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Simulation of Electric Transit Busses for Broome County Transportation

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Abstract: This paper evaluates the impact on route reliability of a New York public transit agency transitioning from diesel and hybrid vehicles to full-electric vehicles. The real-world transit routes are modeled in SIMIO to investigate vehicle behavior under different scenarios. The goal of the model was to determine the impact of vehicle parameters such as battery size, charger power, and system efficiency on transit reliability. The results suggest investments in opportunity charging infrastructure along routes should boost route reliability more than investing in faster depot chargers or larger batteries. Hybrid-electric vehicles, already a large percent of the market sector, offer a flexible alternative for introducing and integrating infrastructure investments in advance of extensive electric vehicle purchases.

Keywords: Electric Vehicle, Fast Charging, Opportunity Charging, Simulation, SIMIO

1. Introduction

Transit agencies in industrialized nations, are investing heavily into vehicle electrification to combat rising health and environmental concerns regarding combustion fumes, greenhouse gases, and energy inefficiency. New York transit agencies were among the first to adopt Hybrid Electric Vehicles (HEV) [Chandler, 2002] and continue to be a world leader in the transition from combustion to electric propulsion power [Judah, 2016]. As industrialized nation's local and federal governments continue to offer better incentives for electric vehicles and institute tighter regulations on emissions, the demand for fully electric vehicles increases [Liu, 2019].

Despite the public and private demand for cleaner and more efficient propulsion bus fleets, investment into commercial Electric Vehicles (EV) remains a difficult decision for transit agencies operating with finite budgets and garage space. Several factors are limiting the "EV revolution", chief among these are cheap batteries with high energy density, long lifespans, and environmental durability [Simpson, 2006]. Current commercial batteries require high upfront cost per unit energy (kWh) to produce and purchase, substantial space and weight, and expensive and complicated Battery Management Systems (BMS) to maintain their already limited lifespan [Vilppo, 2015]. Current battery technologies are vulnerable to high or low temperature or state of charge (SoC) conditions that significantly reduce the lifespan of the battery [Buchmann]. Cooling and heating systems can protect battery modules from thermal degradation; however, busses with low energy must return to the depot to charge, which takes them out of revenue service. Similarly, the efficiency of commercially viable electric propulsion systems is unlikely to drastically improve soon [Barnitt, 2006]. Therefore, the feasibility of EV transit busses requires the design of systems that can meet route expectations without obligating transit agencies to purchase excessively expensive batteries, chargers or propulsion systems.

2. Transit Bus Model

The purpose of this simulation is to evaluate the impact on route reliability when operating electric busses as compared to diesel busses or hybrid diesel and electric busses. The simulated Broome County Transportation (BCT) bus routes serves as the environment in which the simulated vehicles operate. The discrete-event, agent-based simulation is programed using SIMIO to model the objects, define object interactions, animate object movements, and calculate measures of performance. The simulation largely ignores variations in driver behavior, battery chemistry, battery management, electrical transients, and external influences. A baseline EV is defined and compared to the alternative diesel-only and hybrid diesel and electric busses.

The simulation's control parameters will be changed independently to determine the sensitivity of the model to each parameter and identify the most important targets for future research on improving commercial EV reliability.

2.1 Simulation Environment

The roads provide the network that allows busses to move about the SIMIO simulation environment. As shown in Figure 1, the routes are indicated on a high resolution google maps image of the region to create the environment [Broome, 2019]. Each road link is a modified path with length and speed limit parameters. The distances and velocities were estimated using google maps data. Several of the bus stops' tags show the short-hand names for each of the stops. There are four routes operated simultaneously during each simulation. BCT's website was used to collect route pathing and stops for the routes 15, 16, 17 and 47 [BCT, 2019].

Each bus stop is composed of two modified transfer nodes and one basic node. The basic node triggers a function to check if the bus needs to stop at the current node or continue driving on the road. If the bus must stop at the bus stop then the first node allows passengers to depart the vehicle ("OFF") and the second node allowing passengers to enter the vehicle ("ON"). As shown in Figure 1, the basic node is grey, the OFF node is blue, and the ON node is red. All three nodes are connected with zero-length connectors to allow for instantaneous action. The action at the OFF node occurs instantaneously; however, the ON node allows a few minutes for passengers to arrive and allows time for EV's and HEV's to receive opportunity charge.

The vehicle routing nodes and charger node are modified transfer nodes specifically used for transporter logic. The vehicle routing points will re-route the bus to the charger if the state of charge is determined to be too low, otherwise the vehicle will continue with its standard bus route.

The bus will transition to an inactive state after charging completely. The charger node is the default location for the vehicles while off-shift as well, which allows vehicles to re-charge or re-fuel while transitioning drivers.

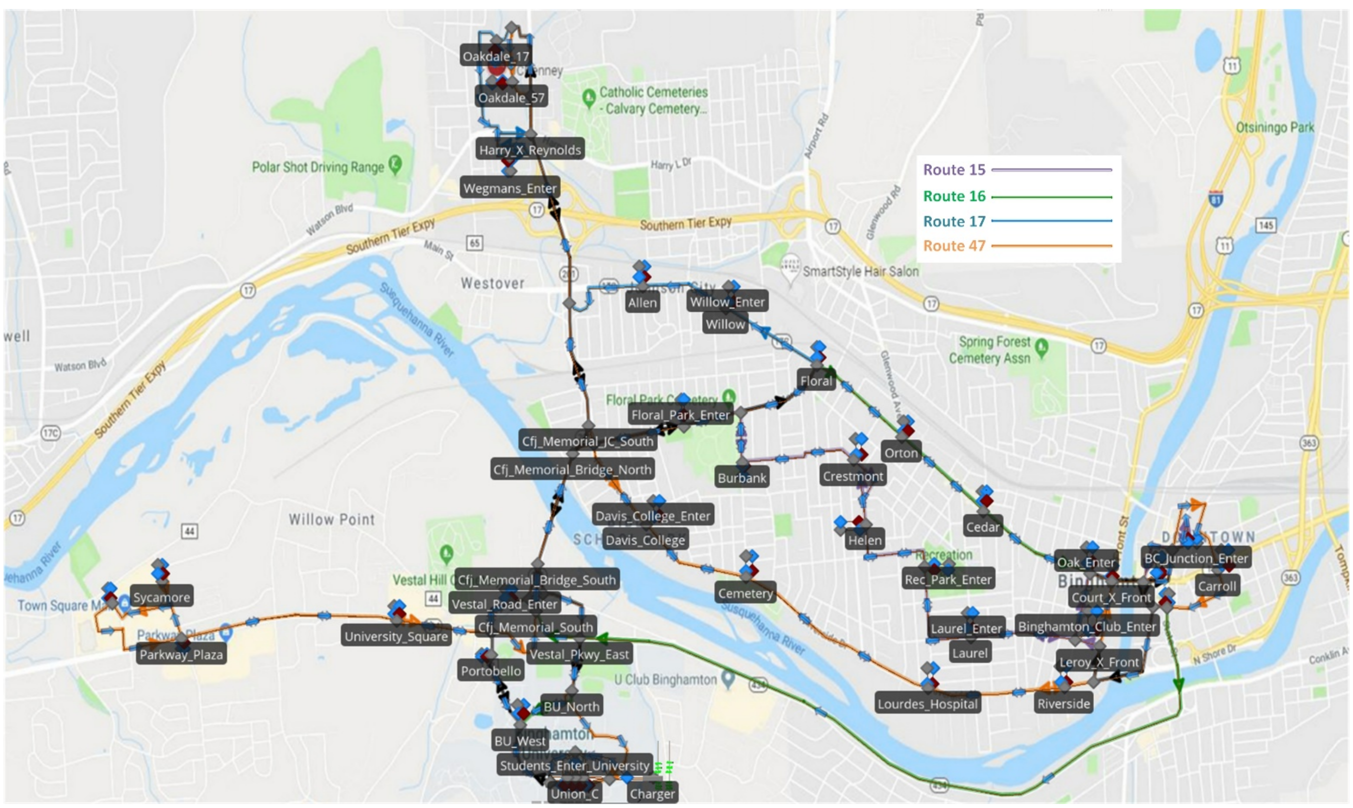

Figure 1. Map of BCT Bus Stops and Paths for BCT Routes 15, 16, 17, and 47

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The passengers are SIMIO entities that are generated at a discrete rate determined by the daily schedule of bus passengers as shown in Figure 2. Only passengers intending to enter or exit the university campus by bus are considered. There are passenger source and sink blocks at every bus stop. Passengers entering the bus at the university are assigned a random destination from a list of available destinations. Passengers entering the bus in the town are assigned to the university. The rates are much lower for the bus stops in the town because each bus stop increases the total number of passengers in the system. Passengers are not generated between 9 PM and 6 AM, and the busses are non-operation during 10 PM and 6 AM. This non-operational time allows the EVs time to charge overnight. The route reliability metric of performance is based on the amount of time passengers must wait and the number of passengers picked up over a simulation run. The rates were selected such that the diesel bus can easily transport all the passengers without overfilling vehicle capacity. Therefore, route reliability of each experimental bus can be inferred from the difference in total riders transported between the current bus and the diesel bus. The long block of off-shift time will result in downplaying the impact of the re-charging at the depot on route reliability.

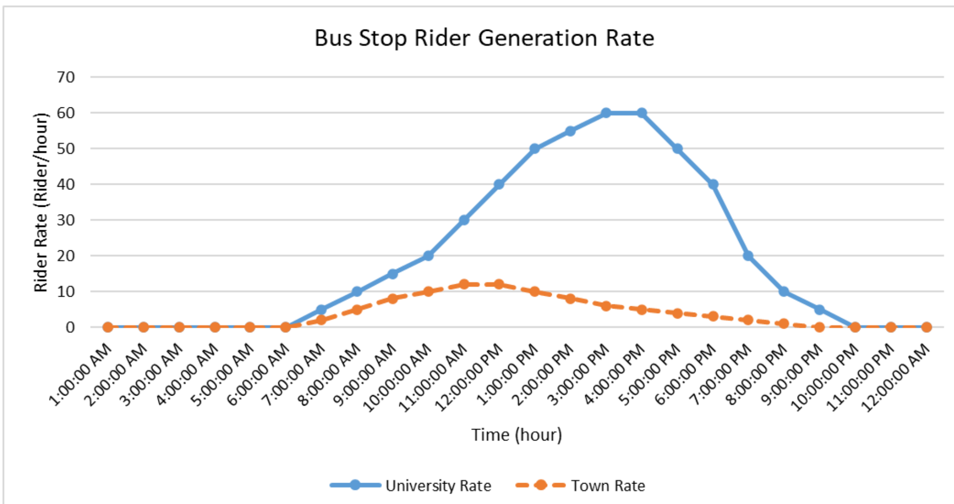

Figure 2. Bus Rider Generation for University and Local Town

The busses are SIMIO transporters with additional functions to calculate, record, and act on current energy capacity status and requested vehicle states. Four routes are available with a dedicated bus that follows the scheduled bus stops of each route while on-shift. The busses have fixed daily schedules, as shown in Figure 3, that define the busses on-shift and off-shift hours. The drivers perform bus operation for four-hour periods with 30-minute bus non-operational periods for driver rotations and lunch break. There is a four-hour non-operational period between 10 PM and 2 AM. The bus will attempt to unload all passengers and return to the charger node when they are off-shift or inactive.

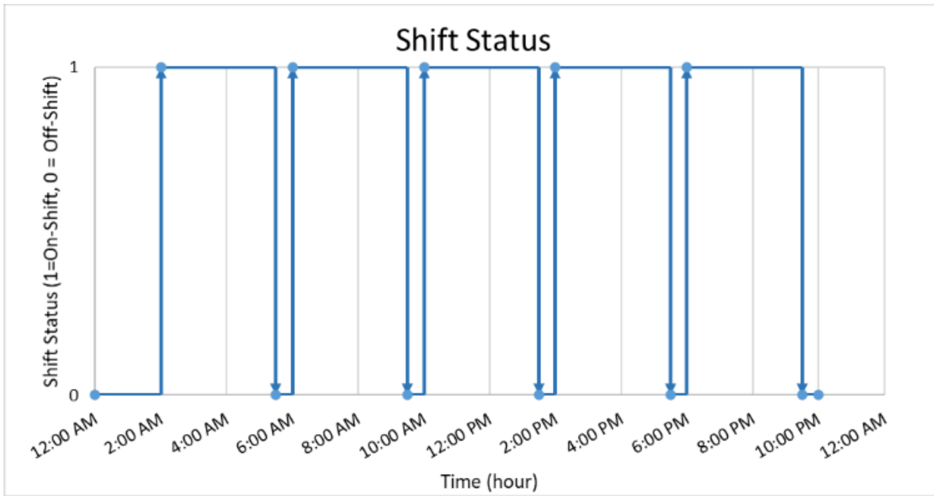

Figure 3. Daily Schedule for Busses

2.2 Experiment Controls

There are four experiment controls to compare the power supply and demand of different busses in the simulation:

- Battery Capacity (kWh)
- Depot Charge Rate (kW)
- Opportunity Charge Rate (kW)
- Power Consumption (kWh/km)

Battery capacity is the total energy available to the vehicle for propulsion and is based on the potential energy storage in the battery or fuel tank. Based on literature regarding similar EV's, a conservative battery capacity for the baseline was assigned to be 250 kWh [Olsson, 2016]. Alternative bus configurations include EV batteries with double the capacity, 500 kWh, or quadruple the capacity, 1 MWh. When the battery state of charge drops below 20% of full capacity the bus will attempt to return to the depot. This is in order to receive charging from the vehicle depot charger prior to running completely out of energy.

Diesel and Hybrid bus configurations are considered in the simulation for comparison to various EV bus configurations. The diesel and hybrid bus entities function the same as the EV bus entities; however, the total capacity and charge rate are determined based on the energy density of liquid diesel fuel. The method to determine energy capacity of liquid diesel fuel is described in (1), and the method of determining charge rate for re-fueling busses is described in (2).

$$\mathrm{E_{fuel}} = \mathrm{GGE_d} * \mathrm{V_{bus}} \tag{1}$$
$$\mathrm{P_{fast}} = \mathrm{E_{batt}} / \mathrm{t_f} \tag{2}$$

Where$\mathrm{GGE_d}$(kWh/gal) represents the energy density per gallon of diesel; V (gal) represents the number of gallons in the vehicle's fuel tank; $\mathrm{Q_{pump}}$(gal/hour) represents the volumetric flow rate of the fuel pump; $\mathrm{E_{fuel}}$ (kWh) represents the total energy capacity of the fuel tank or battery; and $\mathrm{P_{fast}}$ (kW) represents the depot charge rate of liquid fuel busses. Using (1) with the energy of diesel to be 38 kWh/gal and the average size of transit bus fuel tanks [Eudy, 2016], an equivalent diesel energy storage capacity of 4000 kWh was selected for HEVs and diesel busses. Based on standards set by the EPA, the pump rate in the USA is limited by 10 gal/min [EPA, 1997]. Using (2) the equivalent diesel fuel charge rate for the vehicle, value of 20,000 kW was set for the depot charge rate of HEV and diesel busses. As should be expected, the total energy capacity and charge rate of diesel fuel busses is magnitudes higher than EV configurations as a result of the high energy density of diesel fuel.

Large EV's designed with batteries large enough to store 250 kWh are typically paired with high power chargers for depot charging. Based on the literature, a modest baseline depot charge rate for EV's was selected to be 100 kW with improved depot chargers selected to be 200 kW and 400 kW [Yilmaz, 2013]. Charger power rates are simplified in the simulation by assuming that energy requests can be fully supplied by the power grid at the magnitude requested without electrical transients.

The opportunity charging is an experiment control that can only provide benefit to EV and HEV bus configurations. So, the opportunity charge rate is set to zero for diesel busses. A modest 5 kW charger was selected for baseline EV and HEV opportunity charging with alternate chargers selected to be 10 kW and 50 kW [Yilmaz, 2013]. The low power charger option would be relatively cheap for the electronics and should not require an overhaul of the local power grid; however, the much more costly and demanding high-power opportunity chargers are also tested to observe their impact on EV range and reliability. Development of multiple 50 kW opportunity chargers requires costly infrastructural investment by local government and industry, but developed technology

Energy consumption rate is an average value of energy consumption per unit of distance. The baseline energy consumption rate for EV, HEV, and Diesel is identified in New York Transit Agency trade-off study comparing bus performance [Chandler, 2002]. Since this is a discrete-event simulation, the vehicles change velocity discretely. There are no acceleration terms, so the vehicle can transition from full stop to velocity of 55 MPH instantly. The bus efficiency term serves as an average of all energy transferred to usable work, energy recovered from regenerative braking or suspension, and energy lost to irreversible processes while driving. The method to calculate power loss is described in (3) using the simplified power loss equation.

$$P_{fast} = E_{batt}/t_f \tag{3}$$

Where P_{drive} (kW) represents the instantaneous drive power; η_{bus}(kWh/km) describes the average energy consumption for EV's; and $\vec{v}_{bus}$(km/h) describes the discrete velocity of the bus. The energy consumption rate control does not account for environment conditions, elevation changes, driver behavior, etc. The baseline EV energy consumption rate is selected to be 1.5 kWh/km [Chandler, 2002][Judah, 2016][Barnitt, 2006]. The improved power train efficiency case assumes no auxiliary loads (e.g. air conditioner, power steering, etc.), and is set to 1 kWh/km. The HEV and diesel energy consumption rat of 2.5 kWh/km and 4 kWh/km respectively [Chandler, 2002][Judah, 2016][Barnitt, 2006].

Table 1 compares baseline combustion vehicle to alternative bus configurations and opportunity chargers or depot chargers at various charger powers. The first three configurations are baseline Diesel, HEV, and EV configurations. Comparison of the system controls are shown as alternate configurations.

Table 1. Simulated Bus Configurations

Experiment Name	Experiment Controls			
	Energy Consumption Rate (kWh/km)	Depot Charge Power (kW)	Opportunity Charge Power (kW)	Energy Capacity (kWh)
0) Diesel	4	20,000	0	4,000
1) Hybrid	2.5	20,000	0	4,000
2) Baseline EV	1.5	100	0	250
3) Efficient EV	1	100	0	250
4) Better Depot Charger	1.5	200	0	250
5) Super Depot Charger	1.5	400	0	250
6) Opportunity Charger	1.5	100	5	250
7) Better Opportunity Charger	1.5	100	10	250
8) Super Opportunity Charger	1.5	100	50	250
9) Large Battery	1.5	100	0	500
10) Massive Battery	1.5	100	0	1,000

The current energy of the system can be calculated using the initial energy capacity, subtracting energy lost in propulsion, and adding energy supplied by either depot or opportunity charging. There are functions in the bus object to record the cumulative time spent charging, which can be used to determine the total energy supplied to the system. There is also a function to record the total distance traveled, which can be used to determine the total energy demanded by the system. Therefore, the current energy of the system can be determined using (4).

$$P_{fast} = E_{batt}/t_f \quad (4)$$

Where E_s (kWh) represents the total energy of the system; E_0 (kWh) represents the initial energy of the system; ECR (kWh/km) represents the energy consumption rate of the propulsion system; d (km) represents the cumulative distance traveled; P_f and P_s(kW) represents the depot and opportunity charge power rate; t_f and t_s (h) represents the cumulative time spent charging. Each of the terms can also be calculated independently for comparison.

2.3 Performance Measures

Route reliability refers to the ability of a given bus configuration to meet scheduled bus route demand in comparison to the baseline Diesel bus configuration. The energy storage system of EV has significantly lower energy density than diesel fuel, thus the EV configurations are subject to the danger of entering a low-energy condition. When an EV enters low-energy condition it must reduce its rout reliability in order to receive charging at the depot. The route reliability metric is important for determining the EV battery and charger configuration's ability to meet the current vehicle performance.

Minimum charge events are the lowest recorded energy storage state during the simulated week of driving. A value below 20% indicates a point when the vehicle stopped revenue service in order to return to the depot for a charge.

Total energy supplied represents the total weekly energy required to sustain bus routes on the bus schedule for the defined vehicle and system configuration.

Estimated energy per year describes the Megawatts required to power the configuration over the course of a year based on the Total energy of the simulation over the simulated time period.

3. Results and Discussion

Table 2 shows the performance measures for each of the bus configurations. The experiment controls for each bus configuration is listed in Table 1.

Table 2. Experimental Bus Configuration Results

Experiment Name	Experiment Results			
	Route Reliability	Minimum Charge (kWh)	Total Energy Supplied (kWh)	Estimated Energy (MWh/year)
0) Diesel	-	2,910	47,900	2.49
1) Hybrid	100	3,318	31,500	1.64
2) Baseline EV	80.0	15.8	13,500	0.701
3) Efficient EV	88.6	32.5	10,000	0.520
4) Better Depot Charger	85.9	21.7	14,400	0.750
5) Super Depot Charger	91.6	17.7	15,300	0.798
6) Opportunity Charger	87.2	5.9	14,100	0.730
7) Better Opportunity Charger	89.2	28.7	15,000	0.781
8) Super Opportunity Charger	100	73.4	16,800	0.873

Experiment Name	Experiment Results			
	Route Reliability	Minimum Charge (kWh)	Total Energy Supplied (kWh)	Estimated Energy (MWh/year)
9) Large Battery	90.5	55.13	15,100	0.786
10) Massive Battery	99.5	126.5	16,700	0.868

Vehicle energy consumption rate has a drastic impact on the total energy supplied to maintain bus schedules. The benefits of regenerative braking and deficits of combustion engines are highlighted by the 2-3X higher energy consumption per year. Hybrids are able to make use of the regenerated energy, which reduces energy consumption rate compared to traditional Diesel vehicles. The more efficient EV configuration secured notably more route reliability as well as drastically reduced the cumulative energy demand relative to all other configurations. This result reinforces the importance of designing efficient propulsion systems and auxiliary systems to improve the feasibility of electric vehicles. Unfortunately, there may not be significant short-term improvements in the efficiency of feasible electric vehicle powertrains. This is due to the physical limitations and cost constraints of making ultra-efficient electric powertrains.

Improving depot chargers power demonstrated an improvement in the route reliability relative to the baseline EV. The baseline EV suffered an abysmal 20% reduction in reliability compared to diesel vehicles, which is a strong deterrent to EV purchases because the transit agency must expand their vehicle fleet to meet the current bus schedule. After quadrupling the power of the depot's chargers, the route reliability only improved to 92%. The simulation allowed the vehicles to depot charge during the 30-minute off-shift periods in the driver's breaks and driver rotations, so these problem may even be magnified in real-world scenarios. Therefore, ultra-fast depot chargers can charge much faster, but these vehicles may still be unable to meet expected drive range without unplanned intermissions to charge.

Opportunity charger configurations demonstrated the much more immediate improvement in bus reliability than configurations with improved depot chargers. All bus configurations with opportunity chargers experienced drastically improved route reliability. The hypothetical configuration with high-power opportunity chargers demonstrated the only EV configuration that maintained the same reliability as diesel or hybrid buses. Although these results are promising, the cost, safety, and logistics of installing 50 kW+ chargers at every depot poses a serious obstacle; however, the simulation suggests development of low-cost, safe, and simple opportunity chargers may yield the best returns in commercial EV feasibility.

Energy storage capacity significantly improved route reliability compared to the baseline EV. Doubling or quadrupling the battery capacity increased the reliability above 90% and to nearly 100% respectively. The results suggest that the energy storage system can be designed to meet any demand need; however, energy storage cost is the primary cost in an EV system [Chandler, 2002][Judah, 2016][Barnitt, 2006]. Additionally, larger energy storage systems increase vehicle weight and drag, which will increase propulsion system power consumption. Therefore, energy storage systems will need to be optimized to best realize customer cost and performance requirements within physical limitations.

4. Conclusions

Results of this simulation indicate several viable options to improve the route reliability of transit bus EV's. Advancing charger technology, electric drivetrain technology, or battery technology all offer promise to improve the feasibility of electric transit busses. These advanced fleet management strategies should allow smaller battery capacities to be utilized without reducing the route reliability; however, the simulation results suggest that BCT and similar small-city transit agencies would benefit most from investment in opportunity chargers at bus stops or along routes.

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