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Scenario-based electric bus operation: A case study of Putrajaya, Malaysia

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ABSTRACT

Globally, transportation sector has emerged as one of the major sources of air pollution. Correspondingly, green mobility (with electric bus) is gaining increasing attention as an essential step to mitigate emission concern. As such, a proper electric bus network design and fleet planning is important especially for bus operator to acquire an adequate number of electric bus, right on time, in order to operate electric bus system viably. Thus, this paper aims to examine the possibility to operate electric bus as a replacement for the conventional bus operation (with natural gas buses for the study area in Putrajaya, Malaysia). In order to determine a proper-designed electric bus operating system in terms of electric bus route, service frequency and quantity, the proposed methodology is developed with the aid of a traffic modeling software to cater various scenarios. Based on the existing (conventional) traffic and transit system in Putrajaya, the developed electric bus operating model is calibrated accordingly by considering various operational concerns including battery capacity and charging facility. The resultant findings revealed that the developed electric bus operating system in Putrajaya outperforms the conventional bus operation, not only in generating a higher profit margin for the bus operator, but also satisfying the passengers in a better manner (by carrying more passengers per unit of bus with a lower energy consumption).

Introduction

Globally, the emission from road transport was found to cause not only a severe threat to inner-city air quality but also global warming (due to the emission of carbon dioxide, CO_2). In particular, transportation activities involve the side effects (externalities) of noise pollution, air pollution and traffic congestion, which in fact require attentive concern from the relevant authorities (including transport policy makers, operators, public, etc.). Given that the transport sector accounted for more than 25% of worldwide energy consumption, these externalities must be tackled appropriately in order to assure the sustainable growth of transportation (Juan et al., 2016). Specifically, the main contributors to greenhouses gas (GHG)

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emissions from the transportation sector are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Ong et al., 2011; Shahid et al., 2014). In order to preserve the environment, the adoption of electric bus, as a viable public transport, turns out to be a good attempt to kick-start green mobility (Doucette and McCulloch, 2011). Electric bus is the emerging technology which is environmental friendly and designed to reduce carbon emission level (Foltyński, 2014; Jouman et al., 2013). In other words, the application of electric vehicles, as one of the most promising strategies, can be a good solution to relieve the environmental problem (Juan et al., 2016).

Physically, electric bus is quite similar to conventional bus in appearance, but it is totally different in the respective operating system. The difference in power generating mechanism of both buses is the main variation. Technically, a conventional bus consumes either diesel or gasoline and undergoes internal combustion (to convert the chemical energy to mechanical energy) to operate. On the other hand, an electric bus is electrified by chemical energy in batteries box that later turns into electrical energy (generated by electric motor). The function of electric motor is to draw energy from the batteries box and runs the vehicle. Besides, the conventional bus has more moving parts in engine system as compared to electric bus that has motor as the only moving part. Therefore, conventional bus incurs higher maintenance cost as it requires regular oil changing, tune up for better mileage, exhaust system and etc. Conversely, electric bus uses lead acid batteries that are sealed and requires no maintenance. Environmentally, conventional bus emits CO_2 that contributes to global climate change but electric bus is environmental friendly. Thus, the replacement of conventional bus with electric bus is beneficial not only to the social economy but also the environment. Besides, if the electric bus operating system is well-designed with a high reliability and satisfactory performance, it could also results in a shift of travel mode from private to public transport as well.

Over the years, battery capacity and charging technology of electric bus have been improving from low capacity and slow charging to high capacity and ultrafast charging, which emerge to be an important factor in affecting the decision-making of designing electric bus operating system. However, the present electric bus technologies have created some operational concerns. The limited electricity level has brought up the battery limitation. Consequently, electric bus operates in a limited distance and time. In addition, there are some other attributes of the battery, such as high cost, heavy battery pack, long charging time and etc., which greatly affecting the application of electric bus (Gill et al., 2014; Li and Ouyang, 2011). To capture these limitations in operation, a proper-designed electric bus operating system is indeed required.

Correspondingly, this paper aims to look into the possibility to replace conventional bus operation with electric bus, by analyzing the potential benefits for various scenarios (including financial and environmental benefits). By taking into consideration numerous operational constraints, the proposed study allows the bus operator to determine the quantity of electric bus to be acquired (in making fleet planning decision) while the developed electric bus network design is capable to determine a desired electric bus route and service frequency. Besides, this study also contributes on travel forecasting, particularly on demand modeling as well as mode shifting. Notably, the aim of this paper is not to determine the best optimization solution, but to compare and analyze the performance of varying strategies (scenario-based) which might emerge to be the most desired scenario in operating electric bus system in a better manner, specifically for the study area in Putrajaya, Malaysia. Analyzing various alternative scenarios is vital since it appreciates the roles of different strategies and identifies the most performing operating network for electric bus. In particular, scenario-based analysis plays the role to determine the most desired scenario to operate electric bus. This can be done by comparing various operating scenarios with different operating features (include varying number of routes, headway and charging facility). By having different scenarios in place, the developed methodological framework is able to make comparative analysis of electric bus performance not only from demand perspective but also supply aspect. In overall, it is anticipated that the proposed methodological framework as well as the resultant findings would assist the bus operator to acquire and operate electric bus environmentally which will benefit the bus users in return.

The remaining of this paper is organized accordingly by discussing the relevant literature review in Section ''Literature review'', followed by the methodological framework in Section ''Methodology''. In order to examine the applicability of the proposed approach, an illustrative case study is analyzed with a detailed discussion (in Section ''An illustrative case study''). Then, this paper is concluded in Section ''Conclusions''.

Literature review

This section presents the relevant review on electric vehicle (including electric bus), by highlighting the concerned issues of applying electric vehicle in practice. And also, the relevant studies that focus on the performance of electric bus (in terms of economic, environmental, energy and operational aspects) are included and discussed accordingly.

A brief overview on electric vehicle

In view of the fact that transportation sector is 98% relying on fossil oil which is greatly affected by the changes in energy resources, the governments around the world and automotive companies have recognized the value of alternative fuel vehicles (AFVs) for green transportation and have been implemented economic policies to support electric vehicles (EVs) market (Jing et al., 2016). Fontaínhas et al. (2016) highlighted that EVs have several important advantages (compared with internal combustion engine (ICE) vehicles), namely silent operation, zero tailpipe emissions and high tank-to-wheel efficiency. Nevertheless, there are some concerns which impose challenges to the application of EVs. The three major issues of the appli-

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cation of EVs are limited battery capacity, long charging time and scarcity of charging facility (Juan et al., 2016; Jing et al., 2016; Brandstatter et al., 2016).

With regard to the **battery capacity**, the energy consumption and maximum vehicle range of EVs are considered to be proportional to the travelled distance which is considerably influenced by the driving and environmental conditions, e.g. the speed profile (Brandstatter et al., 2016). EVs need to have a minimum electricity level to travel. As such, the travelled distance and time of EVs is relatively limited and hence EVs require frequent charging which has to be performed at a specific charging station. Besides, range anxiety (i.e. the fear of a driver of having insufficient electricity to reach the destination) is also another concern for using EVs (Jing et al., 2016; Dong et al., 2014; Mallig et al., 2016). Range anxiety not only discourages consumer acceptance but also restrains the social benefits as the users of EVs may be forced to use the vehicle only for short trips and drive fewer distance. One way to mitigate range anxiety is through the deployment of public charging infrastructure (Dong et al., 2014).

The charging infrastructure for EVs can be divided into two categories, namely fast charging and slow charging. A fast charging station can quickly recharge an EV in less than 5 min (Wang and Wang, 2010) but this kind of charging can significantly shorten the life of the battery. Conversely, a slow charging station needs a longer time to recharge an EV. For example, vehicles require 2–8 h to fully charge their batteries at slow charging stations of Level 1 or 2 (110–240 V). Therefore, **charging time** has been a critical factor influencing the public acceptance of EVs. A major solution could be to remove the existing battery that is nearly depleted and replace the battery with a fully charged one (Li, 2014). Such a method is called battery swapping. Battery swapping, which requires approximately less than 10 min, is reasonably fast, but all of the vehicles are required to use the identical pallets and batteries. Besides, battery swapping requires a huge investments to set up the system (Jing et al., 2016; Brandstatter et al., 2016).

Another major barrier to the application of EVs is the limited number of charging stations, i.e. the scarcity of **charging facility**. Specifically, the quantity of the charging station is limited and also a station cannot serve more than the arriving vehicles during a specific time. In other words, only a small number of EVs can be charged simultaneously. For the circumstance of battery swapping station, the EVs may need to leave and go to another station if there is no fully charged battery available at the station. Alternatively, they may need to wait for a battery to fully or partially charge in order to complete the swapping process. Apparently, the availability of charging facility is indeed important for EVs to complete the trip. In view of the high capital cost of building this facility, the governments and EV companies are concerned about where to locate a particular charging station.

A brief overview on electric bus

Practically, electric buses operate across different degrees of electrification that rely on the configuration of propulsion system (Bayindir et al., 2011; Miles and Potter, 2014). There are several types of electric buses, including hybrid electric, fuel cell electric and battery electric buses (Ribau et al., 2014; Yong et al., 2015). Technically, the battery electric bus (BEB) is powered by electricity that is stored in a non-board battery package and its engine configuration does not include any mechanical parts (Poullikkas, 2015; Zivanovic and Nikolic, 2012; Offer et al., 2010; Kumar and Jain, 2014). In order to support the operation of electric buses, there are various battery types in the market such as lead acid, NiMH (nickel-metal hydride battery) and lithium-ion batteries (Elgowainy et al., 2013). Lithium-ion batteries are the most common type for BEB buses and provide suitable balance for both energy and power densities. The cost for lithium-ion batteries is high but it performs better than lead acid and NiMH batteries in term of power, energy density and battery lifetime.

The BEB is operationalized in two forms, namely opportunity and overnight which differ in terms of travel range and charging time (Miles and Potter, 2014; FCH-JU, 2012). The opportunity electric bus has a smaller battery package that offers a limited range (20–30 miles) (FCH-JU, 2012) and its full charge (80–100%) can be achieved within 5–10 min. In contrast, the overnight electric bus contains a relatively larger battery package with a range up to 200 miles and a much longer charging time (2–4 h). For the charging infrastructure, overnight BEB requires super or fast charging station at the depot and additional supply of battery if a battery-swapping scheme is in place. Opportunity BEB can operate with various alternatives for charging infrastructure such as charging spots, overhead charging poles and inductive charging (Kakuhama et al., 2011). Currently, there are several schemes in place that are implemented to overcome the long charging time for overnight BEB. Several operators have introduced battery exchange stations to overcome the long charging time for batteries. Conversely, the opportunity BEB benefits from opportunistic charging at stations during the boarding and/or alighting of passengers.

There are several studies that analyze the operating performance of electric buses (as discussed in the following subsections). These studies are mainly developed in terms of economic, environmental, energy and operational aspects. In particular, the operational aspect of electric bus can be further grouped into three categories, namely electric bus route design, charging infrastructure and scheduling.

Economic, environmental and energy aspects of electric bus

Generally, economic studies focus on the cost-benefit analysis of implementing electric bus in transit (Lajunen, 2014; Nurhadi et al., 2014), environmental models investigate the potential of GHG emission reductions from electric bus (Ribau et al., 2014; Elgowainy et al., 2013; McKenzie and Durango-Cohen, 2012; Ou et al., 2010; Xu et al., 2015; Torchio and Santarelli, 2010; Filippo et al., 2014) and energy consumption analysis examines the energy efficiency of electric bus (Lajunen, 2014; Ou et al., 2010).

With regard to the **economic performance**, total cost of ownership (TCO) has been identified as one of the main barriers for the implementation of electric bus. TCO includes manufactured price and also the cost for maintenance, operation, energy distribution, infrastructure, emission, insurance and end-of-life (FCH-JU, 2012). For manufacturing price, it was found that all electric buses are more expensive than their diesel counterpart. In terms of operational cost, electric bus performs better than the diesel bus with an average reduction of 80% in running cost. However, in terms of infrastructure cost, the opportunity BEB is considered the most expensive option. Although overnight BEB require major infrastructure modification for charging stations, the opportunity BEB requires a higher density of charging points along the bus routes, i.e. one charging point for each 10–20 km (Zivanovic and Nikolic, 2012). Although the opportunity bus is relatively cheaper than the overnight bus due to the smaller on-board battery package (Lajunen, 2014; Feng and Figliozzi, 2013), the overnight BEB is more expensive than opportunity BEB based on the TOC. In spite of the various efforts to calculate the TCO of electric buses, the literatures revealed that there is a lot of uncertainty in the estimation of TCO (Lajunen, 2014).

Environmental performance of EB is introduced in the literature in the form of Well-to-Wheel (WTW) assessment of greenhouse gas (GHG) emission. Basically, WTW assessment integrates the generated emissions in two stages, i.e. Well-to-Tank (WTT) and Tank-to-Wheel (TTW). In particular, WTT measures the GHG emissions of fuel (i.e. diesel, hydrogen and electricity) at both production and distribution stages while TTW measures the GHG emissions of the fuel during the usage stage. To calculate the GHG emission for WTT, several models have been developed. These include the GREET model in the US, the GHGenius in Canada and the RED model in Europe. Mahmoud et al. (2016) revealed that the fuel production method has a significant impact on the emitted GHG emission. On the other hand, TTW assessment is typically carried out based on the operational data or vehicle simulation models. The analysis showed that BEB operates with zero local GHG emissions for a 12-metres bus (Mahmoud et al., 2016). In overall, the WTW evaluation shows that BEB has great potential to reduce GHG emissions. Apart from the emission reduction, it was also found that electric bus operates with lower noise and vibration due to the absence of mechanical parts.

In terms of **energy efficiency**, electric buses operate with different sources of energy, e.g. the electricity for BEB, hydrogen for FCEB (fuel cell electric bus) and fossil/biofuel for HEB (hybrid electric bus) (Van Mierlo et al., 2006). Each source of energy possesses unique characteristics that influence the performance of electric bus. Energy efficiency, which is often determined as the net volume of energy required for one kilometer travel, is highly dependent on Energy Storage Systems (ESS) (Zivanovic and Nikolic, 2012; Khaligh and Li, 2010; Catenacci et al., 2013). The efficiency of ESS is evaluated based on three main criteria, i.e. energy density, power density and cost. Correspondingly, Song et al., 2014 highlighted the functionalities of supercapacitor to absorb the regenerative energy. Mapelli et al. (2013) also showed that supercapacitor is the best energy storage device (with the capability of fast charging) to solve the problem of long charging time and short battery life.

Operational aspect of electric bus

Electric bus operations are regarded as the keystone for operating electric bus in the public transport sector (Mohamed et al., 2017). With regard to the performance of electric bus (in terms of bus operation), it was found that most studies mainly focus on the analysis of electric bus route design, charging infrastructure and scheduling (including charging scheduling). However, most of these analysis were discussed separately. In other words, the study that simultaneously analyze the electric bus route design and fleet planning (particularly in the form of scenario analysis) is very limited.

For **electric bus route design**, the consideration of wider objectives and more operational constraints (in comparison to the traditional vehicle routing problem) pose new routing models and application scenarios which consequently leading to more complicated optimization problem (Lin et al., 2014). In view of the fact that exact algorithms can only tackle problems of a relatively small scale, approximate algorithms (including classical heuristics and metaheuristics), which are capable to find very near-optimal solutions for large-scale problems within a very satisfactory computation time, are more commonly used in practice. For electric bus route design, Genetic Algorithm (GA) appears to be a promising metaheuristic approach primarily due to its ability of providing a robust search and also a near optimal solution in a reasonable time (Pattnaik et al., 1998). Beltran et al. (2009) adopted GA to solve transit network design problem by considering green and non-green sub-networks for the city of Rome, Italy. Their optimal outputs include bus routes and the corresponding service frequency (at minimal operating cost). Pternea et al. (2015) solved the transit network design problem for conventional and electric bus by determining the optimal bus route and frequency (with the aid of GA) for the bus network in Crete, Greece. However, Beltran et al. (2009) and Pternea et al. (2015) did not consider the location of charging facility in their optimization models. Besides, Perrotta et al. (2014) simulated the performance of electric bus for three different routes in the city of Oporto, by analyzing the correlation between the type of bus route and the amount of energy required for bus operation. They showed that the most demanding route consumed more energy to operate and wasted more energy on the braking resistance forces. Fusco et al. (2013) determined the vehicle type choice for a mixed fleet of electric and internal combustion buses for the city bus system in Rome, Italy. The results show that the operating scenarios with electric bus have higher investment and personnel costs but they are compensated by lower environmental and energy costs.

Some relevant studies on **electric bus charging infrastructure** can be seen in Rogger et al. (2015), Miles and Potter (2014), Xylia et al. (2017) and Mohamed et al. (2017). In particular, Rogger et al. (2015) performed simulation to analyze the extent existing bus network (in Muenster, Germany) which can be electrified with fast charging battery buses. They showed that battery weight (size) is the limiting factor for the installable battery capacity in electric bus. Thus, they highlighted that a reduction of the demanded passenger capacity is enable to increase the installable battery capacity so that the required charging power can be reduced. By analyzing the city bus network in Milton Keynes, Miles and Potter (2014) also highlighted that battery size has a significant impact on the success of operating electric bus. In particular, they revealed that it is necessary to reduce battery size in order to cut down additional capital cost (by lowering the running cost). Xylia et al. (2017) developed a mixed integer linear programming model to optimize the distribution of charging infrastructure for electric bus, with minimum annual costs and energy consumption. The results, for the bus system in Stockholm (Sweden), showed that the shorter distances between bus stops in inner-city routes favor the use of the electricity buses. And, the optimal location to install charging facility focuses at major public bus transport hubs connecting to the train and subway system. Besides, Mohamed et al. (2017) investigated the implementation of route design of electric bus in Canada by considering flash, opportunity and overnight charging facility. Their simulation results show that flash and opportunity charging are more feasible for bus operation but they suffer from high and intermittent power demand.

With the aim to solve **electric bus scheduling** problem, Zhu and Chen (2013) formulated a multi-objective optimization model not only to minimize the capital investment for electric bus fleet but also the total charging demand. For the study area in China, the results revealed that increasing fleet investment will result in an increase of the total charge demand which subsequently leads to an additional burden on the charging station. Focusing on the charging schedule of electric bus, Paul and Yamada (2014) used *k*-Greedy algorithm to analyze the operation of electric bus system in Japan. The simulation results show that the travel distance of electric bus could be maximized while reducing the fuel cost and CO_2 emission. In order to minimize total construction cost of fuel-cell electric bus operating system, Ke et al. (2016) adopted GA to simulate the operation and battery charging schedule based on an existing schedule and route network in Penghu, Taiwan. Their results showed that although daytime charging involved electricity uses during peak hours and thus incurred additional costs, it contributed to the overall reduction in the construction cost. Besides, Qin et al. (2016) performed simulation to determine an optimal charging strategy for electric bus (with the aim to minimize demand charges) for the bus network in Tallahassee, United States. Their results showed that the demand charge is proportional to the peak demand. And, a higher charging threshold results in larger number of charging events and shorter charging duration. Recently, Wang et al. (2017) developed a model to optimize electric bus charging schedule (with optimal number of charging stations and chargers) that minimizes total annual costs. Their results (for the case study in Davis, California) showed that range anxiety can be eliminated by adopting certain recharging strategies. Besides, the comparative analysis revealed that it was more economical and environmental friendly to utilize electric buses than diesel buses.

Concisely, the afore-mentioned studies highlighted that there are various elements and concerns that must be tackled explicitly in assuring a viable electric bus operating system. However, it is apparent that there are limited study that simultaneously analyze electric bus route design and fleet planning (especially in the form of scenario-based analysis). Besides, the existing studies mainly focus on the big city in the developed countries. In other words, the relevant analysis for the developing country is largely scarce. Thus, a proper-designed methodology (especially in the form of scenario analysis) is indeed required to analyze the possibility of operating a viable electric bus system, particularly for the context of developing country (including Malaysia).

Methodology

In accordance to the aim of replacing fossil fuels as the sole source of energy for transport sector, this paper aims to examine the possibility to operate electric bus (in order to replace the operation of conventional bus) in terms of electric bus network design and fleet planning. The proposed methodology (as shown in Fig. 1) involves four main stages, namely model development (with traffic modeling software), data collection & compilation, traffic and transit system calibration & validation as well as electric bus network design & fleet planning. The outputs include the electric bus route, frequency and quantity to serve the passengers in a better manner.

Stage I: develop base network model

The proposed methodology commences by developing a base network (for electric bus system) with the aid of EMME (Equilibre Multimodal, Multimodal Equilibrium) modeling software. EMME, a macroscopic traffic simulation software, is adopted as it is able to provide not only a complete travel demand modeling system for transportation forecasting, but also possesses particular features for a detailed modeling of transit and traffic system (INRO, 2014). By taking into consideration of Putrajaya, Malaysia as the concerned study area, a conceptual model of the existing traffic condition in Putrajaya has been built in EMME (in order to develop a base network model for electric bus system). In particular, the base network model is formed (with EMME) by adding a set of nodes and links systematically. Besides, a directional connection between two nodes is drawn by adding connector link which connects a centroid to a regular node.

Stage II: collect and compile data

In order to capture demand modeling, the data collection of the number of passengers and also the number of vehicles are considered. A group of student helpers were hired to collect the number of passengers (including the number of boarding

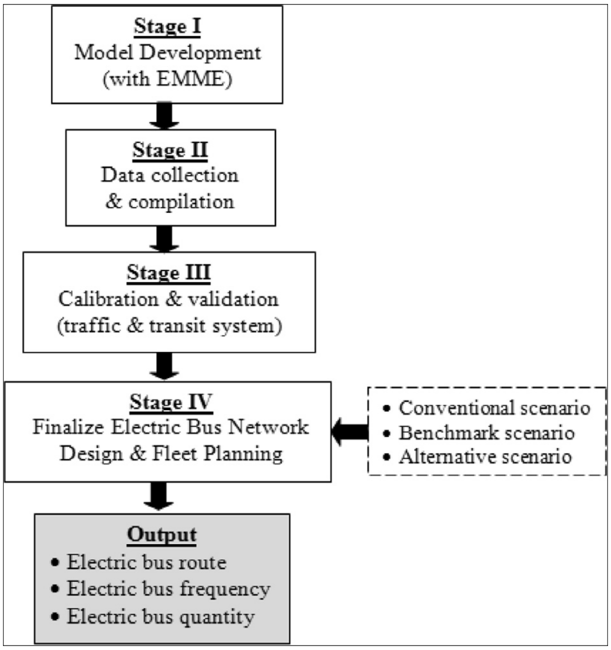

Fig. 1. The proposed methodological framework.

and alighting passengers) at each bus stop for all the bus routes involved in the operating system. In order to reflect the actual phenomena of bus operations, the data collection in Putrajaya has been carried out on Tuesday, Wednesday and Thursday (in June 2015) during the peak hour from 7 am to 8 am and also from 5 pm to 6 pm. The collected data, for a total of seven intersections, four interchanges and one roundabout (with five exits), includes the number of vehicles passing by an intersection of a particular route, vehicle's direction and mode, etc. To compile the collected data, the number of vehicles is converted to Passenger Car Unit (PCU) in order to provide a consistent manner in handling different types of vehicle for transportation modeling purpose. PCU is a measure of the space a particular vehicle needs compared to a passenger car, i.e. 1 PCU is the unit considered for a private car and the rest of vehicles (e.g. motorcycle, lorry and bus) are converted to this unit by a factor. In particular, the number of vehicles (compiled via data collection) is required to reflect the actual traffic condition for traffic and transit modeling. As shown below, Table 1 summarizes the data collection for different type of vehicles.

Stage III: calibrate traffic and transit system

Subsequently, the network editor in EMME was adopted to calibrate and validate the developed traffic and transit system. In particular for traffic system, a street map of Putrajaya was inserted in EMME for which the attributes of the links (such as the number of lanes, speed limit, link length and modes) have been filled up similarly as the actual (real-life) practice. Besides, some centroids were also located in the map. Centroid is also known as trip generator and receiver. Although there was no limitation in locating centroids, it would be more appropriate to add centroids in high population density area. After establishing all the background features, an origin–destination (OD) matrix was formed according to the number of available

Table 1
Data collection for different types of vehicles.

Vehicle type	Quantity (daily)	Mode share (%)
Car	95,419	65.2
Motorcycle	36,000	24.6
Bus*	5,666	3.9
Small lorry	1,561	1.1
Medium lorry	771	0.5
Big lorry	6,926	4.7
Total	146,343	100

Note: *Bus includes all types of bus (e.g. tourist bus, city bus) passing by the locations for the data collection.

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centroids. The value of rows and columns in the OD matrix, which represents the number of trip generated by one centroid to another, is an arbitrary decision initially but it is shifted to a more well-planned decision as traffic assignment runs. The OD matrix was integrated into EMME in order to run the standard traffic assignment through modeler. The output in terms of number of vehicles passing through numerous links, junctions, roundabout and interchange were generated. A trial and error method on OD matrix (after every traffic assignment is done) has been performed necessarily until the simulated result achieved a similarity of 85% with the actual data. The actual and simulated data have been recorded in Excel worksheet to exhibit a linear regression line with the R-squared (R^2) value greater than 0.85. The similarity rate can be checked by constructing XY-chart (scatterplot) with EMME software. In other words, the demand of passengers (in terms of the number of passengers) is modeled by comparing the predicted and observed volumes for all routes, with at least 0.85 of R^2 value. For demand modeling, predicted volume refers to the number of passengers modeled by EMME while the observed volumes are the collected number of passengers (actual data).

The calibration and validation of the transit system is relatively similar to the traffic system except the initial setting. Specifically, the existing Nadi Putra bus routes were added into the map along the links for which certain nodes being set up as bus station or terminal. Nadi Putra is the public bus provider that operates 146 natural gas buses in order to support 13 bus routes in Putrajaya. After adding the bus routes, the attributes to each bus line in terms of headway, travelling speed have been filled up accordingly. Once the set-up of bus routes is done, a new batch of centroids (i.e. representing passengers instead of vehicle) were added. Similarly, the matrix size is formed based on the number of centroids added (including the centroids for traffic system). Notably, an arbitrary decision on the number of people travelling from one point to another will lead to a distribution of people to different bus routes and affecting the number of boarding/alighting passengers at each bus stop. Finally, the simulated number of alighting and boarding at each bus stop for different bus routes was recorded and compared with the actual data. Statistically, the developed model is accepted if the generated linear regression line has achieved 85% similarity.

Stage IV: finalize electric bus network and fleet planning

By completing the calibration and validation of the traffic and transit systems, the proposed model (developed with EMME) is now a viable model to carry on with the electric bus network and fleet planning design (i.e. to determine a desired electric bus route with the corresponding bus frequency and quantity). Concisely, the electric bus operating system commences by modeling (with EMME) a conventional scenario according to the existing Nadi Putra bus route and frequency in Putrajaya. Then, a benchmark scenario with electric bus deployment is outlined according to the conventional scenario. In addition, several alternative scenarios which aim to improve the benchmark scenario were designed and simulated in the EMME model. By examining all the designed options (including the conventional, benchmark and alternative scenarios) with the proposed approach, the most desired strategy (with the most effective electric bus route, frequency and quantity) could be identified.

An illustrative case study

Description of case study

In 2010, the Prime Minister of Malaysia had announced to turn Putrajaya, Malaysia into a Green City by reducing the emission of carbon dioxide by 60% (Putrajaya Corporation, 2012). Thus, this study focuses on Putrajaya as the concerned study area. For the study area in Putrajaya, there are 5 scenarios, namely conventional (C), benchmark (B) and alternative scenario P, Q and R considered for the illustrative case study. Three alternative scenarios (i.e. scenario P, Q and R) are added in order to generate more relevant analysis, particularly to analyze the influential impacts of various key components (including the number of bus routes, headway and charging facility) that affecting the overall performance of electric bus operating system. By having the alternative scenarios in place, the resultant findings (from each scenario) would reveal the extent and benefits of operating electric bus to replace conventional bus system.

The outlines of all considered scenarios are summarized in Table 2. As shown in Table 2, conventional scenario is outlined to operate fuel buses while the other scenarios (i.e. benchmark, P, Q and R) involve electric buses for operations. Specifically, there are 16 available bus routes for scenario P, i.e. 3 more routes compared to other scenarios (for which bus route L07, L08 and L09 are split as L07A, L07B, L08A, L08B, L09A and L09B). In terms of bus headway, scenario R is designed to provide bus services for every 25 min. Comparatively, other scenarios offer a higher bus frequency, i.e. at every 15 min. For electric bus charging facilities, there are fast charging stations available for all the alternative scenario (i.e. P, Q and R). Fast charging station is able to recharge electric bus battery in a short duration (i.e. 80 kWh in 10 min). For the illustrative case study, each bus route is only assigned with one charger (for fast charging) and hence bus queuing condition is required for battery recharging. In addition, scenario Q and R have curbside fast charging kiosk for electric bus operations. In particular, the location of curbside fast charging kiosk is placed at a busy bus stop which has a large number of boarding and alighting passengers. Yet, there is a maximum limit of 3 min charging time at the curbside fast charging kiosk in order to prevent a large increment of passenger's waiting time.

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Table 2
The outlined scenarios for bus operations.

Scenario	C	B	P	Q	R
Bus type	Fuel	Electric			
Number of bus routes	13	13	16	13	13
Headway (minutes)	15	15	15	15	25
Charging station	Nil	Normal	Fast charging		
Curbside fast charging kiosk	Nil	Nil	Nil	3 kiosks, 6 charges	
Average number of bus stations	22.6	22.6	20.8	22.6	22.6
Total of route length (km/trip)	361.76	361.76	365.03	361.76	361.76
Number of passengers (million/year)	36.0	36.0	36.8	35.2	25.3

For the application of electric bus in the illustrative case study, all electric bus routes are designed based on a 12 m long electric bus (which is equipped with a 300 kWh capacity titanium-ion battery) and the bus capacity can accommodate 60 passengers. The layout of the longest bus route for the respective scenario could be seen in Appendix A for which the information on the number of bus stations and the length of bus route are presented in Appendix B. In particular, there are three bus terminals which are named as Terminal A, B and C (as showed in Fig. 2). Notably, only bus route L08 of scenario P requires the battery charging at Terminal C. In terms of charging facilities, level 1 station charging (normal charging) is applied at these bus terminals for overnight charging for all buses. Since normal charging requires a longer duration to recharge (up to 8 h), every bus is provided a level 1 charger for battery recharging after the last trip of a day. However, the number of charger depends on the number of bus in operations (from 6.30 am to 12.00 am). Thus, a sufficient number of charger are provided for each bus to recharge battery and hence there is no queuing condition until the next morning.

Besides, the battery limit set in the transit assignment is 20% of the battery capacity, i.e. the remaining battery capacity of a bus once it reaches the charging terminal must not be less than 20% of it battery capacity. However, an electric bus is designed to continue its journey when battery capacity reaches 80%. As such, the maximum utilized capacity of each trip is 60% of battery capacity. Notably, the energy limit of electric bus (which is fully charged at 100%) is 40% of its battery capacity after completing its first trip. In view that one of the main objectives of this study is to determine the service frequency of electric bus, the scenario analysis is performed under various circumstances particularly in accordance to different headway and charging facility (as shown in Table 1) as well as the demand level of passengers (as outlined in Table 2). Besides, it is anticipated that the service frequency of bus will be higher to meet the demand of passengers for the case that the total available bus capacity decreases. On the contrary, bus frequency would be lower if the total available bus capacity is offered at a higher level (with a larger total available bus capacity).

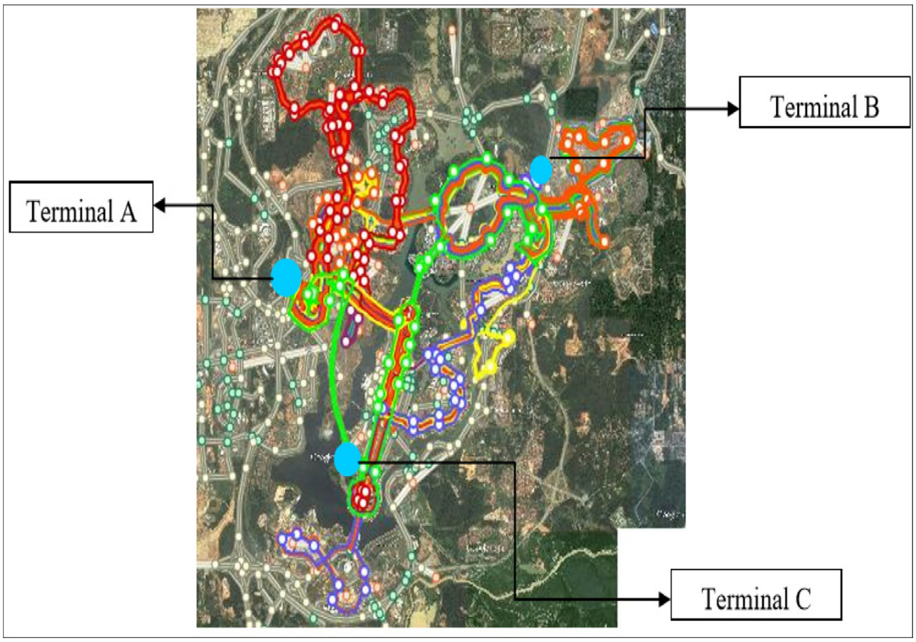

Fig. 2. The study area in Putrajaya.

Results discussion

Number of electric bus and charging facility

Fig. 3 displays the required number of electric buses and charging facilities (daily) for scenario B, P, Q and R. As shown in Fig. 3, scenario P requires a larger number of buses in comparison to other alternative scenarios (Q and R). This happened in accordance to the increase of bus routes in scenario P (with 16 routes). Besides, Fig. 3 also shows that a lesser number of buses is required when fast charging station is employed. This could be explained by a shorter charging duration (30 min to recharge the battery capacity up to 80% for bus operations). In contrast, a longer charging duration (up to 8 h) of normal charging station requires a higher number of buses for operations (for scenario B). Besides, Fig. 3 shows that a total of 169 electric buses are needed in scenario B, i.e. a total of 169 battery chargers are required (for which there are 103 chargers at Terminal A and 66 chargers at Terminal B). Similar practice applies to scenario P, Q and R, i.e. the total number of chargers of each scenario is equivalent to the number of buses needed in operations. Comparatively, the results show that most of the operating buses performed the battery charging at terminal A (which is about 2 times more than terminal B). And also, Table 3 shows that bus route L08B of scenario P requires 5 battery charging at Terminal C.

Bus frequency

In terms of the daily service frequency of bus, Table 4 shows that scenario P provides the highest service frequency. This could be explained by the total number of bus routes (16 routes), i.e. 3 more compared to other scenarios. Besides, the results show that scenario R provides the lowest service frequency. This could be justified from two elements, namely the number of bus routes and headway. Compared to scenario P (with 16 bus routes), scenario R operates 13 bus routes for the entire bus operating system. As such, the total of service frequency for scenario R seems to be lower in comparison to scenario P. In comparison to other scenarios (i.e. conventional, benchmark and Q scenarios), scenario R has a longer headway although the number of bus routes retains the same for these scenarios. Scenario R is outlined to have 25 min for the headway, which is 10 min more compared to other scenarios. As such, the service frequency of scenario R tends to be lower in comparison to the other scenarios. In a nutshell, the results show that the number of bus route and headway are the influential components in determining bus frequency.

Besides, it could be seen from Table 4 that bus route L07, L08 and L09 of Scenario B did not involve any electric bus operation. This happened due to the failure of retaining the battery capacity at a required level for electric bus operation. Although battery limit emerged to be the concerned issue in operating electric bus, the results (in Table 4) show that the replacement of conventional bus with electric bus (with similar headway for scenario B, P and Q) would at least attain the bus frequency of conventional bus, i.e. 702 per day (but not offering a lower service frequency). This is definitely important to meet the demand of passengers.

Bus performance

For the bus performance in terms of total travelled distance, the resultant findings, as presented in Table 5, highlight that scenario R exhibits the best performance, i.e. with 182.8×10^3 km for the travelled distance per unit of bus (yearly). In comparison, this is about 5 times more than scenario B with electric bus operations. Besides, Table 5 shows that the operations of

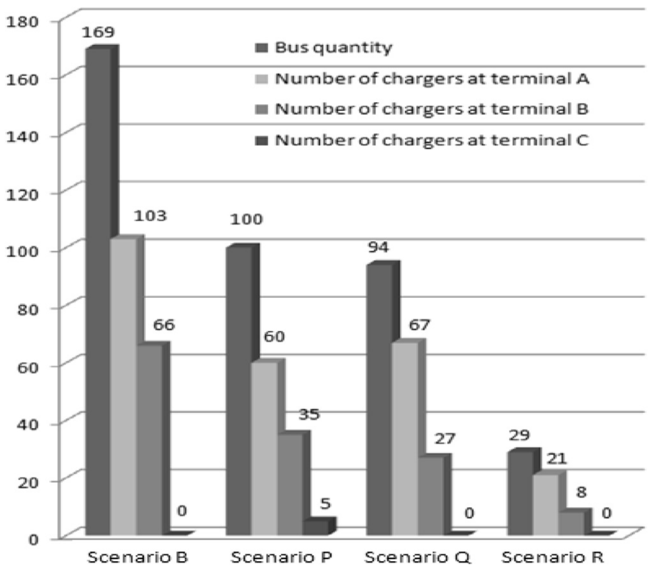

Fig. 3. The quantity of electric bus and electric chargers.

Table 3
The quantity of electric bus and electric chargers for each bus route.

Bus route	Number of electric bus (number of chargers at terminal A, B, C)			
	Scenario B	Scenario P	Scenario Q	Scenario R
L01	18 (18, –)	9 (9, –, –)	9 (9, –)	2 (2, –)
L02A	14 (–, 14)	5 (–, 5, –)	5 (–, 5)	2 (–, 2)
L02B	14 (14, –)	4 (4, –, –)	4 (4, –)	2 (2, –)
L03	16 (16, –)	7 (7, –, –)	7 (7, –)	2 (2, –)
L04	17 (17, –)	9 (9, –, –)	9 (9, –)	2 (2, –)
L05A	16 (–, 16)	6 (–, 6, –)	5 (–, 5)	2 (–, 2)
L05B	19 (19, –)	11 (11, –, –)	10 (10, –)	2 (2, –)
L06	17 (–, 17)	7 (–, 7, –)	7 (–, 7)	2 (–, 2)
L07	–	–	8 (8, –)	3 (3, –)
L07A	–	3 (3, –, –)	–	–
L07B	–	4 (–, 4, –)	–	–
L08	–	–	6 (6, –)	3 (3, –)
L08A	–	4 (4, –, –)	–	–
L08B	–	5 (–, –, 5)	–	–
L09	–	–	4 (4, –)	3 (3, –)
L09A	–	3 (3, –, –)	–	–
L09B	–	3 (–, 3, –)	–	–
L10	19 (–, 19)	10 (–, 10, –)	10 (–, 10)	2 (–, 2)
L11	19 (19, –)	10 (10, –, –)	10 (10, –)	2 (2, –)
Total	169 (103, 66)	100 (60, 35, 5)	94 (67, 27)	29 (21, 8)

Table 4
Bus frequency for each bus route.

Bus route	Bus frequency				
	Scenario C	Scenario B	Scenario P	Scenario Q	Scenario R
L01	Bus 1–10:5 Bus 11:4	Bus 1–18:3	Bus 1–9:6	Bus 1–9:6	Bus 1–2:20
L02A	Bus 1–4:6 Bus 5–10:5	Bus 1–12:4 Bus 13–14:3	Bus 1–4:11 Bus 5:10	Bus 1–4:11 Bus 5:10	Bus 1–2:20
L02B	Bus 1–4:6 Bus 5–10:5	Bus 1–12:4 Bus 13–14:3	Bus 1–2:14 Bus 3–4:13	Bus 1–2:14 Bus 3–4:13	Bus 1–2:20
L03	Bus 1–4:6 Bus 5–10:5	Bus 1–6:4 Bus 7–16:3	Bus 1–5:8 Bus 6–7:7	Bus 1–5:8 Bus 6–7:7	Bus 1–2:20
L04	Bus 1–4:6 Bus 5–10:5	Bus 1–3:4 Bus 4–17:3	Bus 1–9:6	Bus 1–9:6	Bus 1–2:20
L05A	Bus 1–4:6 Bus 5–10:5	Bus 1–6:4 Bus 7–16:3	Bus 1–6:9	Bus 1–4:11 Bus 5:10	Bus 1–2:20
L05B	Bus 1–6:5 Bus 7–12:4	Bus 1–16:3 Bus 17–19:2	Bus 1–10:5 Bus 11:4	Bus 1–4:6 Bus 5–10:5	Bus 1–2:20
L06	Bus 1–10:5 Bus 11:4	Bus 1–3:4 Bus 4–17:3	Bus 1–5:8 Bus 6–7:7	Bus 1–5:8 Bus 6–7:7	Bus 1–2:20
L07	Bus 1–2:5 Bus 3–13:4	–	–	Bus 1–6:7 Bus 7–8:6	Bus 1:14 Bus 2–3:13
L07A	–	–	Bus 1–3:18	–	–
L07B	–	–	Bus 1–2:14 Bus 3–4:13	–	–
L08	Bus 1–12:4 Bus 13–14:3	–	–	Bus 1–6:9	Bus 1:14 Bus 2–3:13
L08A	–	–	Bus 1–2:14 Bus 3–4:13	–	–
L08B	–	–	Bus 1–4:11 Bus 5:10	–	–
L09	Bus 1–10:5 Bus 11:4	–	–	Bus 1–2:14 Bus 3–4:13	Bus 1:14 Bus 2–3:13
L09A	–	–	Bus 1–3:18	–	–
L09B	–	–	Bus 1–3:18	–	–
L10	Bus 1–2:5 Bus 3–13:4	Bus 1–16:3 Bus 17–19:2	Bus 1–4:6 Bus 5–10:5	Bus 1–4:6 Bus 5–10:5	Bus 1–2:20
L11	Bus 1–10:5 Bus 11:4	Bus 1–16:3 Bus 17–19:2	Bus 1–4:6 Bus 5–10:5	Bus 1–4:6 Bus 5–10:5	Bus 1–2:20
Total	702	702	864	702	520

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Table 5
The operating performance of all outlined scenarios.

Scenario	C	B	P	Q	R
Quantity of bus, V	146	169	100	94	29
Total travelled distance					
Annual travelled distance, W (10^6 km)	7.1	5.1	7.2	7.1	5.3
Annual travelled distance per unit of bus, W/V (10^3 km)	48.6	30.2	72.0	75.5	182.8
Passenger quantity					
Total number of passengers, X (10^6/year)	36.0	26.7	36.8	35.2	25.3
Total passenger travelled distance, Y (10^6 km/year)	158.1	116.6	154.6	158.1	124.9
Total number of passengers per unit of bus, X/V (10^3/year)	247	158	368	374	872
Total passenger travelled distance per unit of bus, Y/V (10^3 km/year)	1083	690	1546	1682	4307
Energy consumption					
Annual energy consumption, Z (10^6 kWh)	44.6	31.1	45.2	38.5	28.4
Annual energy consumption per travelled distance, Z/W (kWh/km)	6.28	6.10	6.28	5.42	5.36
Battery limit fulfillment	–	3 routes failed	All routes passed		

electric bus with fast charging (for scenario P, Q and R) demonstrate a much better performance in terms of the total quantity of passengers carried per unit of bus. Similar fact could be seen for the total passenger travelled distance (per unit of bus). This reveals that the charging facility of electric bus is a vital element in providing a better (more) service to passengers.

Besides, scenario R also exhibits the best performance in term of the ratio of annual cost and total energy consumption, i.e. at the lowest value of RM0.70/kWh. Although the total number of passengers, X and total passenger travelled distance, Y for scenario R (as shown in Table 5) seems to be relatively low compared to other scenarios, the respective ratio of X and Y per unit of bus emerges to be the highest for scenario R, i.e. 872,000 and 4307,000 km respectively for the total number of passengers per unit of bus and total passenger travelled distance per unit of bus. As such, it can be seen that scenario R also appears to be the most beneficial option from the service aspect (i.e. scenario R emerges to be the most desired scenario to serve the passengers).

In term of energy consumption, Table 5 shows that all alternative scenarios have fulfilled the energy limit for which the energy consumption of a trip must not be more than 60% of the battery capacity of the operating electric bus. However, 3 routes of benchmark scenario (B), i.e. L07, L08 and L09, failed to meet the battery limit and hence these routes are excluded in the analysis (i.e. cost estimation and route planning) for scenario B. Remarkably, the least annual energy consumption of 28.4×10^6 kWh is found in scenario R. This is also the only bus route design that consumed a lower amount of energy compared to scenario B. In terms of the travelled distance per kilometer, scenario R also outperforms all other scenarios, with the least energy consumption at 5.36 kWh (per kilometer). As such, it can be deferred that scenario R is the most desired operating system in term of energy conservation.

In comparison to scenario C (conventional) which operates fuel bus, Table 5 shows that the operations with electric bus (for scenario P, Q and R) exhibit better performance not only in terms total travelled distance, but also total number of passengers carried and energy consumption, However, it can be seen from Table 5 that the operating performance of electric bus for scenario B (in terms of total travelled distance, total number of passengers carried and energy consumption) is not up to the operating performance of scenario C. This could be justified by the exclusion of 3 bus routes of scenario B that failed to meet the battery requirement. In other words, scenario B served fewer bus routes (only 10) than scenario C (with 13 bus routes).

Financial analysis

In terms of the operating cost, the estimated costing of all scenarios is summarized in Table 6. The results show that the operation of electric bus (B, P, Q and R) generated a lower annual cost compared to the application of conventional bus. In particular, scenario R generates the lowest annual cost at RM 19.9 million. The annual cost includes bus acquisition cost, energy cost (vehicle-specific), energy price (electricity cost), energy storage cost (battery cost), maintenance cost, fuel station cost (only for conventional scenario) and also charging station cost (for scenario B, P, Q and R). The composition of the annual

Table 6
The financial analysis for each scenario.

Scenario	C	B	P	Q	R	Average (B, P, Q & R)
Annual cost (10^6 Ringgit Malaysia)	62.1	38.0 (−39%)	37.3 (−40%)	33.7 (−46%)	19.9 (−68%)	32.2 (−48%)
Annual revenue (10^6 Ringgit Malaysia)	36.0	26.7 (−26%)	36.8 (+2%)	35.2 (−2%)	25.3 (−30%)	31.0 (−14%)
Annual profit (10^6 Ringgit Malaysia)	−26.1	−12.8 (+51%)	−0.5 (+98%)	1.5 (+106%)	5.4 (+121%)	−1.6 (+94%)
Annual cost/energy consumption (Ringgit Malaysia/ kWh)	1.39	1.22 (−12%)	0.83 (−40%)	0.88 (−37%)	0.70 (−50%)	0.91 (−35%)

Note: The value in bracket indicates the respective improvement level compared to scenario C.

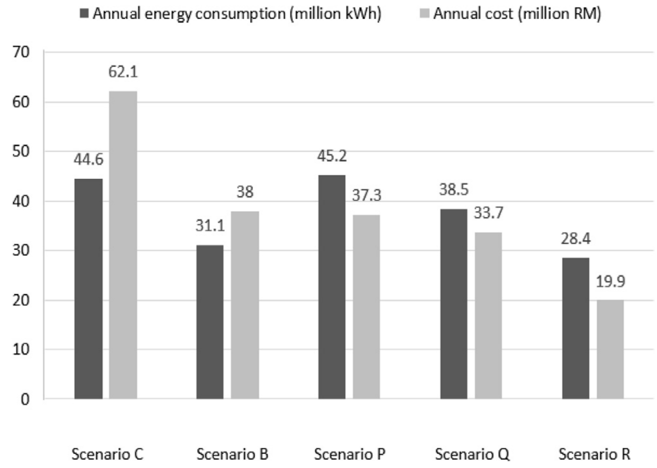

Fig. 4. Bus performance (in terms of annual cost and energy consumption).

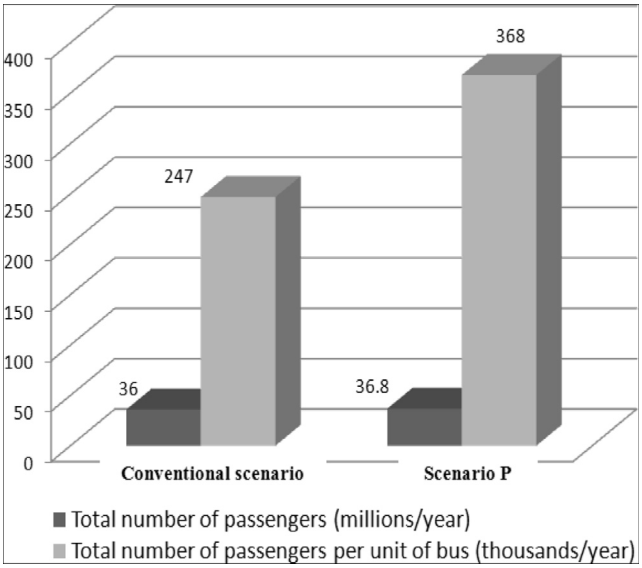

Fig. 5. Mode shift analysis.

cost for the respective scenario is displayed in Appendix C. In addition, the result shows that scenario R produces the highest profit, i.e. RM5.4 million per annum although it gains the lowest annual revenue (contributed by bus fare). Thus, it can be deferred that scenario R is the most beneficial option for electric bus system. In overall, it can be confirmed that effort of replacing the conventional bus with electric bus is promising.

The performance of electric bus in terms of environmental benefit is evaluated by determining the improvement level of scenario B, P, Q and R compared to scenario C (i.e. conventional scenario without electric bus). The improvement level for each scenario and also the average performance are presented in Table 6. As shown in Table 6, electric bus exhibits a promising operation (for scenario B, P, Q and R) by showing a substantial improvement especially in terms of annual cost savings, up to an average of 48% compared to scenario C (without electric bus). Proportionally, this consequently results in a saving of 35% for the average ratio of annual cost and energy consumption. All in all, this constitutes a great improvement of annual profit (up to 94% in average). In particular, scenario R exhibits the most promising performance not only in cost savings but also profit earned in operating electric bus.

Besides, Fig. 4 as displayed below exhibits the performance of electric bus in terms of annual cost and annual energy consumption. As expected, the operating cost tends to be higher when the energy consumption increases. In other words, annual energy consumption and annual cost for the operating system of electric bus exhibit similar trend. The increasing trend of annual cost can be explained by the contribution of the respective component of operating costs including energy cost which is constituted by total energy consumption. This explains the similar pattern of annual energy consumption as well as the annual cost.

Possible mode shift

As shown in Fig. 5, the operation of electric bus particularly for Scenario P (with 16 bus routes) is able to attract more passengers in comparison with the conventional scenario (with 13 bus routes). By increasing the number of bus routes (from 13 to 16 for scenario P), the graphical results in Fig. 5 show that the total number of passengers of using electric bus to travel would increase about 2% (from 36 millions to 36.8 millions per year) and this would contribute an increment of 49% for the total number of passengers per unit of bus (i.e. increase from 247,000 to 368,000 passengers per year). In other words, the potential mode shift of 1% of passengers would contribute a higher occupancy of electric bus, i.e. up to 24.5% per unit of bus (for scenario P). This signifies that the determination of bus routes play a vital role to attract more passengers. However, it is important to note that the mode shift of passengers is not solely driven by a single factor, but affected by various factors, including the socioeconomics and personal characteristics of the passengers, as well as the bus services (e.g. waiting time, reliability, punctuality, etc.). Thus, further works are certainly required to investigate the possible mode shift to a greater extent.

Conclusions

This paper deals with a scenario-based electric bus operation, in terms of routing network design and fleet planning, by taking various operational concerns into consideration. In particular, the resultant findings confirmed the possibility to replace the conventional bus operation by operating electric bus. By examining an illustrative case study, the results show that the operation of electric bus outperforms the existing bus operation with conventional bus. Comparatively, electric bus operating system with fast charging facility and curbside fast charging kiosks exhibit the most desired operational performance in terms of total travelled distance, number of passengers carried, energy consumption and operational profit. Besides, the findings highlight that the operation of electric bus is greatly affected by various factors, including bus energy/battery consumption, operating criteria (e.g. headway) and also charging facility. Concisely, it could be concluded that the proposed study is workable with the deployment of electric bus and the respective charging facilities. However, the proposed study did not incorporate the optimization approach in generating the desired result and hence the findings may not be optimal at the certain extent. This certainly requires more future works in order to reveal more relevant analysis. Besides, this study can be extended to analyze the mode shift of passengers to a greater extent.

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Appendix A. The longest bus routes for illustrative case study

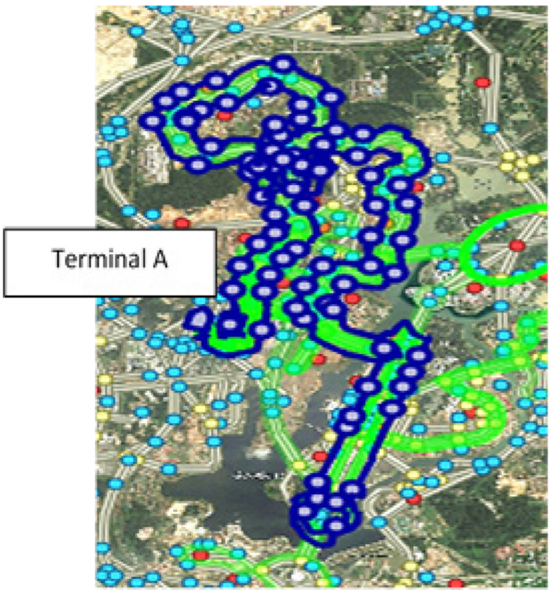

Fig. A.1. Bus route L08 (42.33 km for scenario C, B, Q and R).

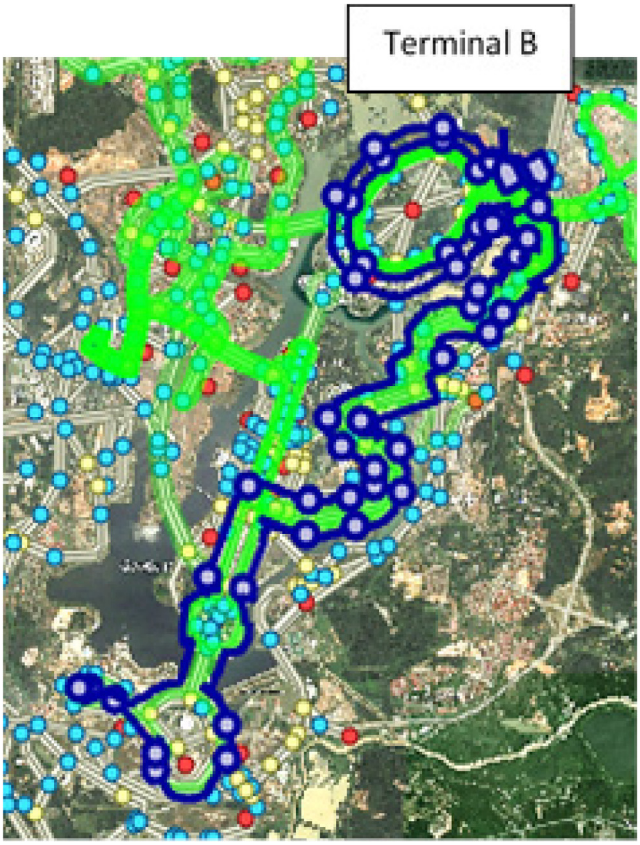

Fig. A.2. Bus route L10 (32.7 km for scenario P).

Appendix B. The operating information for scenario analysis

Table B.1
The relevant operating information for case study.

Scenario	P	B, Q, R
Number of bus stations for bus routes		
Minimum	13 stations (for bus route L09A)	17 stations (for bus route L06)
Maximum	32 stations (for bus route L05B)	32 stations (for bus route L05B)
Total	332 (for 16 bus routes)	294 (for 13 bus routes)
Route length (km/trip)		
Minimum	14.4 (for bus route L09B)	21.87 (for bus route L03)
Maximum	32.7 (for bus route L10)	42.33 (for bus route L08)
Total	365.03 (for 16 bus routes)	361.76 (for 13 bus routes)

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Appendix C. Annual cost for scenario analysis

Table C.1
Annual cost for illustrative case study.

Scenario	Annual cost (in RM)				
	C	B	P	Q	R
Bus cost	13,140,000	16,900,000	10,000,000	9,400,000	2,900,000
Energy storage cost	–	3,380,000	2,000,000	1,880,000	580,000
Energy price	22,137,004	13,183,150	19,177,130	16,316,171	12,044,096
Energy cost	25,480,589	3,668,684	5,185,394	5,138,942	3,806,624
Maintenance cost	438,000	676,000	400,000	376,000	116,000
Level 1 charging station (per charger)	–	270,400	160,000	150,400	46,400
Fast charging station cost (per charger)	–	–	384,000	312,000	312,000
Fast charging kiosk cost (per charger)	–	–	–	144,000	144,000
Fuel station cost	900,000	–	–	–	–
Total annual cost (RM)	62,095,593	38,078,235	37,306,524	33,717,513	19,949,119

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