip, or many sequential trips made using the same vehicle, defined by shared service days and a block ID. A service day identifies a set of dates when service is available for one or more routes. A service block is the combination of a service day and a block. The NJ transit GTFS schedule data used in this study was obtained from Open Mobility Data.

It is noted that the GTFS data does not include the distance and time each bus must travel from Wayne Garage to reach its first stop, nor the distance and time required to travel from its last stop back to Wayne Garage. This distance is known as "deadhead". Consequently, the distance and time were obtained using the Google Maps Distance Matrix API. This API allows the user to obtain estimated distances and times from a set of destinations and origins, represented by latitude and longitude pairs, for a specific date and time. It is assumed that Google Map's algorithm uses intra-day and weekly seasonality as well as known local traffic conditions to forecast transit times. For each deadhead trip to and from Wayne Garage, and for each calendar day and each service ID associated with each trip, the distance and time were queried from the API using Python's google maps package. The average speed was obtained by first multiplying the time by a factor of 1.5, assuming that transit buses are on average 2/3 as fast as personal vehicles, for which the estimate from Google is created. This speed is then combined with the values for temperature in the simulation to produce deadhead predictions for power and energy consumption.

The Wayne Garage can accommodate 200 buses, including 150 inside and 50 outside. Currently the garage operates 10% over capacity. The buses based out of the garage are assigned to complete long routes, with several traveling to and from Manhattan. BEBs generally have a lower range than diesel-fueled buses, therefore one solution to guarantee the routes' completion, while maintaining same SLO, is to increase the fleet size. However, this solution is costly and, in the scenario like Wayne Garage, could be spatially challenging. Figure 3 shows the routes assigned to the buses based out of Wayne Garage.

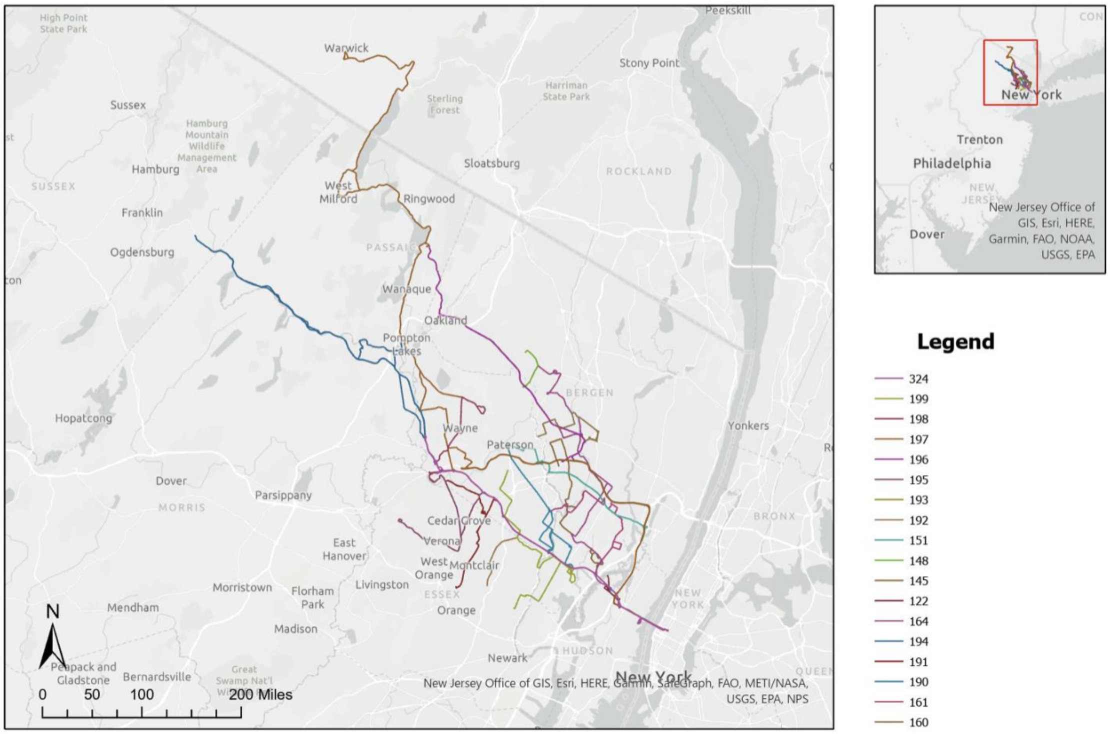


Figure 3 Bus routes based on Wayne Garage

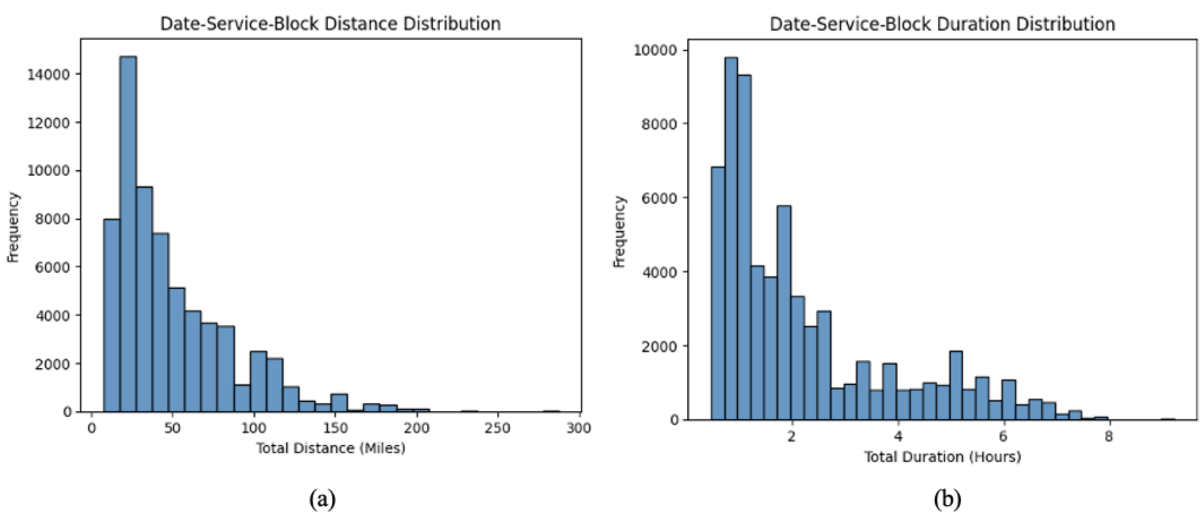


Figure 4 Frequency distribution of date-service block by (a) distance, and (b) duration

Figure 4 presents the date-service-block frequency distribution by (a) distance, and (b) duration. The data is presented in date-service-block to consider all individual blocks, per day, and per service. The same block can be operated on the same day but with different services, which means that the service-blocks can have slightly different trips. The route distances range from 7 to 59 miles, and the average route duration ranges from 29 minutes to 1 hour and 35 minutes. This study analyzed the 2,265 trips across the 358 blocks and 7 service days associated with Wayne

Garage. The total distances for the service blocks range from 7 to 283 miles. Port Authority NY &NJ is the scheduled destination for 1,153 of these trips.

Analysis of Blocks with Battery Limitation

The energy consumption (kWh) for the trips associated with the service blocks based out of Wayne Garage is predicted considering the variations in bus speed and ambient temperature. Since the GTFS data is a schedule, there are no observed values of temperature and speed for individual trips.

There is effectively a planned speed, which can be calculated from the obtained dataset using the distance traveled (miles) divided by the trip duration, which is calculated from the arrival time, and departure time data. This process can be applied to the entire dataset to obtain average speed for each trip, which can then be linked with the corresponding block, service, and route IDs. Furthermore, the final stop ID for each trip can be appended in the same manner, from which can be determined the trip destination. To allow for sufficient variation in the covariate distribution, variance was added to the average speed. Commute speeds of public transportation tend to follow a normal distribution (Gao et al. 2019); therefore, an average speed distribution was created by fitting a normal distribution with the parameters N (average speed, σ^2) for each trip. The average speed is based on the schedule obtained from the GTFS data, while the σ^2 is the assumed variance for average speed obtained from the New Flyer BEBs in Camden data. Each trip was then assigned 50 average speed samples from its associated distribution.

One trip has one associated service day, yet the number of unique dates for a given service day ranges anywhere from 1-129 dates. Accordingly, for the purposes of simulating the predicted consumption distribution, a wide range of temperatures was considered. The air temperatures were bootstrap sampled from the dataset of OpenWeather containing the hourly temperature for each day from 1979 to 2023 in Wayne, NJ. Bootstrap sampling is a method which can be used to estimate a population distribution, by drawing samples repeatedly, with replacement, from the sample data. Each trip was assigned 50 temperatures that were bootstrap sampled from the temperature sampling distribution from the day and time that that trip would occur.

The power consumption (kW) distribution of each block-day was determined by applying the model using the temperature distribution, and speed distribution data. Further calculations used the 99th percentile of the predicted power consumption for each service block. This represents a worst-case scenario wherein energy consumption levels would be high enough such that nearly all blocks can be completed. Then, the predicted energy consumption (kWh) was calculated by multiplying the predicted power by the duration of the trip. The results are presented on Figure 5.

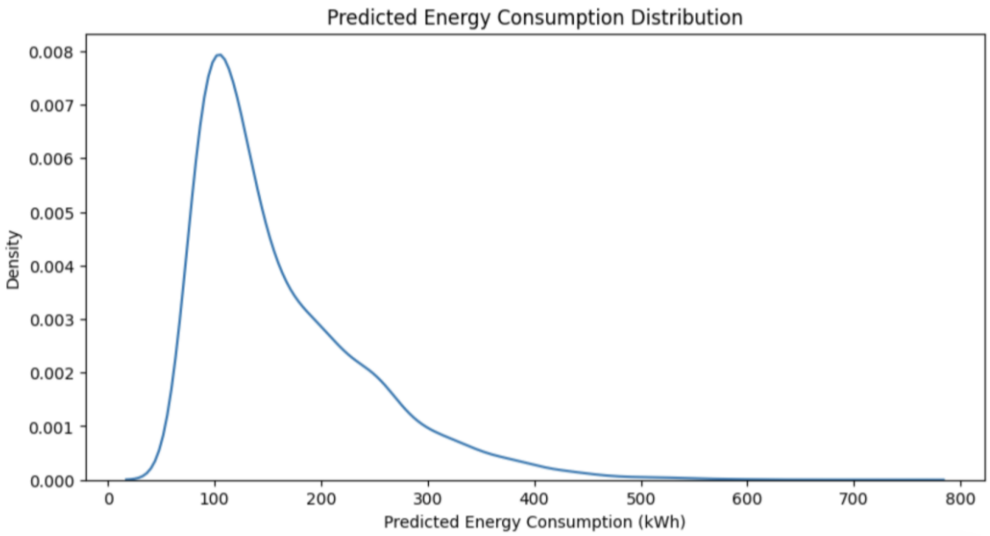


Figure 5 Distribution for Predicted Energy Consumption (kWh)

The minimum, maximum, and average energy consumption of all blocks are 70 kWh, 731 kWh, and 163 kWh, respectively, and 75% of the blocks have its energy consumption lower than 204 kWh. The initial analysis assumed that each BEB in the fleet would be equipped with a battery having capacity of 520 kWh and SOC varying from 20% to 95%, which brings the available energy to 390 kWh. Therefore, if the total energy consumption for a given service block surpasses 390 kWh, the BEB would fail in transit. The simulation shows that the average number of incomplete blocks in a day are 7, however, in one specific day this number reaches 39. This study assumed the worst-case scenario to guarantee the agency's SLO; therefore, 39 blocks will not be able to complete the associated runs and thus require additional buses or opportunity charging.

Four Scenarios of Charging Strategy

Four scenarios are explored to maintain the agency's SLO while overcoming the range limitation of BEB. Scenario 1 considers an increase in the BEB fleet size to guarantee the SLO. The other scenarios involve deploying opportunity chargers at the Port Authority terminal, a common stop along blocks originating from the Wayne Garage operation.

To quantify the number of additional BEBs required in Scenario 1, the bus schedule of the Wayne Garage including 39 blocks was analyzed. The assumptions considered are 1) the additional BEBs would either initiate or finalize the block to cover for the energy deficit for that block; 2) the additional BEBs must have a 2-hour gap between blocks; and 3) the total energy consumption of all runs should consume a maximum of 2/3 of the additional BEBs' batteries. Following these assumptions, 10 additional BEBs are needed to guarantee the agency's SLO.

For the other three scenarios it is desirable that BEBs waiting between trips at Port Authority can be recharged. To optimize the number of chargers needed at Port Authority, it is thereby necessary to find the number of buses waiting simultaneously at Port Authority that cannot complete their blocks. A 15-minutes interval was chosen during which a bus can exclusively utilize one charger while waiting between trips. The bus charging time was calculated based on its real waiting time at Port Authority.

Figure 6 shows the number of buses waiting at the Port Authority terminal between the trips for 15-minute intervals on the service day with the greatest number of buses (39) that cannot complete their blocks. The orange area represents the total number of buses waiting at the Port Authority terminal. The shaded blue area represents the number of buses waiting in the Port Authority terminal that will not complete their blocks without recharging. The maximum number of buses waiting at the terminal simultaneously that cannot complete their block, and therefore need to charge, is 11 buses. This means NJ Transit would need to install at least 11 opportunity chargers at Port Authority to ensure that these BEBs will not have to wait in line to charge. However, if 17 opportunity chargers are installed, all BEBs that stop at the Port Authority will have the ability to charge their batteries without any waiting time. This assumption could yield additional benefits, including reduced battery size, lower battery costs, and improved energy consumption efficiency due to the use of lighter batteries.

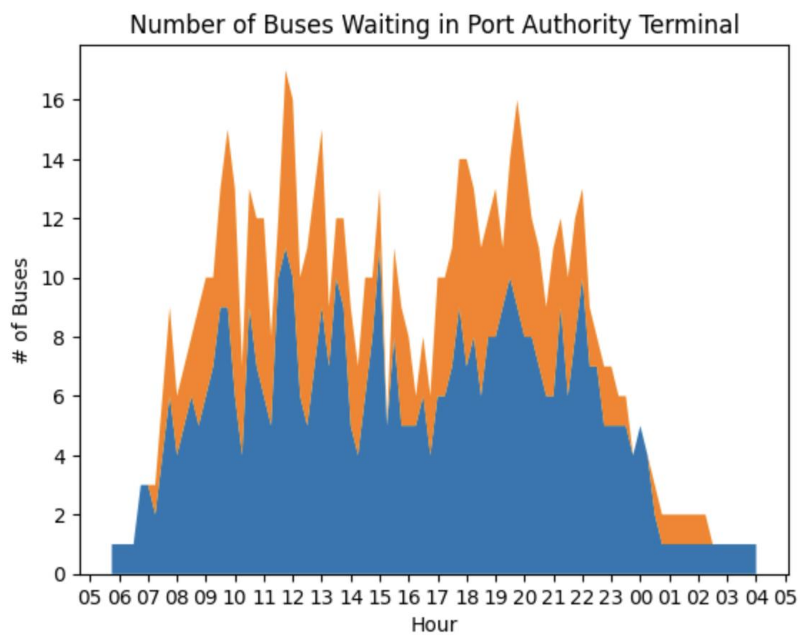


Figure 6 Number of buses waiting at Port Authority (Orange area represents the total number of buses waiting at the Port Authority terminal, and blue area represents the number of buses waiting in the Port Authority terminal that will not complete their blocks without recharging)

Scenario 2 assumes the installation of fast plug-in chargers with 400 kW power and 95% efficiency at Port Authority. All BEBs are equipped with plug-in port; therefore, 17 fast plug-in chargers were assumed in this scenario so that all buses that stops at Port Authority can be charged without having to wait. This option assumes 2 minutes for charging handling every time the bus stops at Port Authority, in which the BEBs are waiting but are not being charged yet. In this scenario, 4 blocks will still be incomplete even with the opportunity charging. This can be calculated by summing the predicted consumption across each service block, subtracting this from the battery capacity, and adding back the amount of energy received from charging while waiting at the Port Authority terminal. This gives the net battery SOC at each node in the service block. To have these blocks completed maintaining the agency's SLO, 1 additional BEB will be require, following the same assumptions used on Scenario 1.

Scenario 3 assumes the installation of inductive chargers at Port Authority. Inductive power transfer (IPT) charges the BEB wirelessly, relieving the driver from handling chargers that require physical contact. This study uses data from wireless charging operation at Antelope Valley Transit Authority (AVTA) in CA, USA, in which the chargers have a power of 220 kWh with an average of 90% efficiency. No additional time for charging handling is considered. In this scenario, all BEBs would be equipped with on-board IPT chargers so they can charge on the 17 off-board IPT chargers without waiting time. However, there are still 6 service blocks that will not be able to complete their runs, requiring 4 additional BEBs.

The last scenario, Scenario 4, assumes the installation of pantograph chargers at Port Authority. While this technology at Port Authority is not viable due to the building's limited floor-to-ceiling height, this scenario is still analyzed to compare with other alternatives. 17 pantograph chargers with 600 kW power and 95% efficiency are considered for this scenario. Although the charger provides high power and high efficiency, there are still 3 service blocks that will not be completed, requiring 1 additional BEBs.

The initial analysis considered a battery size of 520 kWh with SOC ranging from 20% to 95%. However, further analysis was performed to find how many BEBs could use smaller battery; therefore, accounting the benefit of implementation opportunity charging in the cost of the batteries and the efficiency of the vehicle. Three batteries size was assumed 235 kWh, 400 kWh, and 520 kWh, respectively. The battery size needed to complete the service block of each day was calculated and the day when the larger battery is needed was considered. The total number of BEBs, chargers, and batteries are summarized on Table 1 for each scenario.

Table 1 Required Number of BEBs and Chargers for Each Scenario

Item	Plug-in at Depot	Plug-in Opportunity Charging	IPT Opportunity Charging	Pantograph Opportunity Charging
Number of BEBs	230	221	224	221
Number of Overnight Plug-in Chargers	230	221	224	221
Number of Fast Plug-in Chargers	0	17	0	0
Number of off-board IPT Chargers	0	0	17	0
Number of onboard IPT Chargers	0	0	224	0
Number of Pantograph Chargers	0	0	0	17
Number of Battery 520 kWh	71	9	14	7
Number of Battery 435 kWh	61	18	28	16
Number of Battery 345 kWh	88	194	402	198

LIFE CYCLE COST ANALYSIS

LCCA Principles and Assumptions

The LCCA analysis compares the costs of four scenarios that guarantee the public transit SLO. The scenario with the lowest cumulative net present value is the most economical solution. Four main costs are considered in the LCCA: capital costs (C_{CAP}), operation and maintenance costs (C_{OM}), parts replacement costs (C_{REP}), and salvage value (C_{SV}). Equation 2 describes the calculation of the annualized life cycle costs for the studied scenarios.

$$C_{LCC} = C_{CAP} + C_{OM} + C_{REP} - C_{SV} \tag{2}$$

Where, C_{CAP} is capital costs, C_{OM} is operation and maintenance costs, C_{REP} is parts replacement costs, and C_{SV} is salvage value.

The capital costs include the procurement of additional buses (C_{bus}), the procurement and installation of plug-in chargers (C_P), the procurement and installation of opportunity charger (C_{OP}), and the procurement and installation of the onboard component of opportunity charger ($C_{OP\text{-}on}$). These costs are then multiplied by their respective quantities, N_{bus}, N_P, and N_{OP}. The procurement of the batteries for all BEBs, including those both able and unable to complete the routes, are calculated. A benefit of the opportunity charging is to charge the BEB during its operation, which will require batteries with smaller capacity than that for charging overnight only. Equation 3 presents the capital cost and Equation 4 specifies the calculation of battery costs.

$$C_{CAP} = C_{bus}N_{bus} + C_P N_P + C_{OP}N_{OP} + C_{OP-on}N_{bus} + C_{bat} \tag{3}$$

$$C_{bat} = N_{345}C_{345} + N_{435}C_{435} + N_{520}C_{520} \tag{4}$$

Where, N_{225}, N_{400}, and N_{520} represent the number of batteries with capacities of 345 kWh, 435 kWh, and 520 kWh, and C_{345}, C_{435}, and C_{520} are their respective procurement and installation costs.

The operation and maintenance costs consist of the annual maintenance cost of the chargers multiplied by the number of chargers, and the electricity cost to operate the BEB, as shown in Equation 5. The maintenance of the buses will be excluded from the analysis since bus maintenance cost is usually based on miles driven and, regardless of the scenario (each of which differs from the others in the number of buses required) the miles driven remains the same.

$$C_{OM} = C_{M\_P}N_P + C_{M\_OP}N_{OP} + C_{M\_OP-on}N_{bus} + C_{E\_night} + C_{E\_day} + C_{pwr} \quad (5)$$

Where, C_{M_P}, $C_{M\_IPT\text{-}off}$, $C_{M\_IPT\text{-}on}$, and C_{M_FP}, are the maintenance costs for overnight plug-ins, IPT off-board, IPT onboard, and fast plug-in chargers, respectively. The costs of the electricity charged during night and day are represented by C_{E_night}, and C_{E_day}, and C_{pwr} represents the cost of the power demand.

The parts replacement costs (C_{REP}) consist of the batteries that should be replaced at the end of their lifetime. However, the period analyzed in this analysis coincide with the battery's life. Therefore, the cost of battery replacement is zero. The salvage value (C_{SV}) is the price at which the buses and batteries can be sold by the agency at the end of their lifetimes.

The annualized costs are brought to the present value using the discount rate, as shown in Equation 6. Finally, the cumulative net present value is calculated to compare the lifetime costs of the three scenarios.

$$NPV = \sum_{i=0}^{n} C_{LCCi} \frac{1}{(1+r)^i} \quad (6)$$

Where, *r* is the discount rate, and *n* is the number of years considered in the analysis.

Cost Parameters

The procurement and maintenance costs of BEBs and chargers were defined based on costs provided by Antelope Valley Transit Authority, and the study conducted by the National Renewable Energy Lab (NREL) based on projects implemented in the U.S (Aamodt et al. 2021; Johnson et al. 2020). The electricity costs were obtained from the PSE&G and reflects its 2023 tariffs that provides power supply for the studied garage (PSEG 2023). The lifetimes of buses, wireless and plug-in chargers, and batteries were also obtained from AVTA. The pantograph charger is also assumed to have a lifetime of 12 years. After 12 years, the battery salvage value is 40% of its procurement cost (Neubauer and Pesaran 2010) and the BEB salvage value is 15% of its initial cost (Johnson et al. 2020). The discount rate was obtained from the Circular No. A-94 from the Office of Management and Budget. The costs and financial parameters used are summarized on Table 2.

Table 2 LCCA Cost Parameters

Financial and Operational Cost Parameters		
Item	**Value**	**Unit**
Bus life	12	years
Plug-in charger life	12	years
On-board Inductive Charger life	12	years
Off-board Inductive Charger life	12	years
Average Battery Life for buses with Plug-in only	12	years
Average Battery Life for buses with Opportunity Charging	12	years
Light weighting Correction (energy consumption reduction per 10% bus mass reduction)	4	%
Bus weight (with 520kWh battery)	13,800	kg
Bus weight (with 435kWh battery)	12,895	kg
Bus weight (with 345kWh battery)	11,938	kg
Efficiency Correction (435kWh battery)	2.62	%
Efficiency Correction (345kWh battery)	5.4	%
Battery Energy Density	94	Wh/kg
Battery cost per kWh	700	USD/kWh
Battery Salvage Value	40	% of initial value
Bus Salvage Value	105,000	15% initial value
Discount Rate	1.6	%
Procurement cost parameters		
Item	**Cost**	**Unit**
Bus with plug-in chargers	472,000	USD
Bus with pantograph charger	482,500	USD
Battery 520 kWh	364,000	USD
Battery 435 kWh	304,500	USD
Battery 345 kWh	241,500	USD
Overnight Plug-in Chargers	106,000	USD
Fast Plug-in Chargers	140,600	USD
Onboard Inductive Charger	90,000	USD
Offboard Inductive Charger	300,000	USD
Pantograph Charger	430,000	USD
Operation and maintenance cost parameters		

Item	Cost	Unit
Maintenance of Plug-in Charger component on BEB	12,000	USD
Maintenance of onboard Inductive Charger on BEB	-	USD
Maintenance of Overnight Plug-in Chargers	12,000	USD
Maintenance of Fast Plug-in Chargers	18,000	USD
Maintenance of Inductive Chargers	-	USD
Maintenance of Pantograph Chargers	6,500	USD
Electricity Rate On-Peak	0.08	USD/kWh
Electricity Rate Off-Peak	0.06	USD/kWh
Capacity Charge	10.73	USD/kW

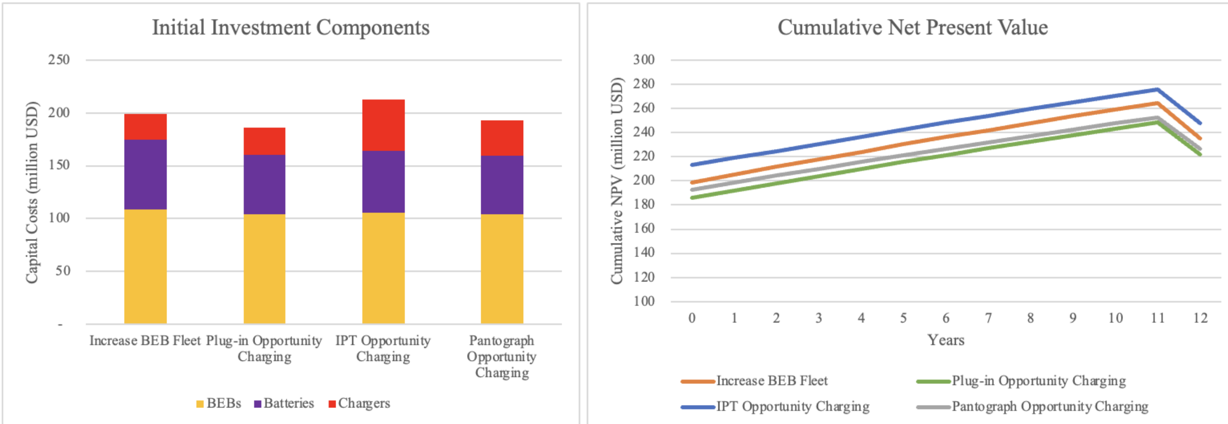
The bus, battery, and charging infrastructure have lifetimes of 12 years; therefore, the LCCA activity timing is set to 12 years. Consequently, there are no battery replacements within the timeframe. The salvage value of the chargers and chargers' components is assumed to be zero at the end of service life. According to AVTA, the inductive chargers have no maintenance costs within the first 2.5 years of operation due to the manufacture warranty. After this period, the maintenance cost is assumed to be the same as the plug-in charger (Momentum Dynamics 2019).

Life Cycle Costs Results

The LCCA analyzes the total lifetime cost of the fleet and charging equipment to find the most economical option. The capital costs and cumulative net present value are presented in Figure 7.

The comparison results show that Scenario 2 presents the lowest initial investment as well as the lowest cumulative net present value. While the initial investment in BEBs for all four scenarios is relatively similar, the initial investment in chargers is substantially lower for Scenarios 1 and 2. Whereas for Scenario 1 the low cost is due to avoiding investment in extra opportunity chargers, for Scenario 2 the low cost is due to the type of charger itself. Therefore, Scenario 2 gains an advantage over Scenarios 3 & 4 by virtue of the lower-cost charger, yet also gains an advantage over Scenario 1 by providing enough power through extra chargers to reduce the battery size of the BEBs, thereby lowering the battery cost. This is evident in Figure 7b which shows the initial cost for batteries is similar for Scenarios 2, 3, and 4 while relatively higher for Scenario 1.

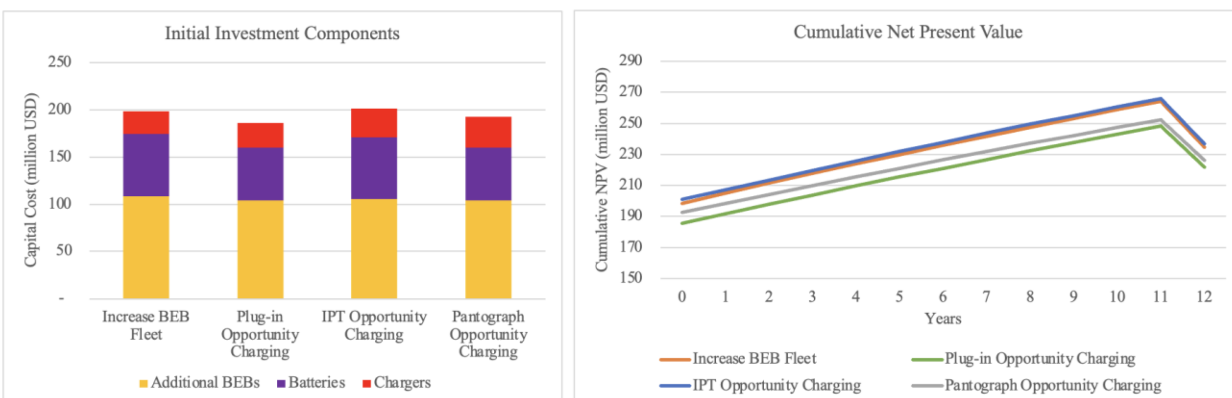
Figure 7c shows that although the Cumulative Net Present Value of Scenario 2 remains the lowest throughout the 12-year period, towards the end of 12 years Scenario 4 is comparable. The pantograph charger in Scenario 4 has higher power than that of the fast plug-in charger of Scenario 2; therefore, buses can recharge their batteries at a faster rate during the day in Scenario 4. This results in a lower demand charge for Scenario 4 when compared to Scenario 2, which over time brings the NPV curves of each Scenario closer.



(a) (b)

Figure 7 LCCA (a) Initial Investment, (b)Cumulative Net Present Value

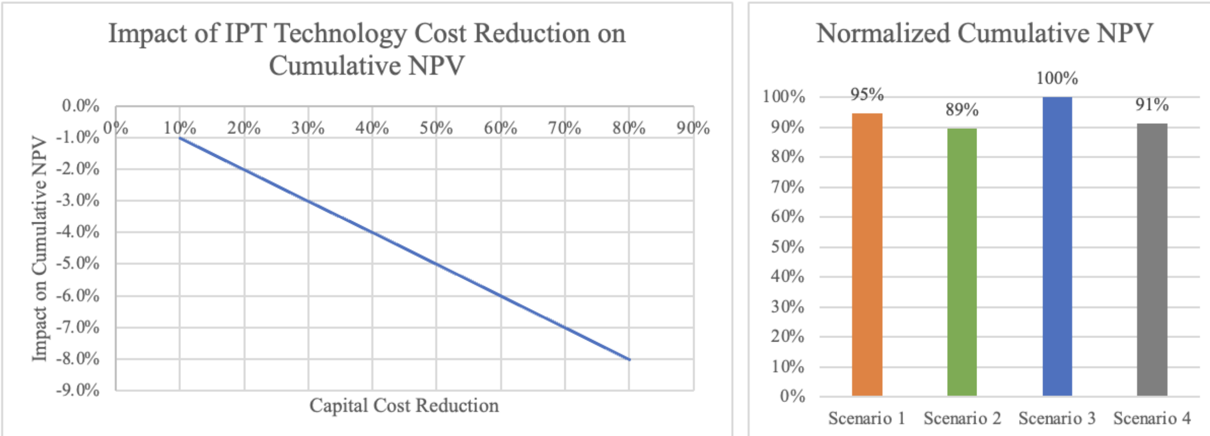
A second analysis assumed the implementation of the minimal number of IPT chargers, just enough to charger the BEBs associated with incomplete blocks. In this new analysis, 11 off-board IPT chargers are assumed to be installed at Port Authority and 39 BEB have the onboard IPT. The results showing the capital costs and cumulative net present value are presented in Figure 8, and the impact of capital cost reduction of IPT chargers on the cumulative net present value is presented in Figure 10.



(a) (b)

Figure 8 LCCA (a) Initial Investment, (b) Cumulative Net Present Value

The cost of a technology, such as EV chargers, tends to decrease over time in proportion with the technology's maturity and market penetration. This trend is more prominent in newer technologies such as IPT. Figure 9 shows the impact of capital cost reduction of IPT chargers on the cumulative net present value.

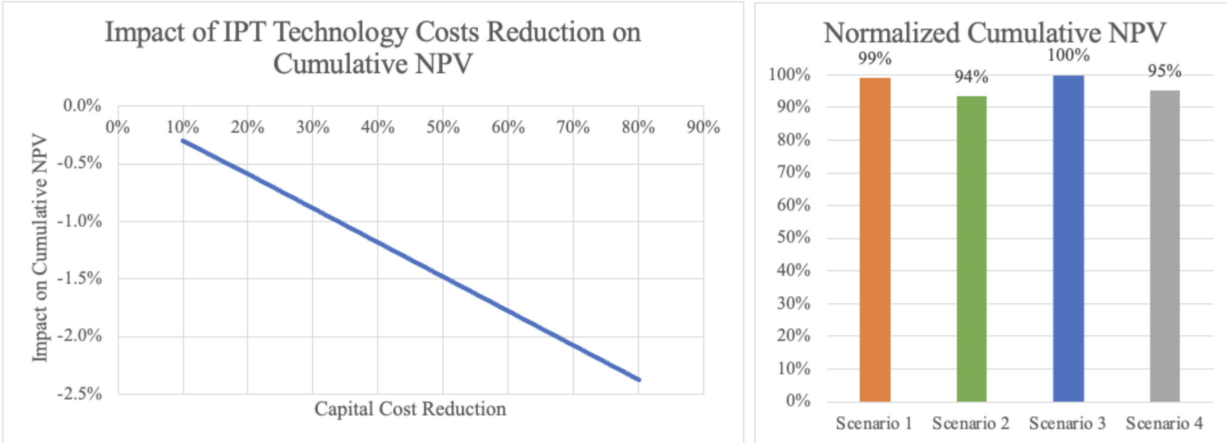


(a) (b)

Figure 9 (a) Impact of Reducing Technology Costs on Cumulative Net Present Value on Scenario 3, and (b) Normalized Cumulative NPV based on Scenario 3

A 10% reduction in the initial technology costs corresponds to a 1% reduction in cumulative NPV. Considering that the difference between the most economical option (Scenario 2) and Scenario 3 is 11%, the latter would never be the most cost-effective option, because costs cannot be reduced by more than 100%. Furthermore, for Scenario 3 to surpass any other scenario in terms of cost-effectiveness, a substantial 50% reduction in technology costs would be required—a prospect unlikely to happen in the near future.

The new assumption does lead to a reduction in the initial investment and cumulative NPV for Scenario 3. Nevertheless, this scenario remains the least economically favorable option. Furthermore, the utilization rate of the IPT chargers will be quite low, given that only 39 BEBs are equipped with the onboard IPT component. Interestingly, both Scenario 1 and Scenario 3 exhibit very similar initial investment and cumulative NPV figures. While Scenario 1 has a slight economic edge, Scenario 3 offers certain conveniences, such as a smaller fleet, which requires less garage space and involves lower logistical complexity. Moreover, as shown in Figure 10, the influence on technology cost reduction is less pronounced compared to the previous assumption due to the reduced charger usage. However, if the capital cost reduction exceeds 35%, Scenario 3 becomes more cost-effective than Scenario 1.



(a) (b)

Figure 10 (a) Impact of Reducing Technology Costs on Cumulative Net Present Value on Scenario 3, and (b) Normalized Cumulative NPV based Scenario 3, with new assumption for Scenario 3

LIFE CYCLE ASSESSMENT

LCA Goal and Scope

This study conducted LCA analyses to compare the environmental impacts of the four aforementioned scenarios: increase BEB fleet, Plug-in opportunity charging, Wireless opportunity charging, and Pantograph opportunity charging. The environmental impacts assessed are the Cumulative Energy Demand (CED), which measures the total primary energy requirements of renewable and non-renewable sources, and the Global Warming (GW) Impact, which measures the warming effect on the Earth's surface from greenhouse gas (GHG) emissions.

The functional unit, an important element in the LCA, is used to provide a reference to relate the input and output of the system defining the service that needs to be delivered by the system (Soares and Wang, 2020). The functional unit used in this study is service required to complete all blocks coming out of Wayne Garage in a period of 12 years. The system boundary accounts for the burdens (including the material extraction, production, and manufacturing) of chargers, batteries, and additional BEBs. The maintenance of the BEBs and use-phase are not considered since the most data presents the impacts per mile and kWh, in which are the same for all scenarios. Likewise, vehicle and equipment end-of-life is considered equivalent regardless of the charging type. Usually used BEBs and equipment are sold to smaller carriers (Kerrigan, 2020) and is not within the scope of this LCA analyses.

Life Cycle Inventory

The CED and GW calculations are based on various secondary data source such as academic publications, online databases, and industry reports. Table 3 presents the main components of this study and their respective CED (MJ) and GHG ($kgCO_{2\text{-}eq}$).

Table 3 Life Cycle Inventory

Component	Unit	CED (MJ)	GHG (kg CO2-eq)
Bus Manufacture	1 bus	710,000	48,000
Battery Manufacture	kWh	1,126	73
On-Board Wireless Charger	1 charger	36,000	2,060
Off-Board Wireless Charger	1 charger	152,000	9,060
Overnight Plug-in Chargers	1 charger	80,368	4,886
Plug-in Charger	1 charger	156,461	9,512
Pantograph Charger	1 charger	625,844	38,047

The BEB life cycle inventory was obtained from Soares (2020) and includes the energy demand used in obtaining and refining the raw materials, and the energy used to produce each component. The CED used is 710 GJ while the GW used is 48 10^3kgCO2. For the battery manufacture, the CED used is 1.13 GJ per 1 kWh of battery and the GW used is 72.9 kgCO2, also per 1 kWh of battery (values were obtained using the Argonne National Laboratory Greenhouse Gases, Regulated Emissions and Energy Use in Transportation – GREET - Model). These values include energy consumed by the raw material production and transportation in addition to the battery manufacturing process (Dai et al., 2019).

The data for the chargers were obtained from the from an all-electric bus system study (Bi et al., 2015). The wireless charges components were modeled based on a 60-kW wireless charger that was under development at University of Michigan-Dearborn and the ratio used to scale it was based on its power. The conductive charger was modeled based on a 2013 Chevrolet Volt charger, also 60 kW. However, different from the wireless charger, for the conductive options the ratio used was based on the power cabinet dimensions. The dimension data for the 60-kW charger was obtained from the Proterra chargers' product (Vederek.com/Proterra), while the dimensions for the other conductive chargers was obtained from ABB. While the 60-kW charger has a power cabinet of 0.88 cubic meters, the overnight plug-in, fast plug-in charger, and pantograph charger have their power cabinet dimensions of 0.94, 1.83, and 7.32, respectively.

Life Cycle Assessment Results

The goal of life cycle assessment (LCA) is to compare the environmental impacts of four charging strategies, in terms of the functional unit. The impact categories considered in this analysis are cumulative energy demand (CED), and Global Warming (GW). The life-cycle phases analyzed included the manufacturing of the vehicle, battery, and chargers. The operation is not considered since all scenarios operates the same scheduling using the same energy source from the grid.

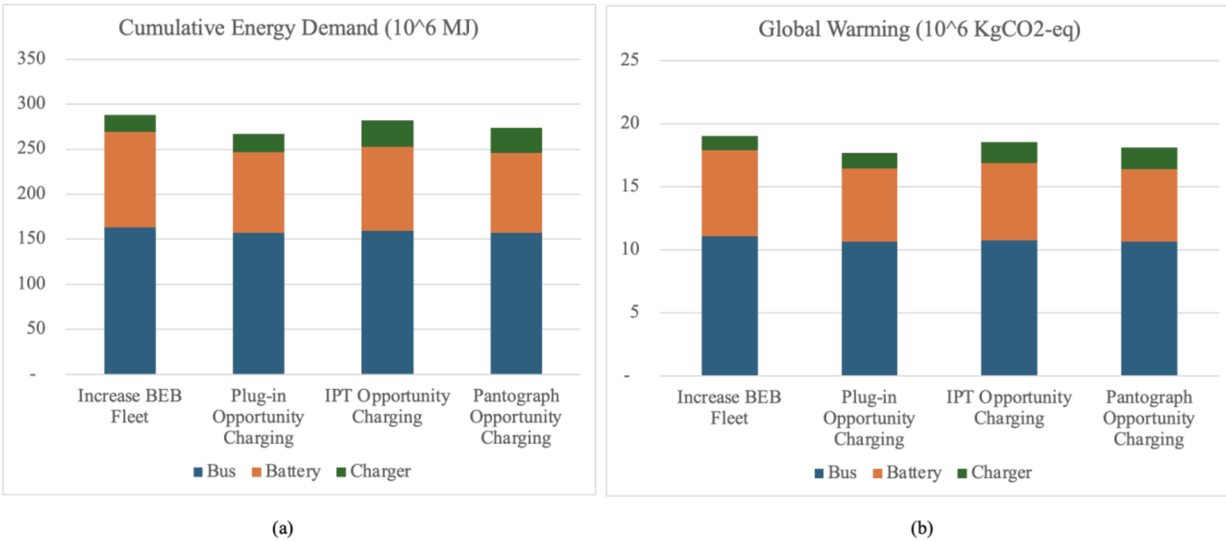


Figure 11 LCA Results (a) Cumulative Energy Demand, and (b) Global Warming

The CED impact analysis quantifies the total primary energy required throughout the life cycle of a product, material, system, or process. Figure 11(a) provide a summary of CED values per phase and for each charging strategy considered, based on the functional unit of the LCA. Across all scenarios, bus manufacturing emerges as the most energy-intensive phase, followed by battery manufacturing and charger manufacturing. Scenario 1, increase BEB fleet, presents the highest CED due to the energy required for the batteries manufacturing. The strategy also shows the highest CED for bus manufacturing. Despite having the lowest CED during the charger manufacturing phase compared other scenarios, the energy is not low enough to compensate the additional buses and larger batteries required by this strategy. Scenario 3, IPT Opportunity Charging, ranks as the second highest in CED among the strategies. The charger phase has the highest CED among the other options, although very similar to the Pantograph option. However, the pantograph opportunity charging has the lowest CED for battery and bus manufacturing. Conversely, Scenario 2, plug-in opportunity charging, presents the lowest overall CED. This strategy has the lowest CED for bus manufacturing along with scenario 4, and second lowest CED for battery and charger manufacturing. The combination of these lower CED phases results in a total CED of 267.106MJ, 7% lower than the CED of scenario 1.

Global Warming impact assesses GHG emissions using Global Warming Potential (GWP). GW has a strong relationship with overall environmental impacts and is therefore a primary factor in comparing the environmental load of different systems. Figure 11(b) summarize the GW values per phase and charging strategy based on the function unit of the LCA. The GW results parallel the CED findings in terms ranking the charging strategies from highest to lowest environmental impact. The GHG emissions and CED are closely tied to the number of buses, batteries, and chargers used in each strategy, resulting in similar trends when analyzing each category individually. Specifically, the GHG emissions for the scenarios of increase BEB fleet, plug-in opportunity charging, IPT opportunity charging, and pantograph opportunity charging are 19.0 106KgCO2-eq, 17.7 106KgCO2-eq, 18.6 106KgCO2-eq, and 18.1 106KgCO2-eq, respectively. Therefore, increase BEB fleet presents the highest GHG emissions followed by IPT opportunity charging, pantograph opportunity charging, and plug-in opportunity charging.

CONCLUSIONS AND RECOMMENDATIONS

This study conducted comparison analysis of charging system designs for BEBs based on case study of Wayne garage at NJ Transit. LCCA results showed that installing fast plug-in charger as opportunity charging has the lowest cumulative net present value, followed by installing pantograph chargers. These low-cost solutions are mostly driven to lower cost of batteries compared to Scenario 1 – increasing BEB fleet size, and lower cost of chargers compared to Scenario 3 – installing inductive chargers. LCA results show that two impact categories on energy and carbon emission present similar results in terms of the highest to lowest impact per strategy and per component manufacturing. Scenario 1, increasing BEB fleet, presented the highest impacts mostly driven by higher number of BEB and bigger batteries when compared to the other scenarios. While Scenario 2, plug-in opportunity charging, presented the lowest impact. Therefore, installing fast plug-in chargers for opportunity charging is the best solution when considering economic and environmental analysis.

Further research should focus on two primary areas: expanding the scope of the bus route network and increasing the accuracy of energy consumption model. By expanding the scope of the bus route network, it will have further-reaching impact and allow for more comprehensive cost analysis. The accuracy of energy consumption model can be improved by including more variables such as elevation, ridership, and number of stops that yield better estimations in simulating hypothetical scenarios for a given bus route.

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