Electric Bus Operational Design for Sub-urban City Service: A Case Study of Putrajaya, Malaysia

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Abstract: This study investigates the best design for electric bus system for sub-urban service. A case study of a sub-urban town in Malaysia, i.e. Putrajaya, is modelled in the Emme software to evaluate the proposed 7 design scenarios. This study took a novel approach by considering the energy spent by each bus line instead of route length, using a quadratic energy consumption-speed relationship. Results reveal that it is not necessary to amend the bus route network when electric bus system is introduced. The best design scenario (with the highest profit) maintains the existing bus route network and service frequency, but with fast charging systems installed at both terminals and curb side kiosks to charge the electric bus at a faster rate. From the passenger perspective, a short headway is preferable as it could capture more passenger demand, although the revenue is not high for the operator due to higher annual cost.

Keywords: Electric bus, bus fleet, opportunity charging, bus route, bus frequency

1. INTRODUCTION

Transportation sector is one of the major sources of greenhouse gas (GHG) emission in which it accounts for 23% of the total carbon dioxide emission in Malaysia (Shahid et al., 2014). The situation is expected to be worsen as the household and vehicle population size is growing rapidly if no mitigation action is taken. The invention of electric vehicle is one of the effective strategies to reduce greenhouse gas emission. Electric vehicles that run on batteries have zero emission, less noise, and energy efficient. Currently, there are electric cars (for private use) and electric bus available in the market. In order to replace the conventional bus with the electric bus, the social economy and natural environment need to be benefited. As comparing in term of environmental, the conventional bus is accountable for the emission of CO2 that contributes to global climate change but the electric bus is environmental friendly. Besides, conventional bus incurs higher maintenance cost as it requires oil changing and regular tune up for better performance. On the contrary, electric bus uses state-of-the-art lead acid batteries that are sealed and require no maintenance. Additionally if the bus planning is well-designed with satisfying performance, it could results in a shift of transportation mode from private to public as well. Thus, the reduction of CO2 emission is significant, meanwhile bringing comfort and quieter environment.

Battery and its charging system, i.e. battery capacity, charging station and system, charging method and charging duration, is the major concern in deployment of electric vehicles. The battery capacity indicates the maximum energy that a battery can store. A battery with larger capacity stores more energy and could travel longer distance before the need to recharge. However, it is usually heavier and would affect the vehicle performance such as its speed. Battery with larger capacity also means that it requires longer recharging time. The charging station is the place where the charging system is fixed or available to recharge the electric vehicles (Dong, et al., 2014). It is related to the types of battery used and the charging method. Fixed or overnight charging requires an area to place the charging system and the electric vehicles are connected to the facilities during recharging. Opportunity charging or en-route charging has charging stations built along the roadways which allow the vehicles charged partly while on the route. This allows for the use of a smaller and lighter battery pack which could reduce the overall weight of the vehicle. The inductive power transfer (IPT) charging technology provides a contactless inductive charging which allow the electric vehicle to be charged in a wireless manner (Jung et al., 2012). This could save up the charging time and extend the travel distance as the charging could be carried out frequently.

Korsesthakarn and Sripakagorn (2014) mentioned that the choice of electric bus and its charging system would affect the planning of electric bus service. Most of the existing study (Pternea et al, 2015) consider the maximum distance an electric bus could travel (per charge) when designing bus route while the charging system and duration is considered when determining the service frequency (Filippo et.al, 2014). In fact, the maximum distance that an electric bus could travel is not fixed, but it is subjected to the energy consumption which is depended on its vehicle characteristics (such as size and weight, acceleration and deceleration) (Soylu, 2014), road condition (such as flat or slope) (Cheng et al, 2009), and traffic condition (Perrotta et al, 2014). Thus, the maximum distance travelled is a variable since the traffic condition is uncertain during peak hours. Severe congestion might happen unexpectedly which causes delay to the bus and consumes more energy than is expected. If this happens, the bus might not have sufficient energy to complete its route. As such, traffic condition should be taken into consideration when designing the electric bus route. Opportunity charging system installed at the bus stops or along the bus route provide fast charging to electric bus. The quantity and the location to be installed required proper planning in order to maximize the cost benefit (Miles and Potter, 2014). For example, Cheng et al. (2009) mentioned that a charging station should be provided along the steep road to boost the electric bus energy as more energy lost when the bus is travelling uphill.

The objectives of this study comes in twofold. First, it aims to find the best bus route and frequency design for sub-urban city bus services that utilize electric bus. Instead of considering maximum route length, this study considers the traffic condition along the bus routes that could impact the energy consumption level by obtaining the bus average travel speed from one stop to another. A quadratic relationship of energy consumption and bus speed is assumed to determine the energy required per route. Second, the study also aims to perform cost benefit analysis of using electric bus as compared to using conventional diesel bus. Two different types of charging system are considered, i.e. normal charging (or fixed charging) at terminals, and fast charging (or opportunity charging) at both terminals and bus stops. The set-up cost of charging system and operational cost of electric bus is computed. A total of 7 different design scenarios are defined and evaluated using judgmental approach. The total passenger, total passenger travelled distance, total passenger travelled time per year, and profit are among the parameters considered. Emme model (INRO, 2014) is adopted to perform transit assignment in order to optimize the bus route and frequency design. A case study of Putrajaya, Malaysia is developed to test and study the feasibility of replacing electric bus over conventional bus, with engineered transit network to integrate the charging technology into it. Putrajaya is the right place for this study as the government has the intention to convert it into a Green City with one of the objectives to reduce the carbon dioxide emission by 60%. Apart from constructing green buildings, the deployment of green vehicles in transportation is needed to support the plan (Putrajaya Corporation, 2012).

2. LITERATURE REVIEW

The adoption of electric bus system in replacing of the conventional bus required careful planning. Many research studies (Kuhne, 2010, Lorenzo et al., 2014, Cheng et al., 2009; Khaligh and Li, 2010, Li and Zhang, 2009) have shown that the charging system, i.e. the type of battery used and the charging system could affect the bus service operation. The recent charging system of electric bus that being used in various countries, for example in China, an electric bus (with combination of supercapacitors and battery) is introduced by local transportation authority (Gas2, 2015). An electric bus (charged in certain station through wireless charging) was introduced for the first time in Milton Keynes, England (Schofield, 2014). Besides, in Korea the Online Electric Vehicle (OLEV) applies the same method (wireless charging) with different concept of charging is introduced (Jung and Jang, 2015).The major constraint of electric bus is that its operation is limited by the battery capacity (Miles and Potter, 2014) and the battery needs to be charged frequently (Filippo et al., 2014). In addition to this, the attribute of battery such as prolong charging time and weight of battery also play some important role on limiting the electric bus operation (Gill et al., 2014, Li and Ouyang, 2011). All these would have impact on the bus route design and the service frequency.

One of the earliest studies that take into account the environmental factor for bus planning was by Beltran et al. (2009). They considered the environmental factor during bus route planning by dividing the routes into conventional and green paths. The green paths are those part of network which has high concern on the emission and pollution, e.g. residential area, school area, or hospitals. Their model determined the best bus route configuration and service frequency for these green paths. In searching for the optimal solution, genetic algorithms are used to minimize the operator’s costs, user costs and external costs. Fusco et al. (2013) dealt with the problem of transit system design for a mixed fleet of electric and internal combustion buses and introduced a model for the vehicle type choice that involves computation of lifetime internal and external cost. Nevertheless they did not perform the transit network design. The sets of routes for electric bus are fixed. They investigated several scenarios with different fast charging alternatives and constraints related to battery autonomy energy consumption and power transfer from electricity grid. Feng and Figliozzi (2014) developed an intelligent optimization tool for the operator to intelligently dispatch buses and select new technologies that are tailored to their needs and business. They consider the bus life cycle cost model, simulate and predict every capital and operational cost category for different bus technologies.

Korsesthakarn and Sripakagorn (2014) developed an integrated bus scheduling simulation model with the energy storage system. The study showed that the fleet management for different type of energy storage system could affect the quality of bus ridership. Three modules were included into the simulation model, i.e. bus schedule, passenger queue, and bus movement. Results showed that using the super capacitor hybrid and lithium-ion battery could improve the passenger waiting time significantly. Perrotta et al. (2014) carried out a case study to investigate the performance of electric bus on different route types in relation with its energy consumption. An integrated simulation platform with traffic system (simulated using SUMO) and electric bus system (simulated using Simulink) was established for the analysis purposes. It was shown that urban routes (compared to interurban and tortuous route) has the best performance in which least energy per km and less energy was wasted in the braking. Filippo et al. (2014) developed a simulation model for the electric bus system in The Ohio State University to study the feasibility of deploying the electric buses in placed of conventional buses. The findings of the study showed that charging infrastructure design and layout is important in deploying electric bus fleet. Jovanovic et al. (2014) proposed a model for routing of green buses in Belgrade city. The model takes into account user costs, operator costs and the environment state. The model was solved using the neuro-fuzzy logic and Kruskal's algorithm for network design. Pternea et al. (2015) addressed the transit network design problem by incorporating environmental aspects in the forms of emissions minimization and deployment of green vehicles. The decision variables of the model are bus route structure, vehicle type, and service frequency. It was shown that the average bus speed has a strong impact on average travel time and fleet size, while the percentage of satisfied demand depends on the additional distance that passengers are willing to walk. Air pollution is affected by bus speed as well as the number of charging stations.

As a summary, it is important to have a careful planning when electric bus were to be used to replace the fuel bus to serve the routes. Despite its importance, there is limited studies in existing studies to deal with the electric bus planning issue. Hence, this study aims to shed some light on the issues related to electric bus planning.

3. THE STUDY AREA

Putrajaya is the Federal Administration Centre of Malaysia. It is located approximately 25 km at the southern part of the Greater Kuala Lumpur with an area of 11,320 acres and population of about 88,300 people (Wikipedia, 2016). Figure 1 shows the location of Putrajaya. The main transport mode in Putrajaya is by car where it is accessible via a network of highways. In terms of public transport, it is served by the Express Rail Link (ERL) where a station is constructed at Putrajaya Sentral. The ERL is an airport express rail that connects the downtown Kuala Lumpur with the Kuala Lumpur International Airport. It has several stations along the line in which Putrajaya is one of them. Public bus service is provided in the city by a company named Nadi Putra which is operated by Putrajaya Corporation (PJC). It provides 4 types of bus lines, i.e. local, night, direct, and outward services. The Local bus line has 11 routes serving the residents inside Putrajaya from 6 am to 12 midnight daily. The Night bus line has 8 routes that will only be operated on 10 pm, 11pm, and 12 midnight, i.e. only 3 trips per day. The Direct bus line has 31 routes operating during morning and evening peak hours on working days. These lines mainly transport the government servants from/to the residential areas (in various precincts in Putrajaya) to the government office. The Outward bus line has 2 routes transporting residents in Putrajaya to/from the nearby towns such as Cyberjaya.

A total of 146 natural gas buses are used by Nadi Putra to provide the services. Two types of buses are used, the conventional bus with capacity of 63 persons (40 seated and 23 standee), and the mini bus with capacity of 40 persons. Putrajaya has provided a 3.2 km long dedicated bus lane specially cater for public buses and taxis. This is to ensure priority is given to the public buses at the congested stretch for a more reliable bus service. To further improve the bus services, GPS and GPRS systems are installed on all Nadi Putra buses that allow the location of buses be determined real time. The Small Variable Message Sign (SVMS) and plasma display are installed at the bus stops to provide bus arrival information and real-time bus departures information to passengers. Electronic ticketing system is introduced as well to facilitate cashless fare collection.

It has been the government's aim to develop Putrajaya as a Green Technology City with one of the objectives to reduce the carbon dioxide emission by 60%. Apart from having green buildings in Putrajaya, provision of green transportation could help achieving the aim. The initiative to replace the existing bus fleet to electric bus would further push forward to achieve the aim. As such, Putrajaya is a good test bed for electric bus implementation considering that: (1) the town is medium in size; (2) the road network is simple and straightforward; (3) the bus route network is simple and the route length is medium in size.

Figure 1. The Study Area: Putrajaya, Malaysia

4. METHODOLOGY

This section highlights the methodology adopted in the study. The bus transit model is developed using the EMME software in which the transit assignment is performed to estimate the bus ridership and passenger volume. The setting of the electric bus system, particularly on the battery capacity limit and charging rate is highlighted as well. The battery energy consumption model adopted to compute the energy used for each bus route segment based on the bus speed (obtained from Emme model) is presented. Lastly, the performance measures used to evaluate the performance of different design scenarios are explained.

4.1 Electric Bus Network Design with EMME

Emme software is adopted to perform the electric bus transit network and frequency design. Two types of network are created, i.e. traffic and bus transit network based on current condition. On-site data collection is carried out to collect the traffic flow data at junctions and roundabouts, especially at the boundary of the model. This is important for the origindestination (OD) matrix estimation and model validation. The traffic volume obtained from the model is compared to the site data collected. A linear regression line is drawn to represent the fitting of model and site data. An 85% fitting of the regression line (i.e. $R = 85\%$) is acceptable. In terms of bus transit system, the bus route, bus stop (or terminal), bus service frequency, and ridership data is collected by assigning research assistants on-board.

A total of 13 bus routes are modelled in Emme representing existing condition operated in fuel bus. First, bus stops are created in the network on top of the traffic network. Then, the bus routes are built by associating the routes to the stops. Dwell time at stops are set. Lastly, the transit assignment is performed by using the travel time generated from the traffic assignment. The travel speed is then derived from the travel time obtained and the known route length. The energy required (or consumed) for each transit segment is then computed. If the existing bus routes fail to fulfil the energy requirement constraint, it will be amended. The amended bus routes is then modelled in Emme to estimate the ridership and passenger volume. At any of the time, the bus should have a minimum of 20% of battery storage for emergency usage.

4.2 Electric Bus System Setting

This section presents the electric bus system setting. This includes the battery capacity limit and definition of its charging rate. The battery energy consumption model for bus is presented as well.

4.2.1 Battery Capacity Limit

The bus battery capacity is assumed as 300 kW. It is set that the minimum battery storage during any trip and at any time is 20% of its capacity. This means that the battery capacity of buses could not fall below this level when they arrive at the terminal. They will be charged to level of 80% of its capacity before it is allowed to continue for its next trip. At the end of the day, the buses are charged for overnight. As such, the maximum utilized capacity of each trip is 60% of battery capacity. The maximum utilized capacity is the same in every trip of a bus line. Based on such design and by using backward calculation, the energy limit of an electric bus after completing its first trip is 40% of the battery capacity. This means that the existing bus route will fail if the balance battery storage is lesser than 40% of its capacity after completing the first trip. Such bus routes need to be amended.

4.2.2 Charging System: Station and Rate

Some assumptions are set for the charging system. Two types of charging systems are investigated in this study, namely normal and fast charging system. The normal charging system is installed at the terminals to provide end trip or/and overnight charging. The charging rate is assumed at 0.715 kWh per minute. Each bus line is provided with one charger at the terminals in which no queuing is considered. In such a case, it is assumed that a large piece of land is available at the terminals for charging system installation. The fast charging system charges the battery at a faster rate, i.e. 8 kWh per minute. The charges are installed at the curb side for en-route charging as well as at the terminals for end trip charging. A curb side charging kiosk will be installed if the bus stop is busy with a minimum of total passenger volume of 20 people. The stops with higher number of passenger volume are given priority for the installation. A charging kiosk could be installed with 2 or 3 charges. It is assumed that the number of charges is sufficient to serve the buses with no queuing is considered. A maximum of 3 minutes charging time is assumed at the stops.

4.2.3 Battery Energy Consumption Model

Greaves et al. (2014) established a quadratic relationship to describe the relationship between battery consumption with travel speed is shown in Figure 2. The graph shows that the battery is consumed least at travel speed in the range of 40 km/hr to 60 km/hr. Otherwise if the travel speed is lower than this range, the energy consumption increases with the decrease of speed (for speed lower than 60 km/hr). If the travel speed is greater than 60 km/hr, the energy consumption increases with the speed. This quadratic relationship is adopted in this study to compute the stop-to-stop energy consumption by the bus. The travel speed is computed from the bus route segment travel time obtained from the Emme bus transit model developed.

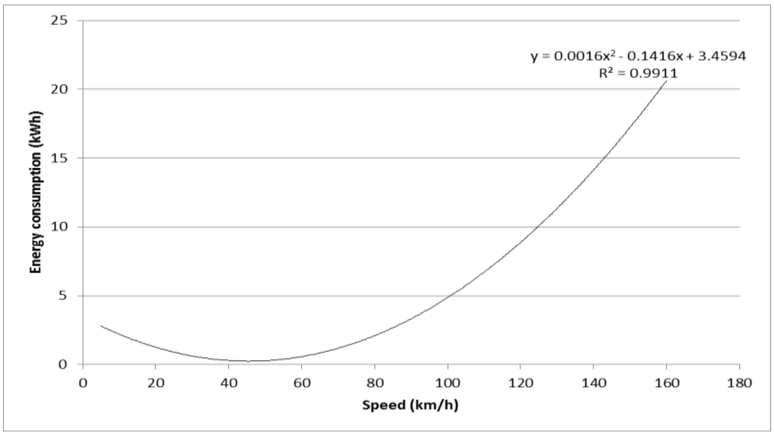

Figure 2. Battery Energy Consumption Vs Travel Speed (Greaves et al., 2014)

4.2.4 Computational of Bus Fleet Size

Bus fleet indicates the number of buses required for each bus line in order to fulfil the passenger demand. Schedule-based method is adopted in this study to compute the bus fleet size. For each bus line, the line average travel time is obtained from the Emme bus transit model. It also takes into account the bus layover time and battery charging time at terminals. The charging time required is based on the charging system and its rate as mentioned in Section 4.2.2. The bus line service frequency is also taken into consideration. The bus fleet size, N, is computed by eqn.(1).

$$N = \text{nhint}\left(\frac{\theta}{h}\right) \tag{1}$$

where θ is the cycle time expressed in eqn. (2) and h is the service headway.

$$\theta = T + t_l + t_L + t_c \tag{2}$$

where T is the total stop-to-stop travel time, i.e. $\sum_{\forall i} t_i$, t_l is the minimum layover time required, t_L is the excess layover time needed to make the cycle an integral multiple of the headway, and t_c is the battery charging time at terminals or/and curb side kiosks based on the charging system and rate specified in Section 4.2.2.

4.2.5 Cost Assumption

Many studies (such as Fusco et al, 2012) commented that the acquisition of electric bus involves high capital cost, but with lower operating and yearly maintenance cost. Some assumption is made on these costs to enable the comparison of costs involved for various electric bus design scenarios. The cost assumed is shown in Table 1. It is assumed that the life span for an electric bus and its battery is 12 years. It has no salvage value at the end of Year 12. It is also assumed that the normal and fast charging station could be used for 10 years once installation is done.

Table 1. Electric bus and its associated cost

Description	Cost (RM)*
Electric Bus (BYD Auto, 2016)	1.22 million per bus
Energy price	0.42 per kWh-day
Energy cost (Aber, 2016)	0.72 per km-day
Maintenance cost (Aber, 2016)	13,000 per year
Normal charging station (Agenbroad and Holland, 2016)	16,000 per charger
Fast charging station (Agenbroad and Holland, 2016)	240,000 per charger

*Note: 1 USD= RM 4.40 (at 27th December 2016)

4.2.6 Performance Measures

The Measures of Effectiveness (MOE) adopted for evaluation of various design scenarios are: total passenger per year, total passenger travelled distance per year, total passenger travelled time per year, total energy consumption per year, annual cost (maintenance and capital cost), revenue, and profit. The total passenger per year, P, gives the total passenger volume for the entire fleet for a year as shown in eqn. (3). It is expressed in the unit of million-passenger per year

$$P = \sum_{j=1}^{J} \left[N_j * R_j * p_j * 365 \right] \quad (3)$$

where N_j is the fleet size, R_j is the number of trip per day, p_j is the passenger volume per trip for bus line j, and J is the total number of bus lines in the study. The passenger volume per trip is obtained from Emme bus transit model and assumed to remain the same for all trips.

The total passenger travelled distance per year, D, is expressed in eqn.(4) in the unit of million passenger-km per year. The passenger travelled distance per trip, d_j is obtained from Emme bus transit model and assumed to remain the same for all trips.

$$D = \sum_{j=1}^{J} \left[N_j * R_j * d_j * 365 \right] \quad (4)$$

The total passenger travelled time per year, TP, expressed in million passenger-hour per year with the passenger average travel time per trip, tp_j, obtained from the Emme bus transit model, is expressed as follow:

$$TP = \sum_{j=1}^{J} \left[N_j * R_j * tp_j * 365 \right] \quad (5)$$

The total energy consumption per year, E, expressed in million kWh is computed manually based on the line average travel speed (station-to-station) converted to the enery consumed, e_j. It is then assumed that the energy required per trip remains constant over the year.

$$E = \sum_{j=1}^{J} \left[N_j * R_j * e_j * 365 \right] \quad (6)$$

The annual cost includes the depreciated electric bus cost, the energy spent, maintenance cost, and depreciated charging station installation cost. The revenue is computed by multiplying the annual ridership projected for each bus line with the bus fare assumed as RM 1 for each trip. The profit subtracts the cost from the revenue.

5. DESIGN SCENARIOS

This section presents the various scenarios set in the study to test the impact of different factors to the electric bus system and design.

5.1 Conventional Scenario

The existing Nadiputra bus transit system in Putrajaya consists of 13 bus lines with an average frequency of 15 minutes (during peak hours). The current bus fleet size is 146 running in between of two bus terminals.

5.2 Electric Bus Design Scenarios

A Benchmark scenario is created by taking the same bus route system specification as the conventional scenario. Normal charging stations are assumed to be installed at three terminals on these routes. A charger is reserved for each bus at the terminals by assuming that there is no land area limitation for charger installation. The number of chargers installed at each terminal is depended on the number of buses originate/destine to the terminals. The terminals are shown in Figure 3. It could be seen that (as will be presented in the Results Section), some of the bus lines could not fulfil the energy requirement if the existing bus routes network and frequency are used for electric bus. Thus, various scenarios are created to investigate the best approach in electric bus route design. Design Scenario 1 (DS 1) studies the change of bus route network by splitting the failed bus routes into shorter route. A total of 16 routes are considered. Design Scenario 2 (DS 2) investigates the impact of charging type on the electric bus system. DS 2 differs from DS 1 as an additional of 16 fast chargers are installed at the terminals for end trip charging with a faster charging rate. Design Scenario 3 (DS 3) maintains the route network as in Benchmark Scenario (i.e. 13 routes), but study the impact of boosting the electric bus energy en-route with fast charging facilities. Four charging kiosks (with 9 chargers) are assumed to be installed at four busy bus stops to provide en-route charging for buses. The location of the kiosks are shown in Figure 3.

Design Scenario 4 (DS 4) investigated the impact of changing the type of charging system. Instead of only providing fast charging system at curb side, a total of 13 chargers are assumed to be installed at the terminals to provide fast charging at end trip. The en-route chargers are reduced to 3 kiosks (with 6 chargers). The last 2 scenarios looks at the best frequency designs. In Design Scenario 5 (DS 5), a frequency of 10 minutes are set for all bus lines while for Design Scenario 6 (DS 6), a frequency of 25 minutes are used. This represents deigns with shorter and longer headway compared to the headway setting in DS 4. The summary of the design scenarios and their setting is shown in Table 2.

Table 2. Design description for all scenarios

	Conventional	Benchmark	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Type of bus	Fuel				Electric			
No. bus lines	13	13	16	16	13	13	13	13
Headway (min)	15	15	15	15	15	15	10	25
Terminal charging	-	Normal	Normal	Normal &Fast	Normal	Normal &Fast	Normal &Fast	Normal &Fast
Terminal location	-	A &B	A,B &C	A,B &C	A&B	A&B	A&B	A&B
Curbside charging	-	-	-	-	Fast	Fast	Fast	Fast
Kiosk location	-	-	-	-	1,2,3,4	1,2,3	1,2,3	1,2,3
No. of curbside charger	-	-	-	-	2 per kiosk, 3 at kiosk 1	2 per kiosk	2 per kiosk	2 per kiosk

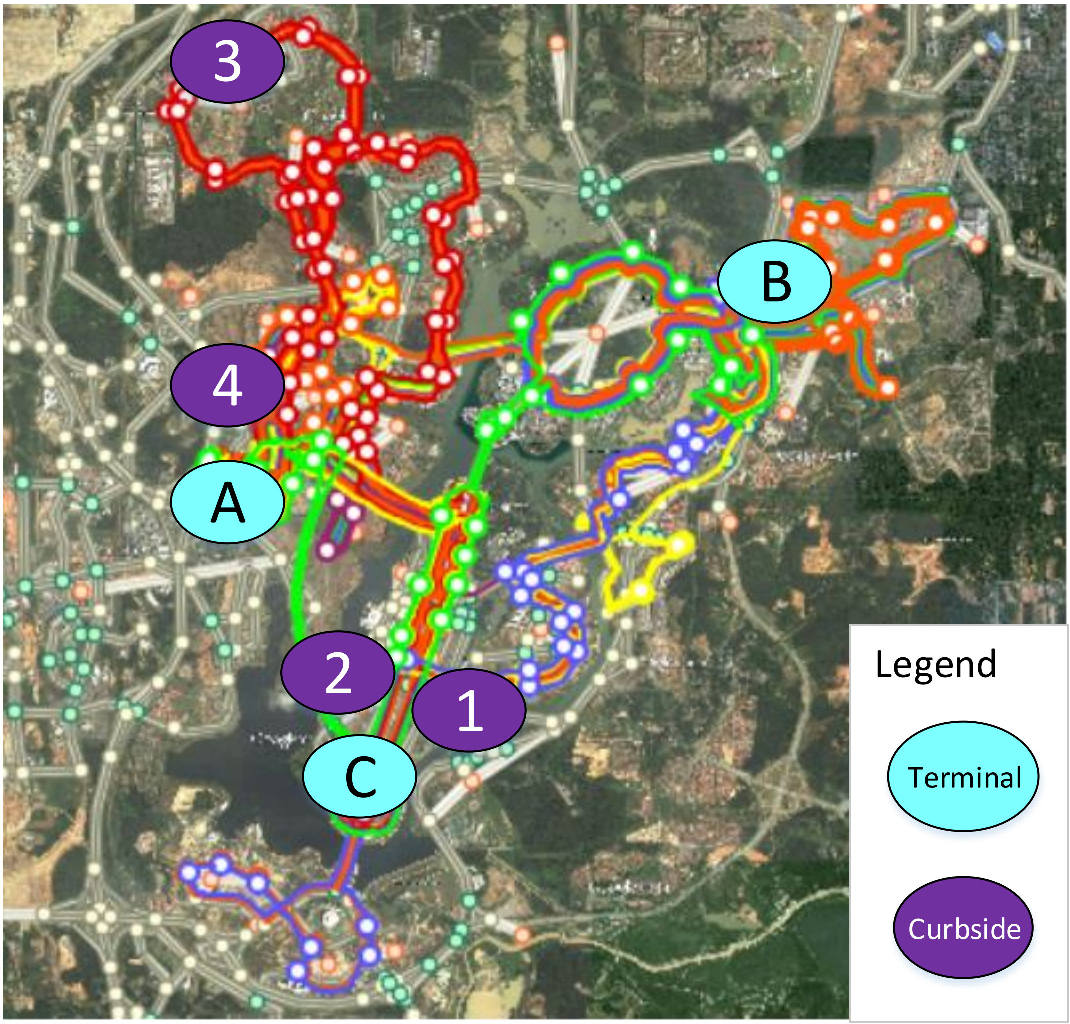

Figure 3. Location of chargers: Terminal and curbside

6. RESULTS AND DISCUSSION

The results of various scenarios are presented in Table 3. Results include the bus fleet, size, number of chargers and their locations, the system's performance, and cost/revenue analysis. The following sub-section discusses these findings.

6.1 Impact of Electric Bus Acquisition

When the electric bus is planned based on the original bus routes (run by the fuel buses), it was found that 3 out of 13 lines fail to fulfil the minimum energy storage set in this study. Figure 4 shows the remaining battery capacity at the end of the trip. The threshold set is 40%. It could be seen clearly that Line 07, Line 08, and Line 09 do not satisfy this requirement. Hence, the buses running on these lines might not have sufficient battery to finish their trips. This is mostly due to long travel time for these routes. It is thus suggested that these failed lines should be cut short and splitted into two routes. DS 1 shows the results when the routes of these lines are splitted into two shorter routes. The bus fleet size required to serve all passengers increases from 169 buses to 255 buses, i.e. about 34% increase. This is accompanied by the increase of annual cost and total energy consumption. The passenger volume and revenue increase as well, but with the profit lesser than those in benchmark scenario. However, it is important to note that the results of Benchmark scenario presented in Table 3 is computed for 10 bus lines only (except the 3 failed bus lines).

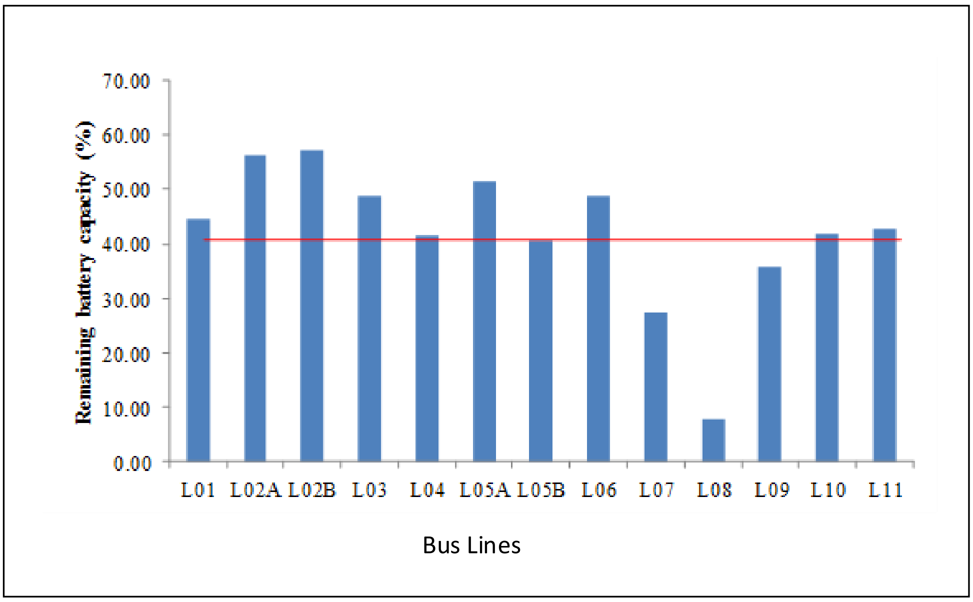

Figure 4. Energy balance at end trip 1

6.2 Impact of Charging System

DS 1 requires a fleet size of 255 electric buses to serve all the 16 routes by adopting normal charging for end trip and overnight charging at the terminals. The charging rate for normal chargers are 0.715 kWh per minute. If fast charging system is adopted for end trip charging with a faster rate of 8kWh per minute, the fleet size required to serve all the 16 routes is 100 electric buses, which is about 60% lesser. With such smaller fleet size, the annual cost spent is lesser but with same passenger volume served and revenue earned. As such, the deficit (instead of profit) is smaller for DS 2 when compared to that in DS 1. This indicates that it is worthwhile for the bus operator to spend more on the charging system since the cost could be offset by the needs to have more bus fleet.

If the fast charging system is not provided for all bus lines at terminals, but fast charging kiosks are provided for en-route charging. DS 3 shows that 4 kiosks with 9 chargers are provided at 4 different locations as shown in Figure 2. However, it is to note that these fast chargers could only be used by 3 bus lines (L07, L08, and L09) as they pass through these locations. As such, it could be seen that a large number of bus fleet is still required, especially to serve others lines with normal charging system at terminals. This indicates that importance of the choice of fast charging kiosks locations. This study decides the kiosks location based on passenger volume, another way of setting the kiosks location could be based on the bus density at stops. The bus fleet required by DS 3 is thus higher than DS 2, as every bus line has a fast charger in DS 2 oppose to DS 3 in which only some bus lines have the fast charger. However, the bus fleet required by DS 3 is still smaller than DS 1. As expected, the deficit is higher for DS 3 compared to DS 2. If fast charging system is provided in both terminals and cur sides, the fleet size required is the smallest, i.e. only 94 electric buses. A lower cost is required since the electric bus fleet is smaller which makes the bus operator to be able to enjoy a profit of 1.5 million. Comparing all the scenario, DS 4 shows the best design scenario.

Table 4. Results for various design scenarios

	Benchmark	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
No. bus lines	13	16	16	13	13	13	13
Headway (min)	15	15	15	15	15	10	25
Bus fleet	169	255	100	216	94	142	29
Terminal charging	Normal	Normal	Normal &Fast	Normal	Normal &Fast	Normal &Fast	Normal &Fast
No. of charger at Terminal A*	103N	144N	60N, 9F	150N	67N, 9F	100N, 9F	21N, 9F
No. of charger at Terminal B*	66N	96N	35N, 6F	66N	27N, 4F	42N, 4F	8N, 4F
No. of charger at Terminal C*	-	15N	5N, 1F	-	-	-	-
Total Passenger (MPassenger/yr)	26.7	36.8	36.8	36.0	35.2	41.7	25.3
Total passenger distance travell (MPassenger.km/yr)	116.6	154.6	154.6	158.1	158.1	169.0	124.9
Total Passenger Travel time (MPassenger.hr/yr)	1.63	2.2	2.2	2.2	2.2	2.4	1.7
Total energy consumption per year (million kWh)	31.1	45.2	45.2	38.5	38.5	42.8	28.4
Annual cost (RM million)	39.5	56.4	37.3	48.8	33.7	42.2	11.9
Projected Revenue (RM million)	26.7	36.8	36.8	36.0	35.2	41.7	25.3
Projected Profit (RM million)	(12.8)	(19.6)	90.5)	(12.8)	1.5	(0.4)	5.4

Note*: N stands for Normal charger, F stands for Fast charger

6.3 Impact of Service Frequency

The charging system of DS 5 and DS 6 is set the same to those for DS 4. DS 5 has a shorter headway (i.e. 10 minutes) while DS 6 has a longer headway (i.e. 25 minutes). It could be seen that with shorter headway, the fleet size required is higher, i.e. 142 electric buses, about 50% more (for DS 5), while a longer headway required smaller fleet size (for DS 6). Likewise, DS 5 could serve higher passenger volume and utilize more energy. Nevertheless, the operating cost is higher (as compared to DS 4) which causes a slight deficit to the bus operator although its revenue is the highest among all the scenarios. DS 6 serves the smallest passenger volume with the lowest revenue earned. But due to its small fleet size that causes lower annual cost, it shows the highest profit among all scenarios. Nevertheless, DS 6 is not preferable as it means that the bus service could not capture most of the passenger demand.

4. CONCLUSIONS

This study adopts the judgemental approach to investigate the best design for electric bus system for sub-urban service by taking into account the bus routes and frequency, charging system types and their locations. Emme model is developed to find the stop-to-stop travel time and to predict the passenger volume and travel distance. Instead of considering the maximum route length constraint by the electric bus battery, this study took a novel approach by considering the energy spent or required by each bus line. This is carried out by converting the stop-to-stop speed to the energy required by using a quadratic speed-energy consumption relationship.

A total of 7 scenarios are tested and the results reveal that it is not necessary to amend the bus route network when electric bus system is introduced. The best design scenario (with the highest profit- DS 4) maintains the existing bus route network and service frequency, but with fast charging systems installed at both terminals and curb side kiosks to charge the electric bus at a faster rate. From the passenger perspective, a short headway is preferable (with the shortest headway, 10 minutes- DS 5) as it could capture more passenger demand, although the revenue is not high for the operator due to higher annual cost (with larger fleet).

The limitation of the study is to deal with the assumptions made. The large number of charger at the terminals are not feasible and always constraint by the land area. Queuing condition for charging services which could impact the service frequency and schedule should be considered as well. Lastly, the annual maintenance cost should take into consideration the maintenance cost for the charging facilities. It is recommended that these limitations are looked into and handled properly in the future study.

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