32nd Electric Vehicle Symposium (EVS32)
Lyon, France, May 19 - 22, 2019

An Evaluation of Electric Bus Energy Consumption in Bangkok Traffic Conditions

Kitchanon Ruangjirakit[1*], Yossapong Laoonual[1] , Poj Tangamchit[2] and Ocktaeck Lim[3]

[1]*Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, 10140, Thailand.*

[2]*Department of Control System and Instrumentation Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, 10140, Thailand.*

[3]*School of Mechanical Engineering, University of Ulsan, 44610, Republic of Korea.*

**corresponding author, email: kitchanon.rua@mail.kmutt.ac.th*

Summary

This study aims to evaluate the effects of traffic conditions on the energy consumption of an electric bus manufactured by Edison Motors Co., Ltd. (Republic of Korea) operating in real traffic conditions in Bangkok, Thailand. The electric bus was operated on two different routes, which were selected based on distance, traffic condition and public visibility criteria. Moreover, in order to effectively evaluate the performance of the bus, it was operated according to the normal service schedule set by the Bangkok Mass Transit Authority (BMTA), which is in average 6 rounds per day. The results of average speed at different time of day suggest that the traffic conditions of routes 137 and 36 are relatively similar, and the difference in traffic pattern between weekdays and weekend can be clearly noticed. On weekdays, heavy traffic is observed during rush hours in the morning and in the evening, whereas, for weekend, moderate traffic conditions are observed from late morning onwards throughout the day. From the energy consumption results, it can be seen that the energy consumption reduces non-linearly as the average speed increases, and the energy used to operate the bus is approximately 3 times higher for congested traffic condition compared with moderate and light traffic.

Keywords: Energy consumption, EV (electric vehicle), Bus, Public Transport

1 Introduction

Many megacities around the world have realized the effects of urban air pollution produced by road vehicles; therefore, various measures have been introduced to reduce carbon emissions in the city. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH [1] has proposed an approach known as A-S-I, which is an abbreviation for Avoid-Shift-Improve, to reduce greenhouse gas emission in transport sector. For the GIZ concept, “avoid” means to reduce the need to travel, “shift” refers to the change of the mode of transport from personal to public, and “improve” means to use more efficient mode of transport or vehicle technology. Therefore, one effective solution to sustainably resolve urban air pollution issue arisen from tailpipe emissions is to encourage commuters to use public transport in order to decrease the number of personal vehicles on the roads. Furthermore, the conventional combustion engine public fleets, such as buses and taxis, should be substituted with electric vehicles (EV) to promote greater effects on greenhouse gas reduction in metropolitan areas. Buses can be considered as the most effective type of vehicles to transport people in populated city areas as the cost per unit is relatively cheap compared to rail network and no additional infrastructure is required. Therefore, replacing the current fossil-fuel-powered buses with battery electric buses provides sustainable solution to overcome urban air quality problem. According to the study by Bloomberg New Energy Finance [2], the number of electric buses around the world reached 385,000 units in 2017. However, 96% of the total figure or around 370,000 units were operating in China [3].

To evaluate the performance and energy consumption of electric bus, two popular test methods are normally applied. First, a laboratory testing of the bus using a dynamometer running under a predetermined driving cycle is employed. For example, Barnitt and Gonder [4] have demonstrated a laboratory test of different plug-in hybrid (PHEV) school buses. Although the procedure and parameters of the laboratory test can be accurately controlled, the main disadvantage for this test method is the need for expensive laboratory and testing equipment. Therefore, another test method utilized by many researchers [5, 6], especially for light-duty vehicles, is the real-world test. Zhou *et al.* [7] have investigated the performance and energy consumption of three battery electric buses (BEBs) in Macao downtown and business areas using real-world test method. The battery current and voltage data were recorded using OBD decoders and the charging energy data was provided by local power company. From this study, it was found that the battery electric bus performs better in terms of fuel savings compared to a diesel bus under heavy traffic and high passenger load situations.

In Thailand, the government has announced a plan to promote domestic electric vehicle industry. Therefore, a number of plans and measures to support electric bus along with electric two-, three- and four wheelers as well as important EV components and charging infrastructure have been introduced. In order to prepare for full-scale operation of electric bus fleets, an evaluation of electric bus performance in actual traffic and operating conditions is crucial. Therefore, this study aims to evaluate the effects of traffic conditions on the energy consumption of the electric bus operating in Bangkok, Thailand. The results obtained from this study are beneficial for researchers and engineers involved in the project to improve electric bus systems suitable for Bangkok conditions. Moreover, the bus operator can use the data for electric bus procurement, infrastructure preparation, route planning and fleet management.

2 Methodology and Route Selection

2.1 Methodology

In this study, the electric bus manufactured by Edison Motors Co., Ltd. (Republic of Korea) as shown in Figure 1 was used and the specifications of this bus are shown in Table 1.

Figure 1: Appearance of the Electric bus manufactured by Edison Motors Co., Ltd. (Republic of Korea).

Table 1: Specifications of the electric bus manufactured by Edison Motors Co., Ltd.

Items	Details
Body structure	Carbon Fiber Reinforced Plastic (CFRP)
Performance	32
- Max speed	85 km/hr.
- Range per charge	173 km
Motor	
- Type	In-wheel
- Max power	250 kW / 2,538 rpm
- Torque	99 kg-m
Battery	
- Type	Li-Polymer
- Capacity	162.5 kWh
Weight	
- Empty vehicle weight	11,060 kg
- Gross weight	13,920 kg
Dimension	
- Length x Width x Height	11,030 x 2,495 x 3,310 mm
- Wheel base	5,400 mm

The schematic diagram showing how each measuring equipment was connected to the data acquisition module is presented in Figure 2. The instantaneous current and voltage, as well as the battery temperature, were measured at the battery terminal and the data was sent to the data acquisition unit or DAQ (Dewesoft SIRIUS) through CAN Bus. The operating time of each trip was also measured and logged using the DAQ. The location and distance of the bus were measured using a GPS receiver connected to the data logger while the linear and angular velocity, and the acceleration were measured using Inertia Measuring Unit (IMU). The footage of the traffic was recorded using the video recorder installed at the driver cabin. The above data sets were recorded at 1 Hz and were used to calculate the energy consumption of each trip using equation (1). As the energy consumption was calculated from the electricity data measured directly from the battery, the energy consumption data in this study is then referred to as “Battery-to-Wheel” energy consumption.

$$E_c = \sum_{i=1}^{n} \frac{\left(\frac{I_i V_i}{1{,}000}\right) t_i}{s_i} \tag{1}$$

where

E_c	is the energy consumption of each trip [kWh/km]
I_i	is the instantaneous current [A]
V_i	is the instantaneous voltage [V]
t_i	is the time step of each reading [hr.]
s_i	is the distance travelled in each time step [km].

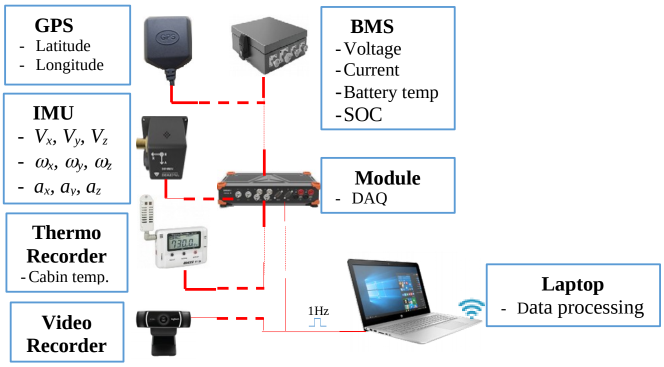


Figure 2: Schematic diagram of measuring equipment.

In order to maintain a high service standard, the electric bus was fully charged from a 200 kW charger before dispatching. The charging data, which includes current, voltage and charging time, was also measured in this study.

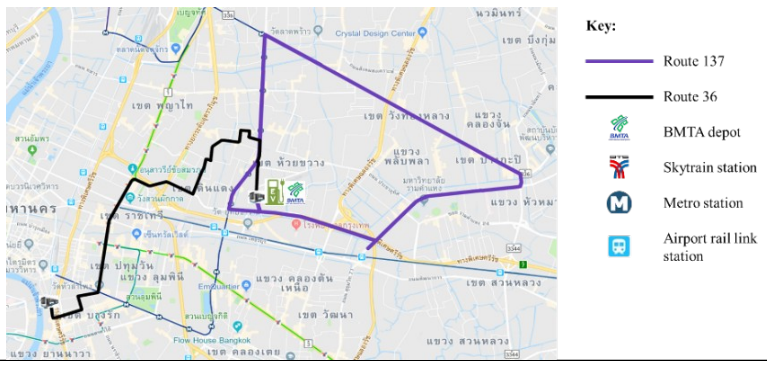
2.2 Route Selection

In order to effectively evaluate the performance of the electric bus in Bangkok, the routes were jointly decided by the researchers and the operation team of the Bangkok Mass Transit Authority (BMTA), the state enterprise bus operator, based on the following criteria.

1. Total distance of each trip should be less than 80 km.
2. The traffic condition should be relatively heavy.
3. The route should start and finish at the main depot where the charger is installed.
4. The route should pass populated areas to gain more visibility.

In addition to the above criteria, the electric bus was operated according to normal BMTA schedule to avoid service disruption. After a thorough consideration, two routes were chosen as detailed in Table 2 below.

Table 2: Details of selected operating routes.

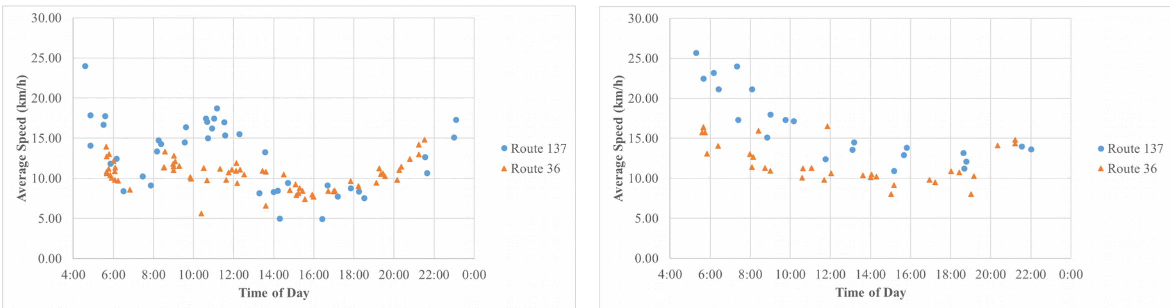
	Route No. 137	Route No. 36
Distance per trip (km)	30	28
No. of trip per day	6	6
Characteristics of the routes	• Pass 3 major department stores • Pass 4 skytrain stations, 1 metro station and 1 airport rail link station	• Pass 2 major department stores • Pass 6 metro stations
Map		

3 Results and Discussion

The electric bus was operated on route 137 and route 36 for approximately 6 weeks (3 weeks on each route). On each day, the bus was run from 04:30 to 21:00; therefore, information on traffic conditions could be observed at different time of the day. The summary of the test results is shown in Table 3. One indicator which can be used to reflect the traffic conditions is the average speed of the bus in each trip. Low average speed indicates that the traffic is congested and the bus spends relatively long stopping time on the road; hence, the energy consumption would be high, while higher average speed shows that the traffic is light and, as a result, low energy consumption is expected. The average speed of each trip against time is plotted and shown in Figure 3.

Table 3: Summary of test results.

	Route No. 137	Route No. 36
Total No. of trips	94	100
Average distance per trip (km)	29	28
Average velocity per trip (km/h)	14.28	10.98
Average energy consumption (kWh/km)	1.46	1.65

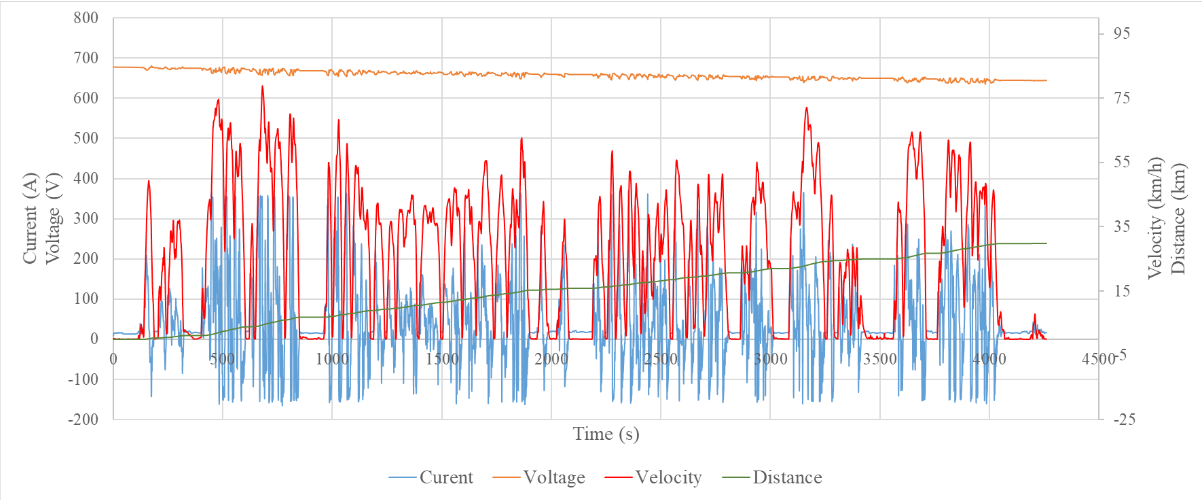


(a) Weekdays (b) Weekend

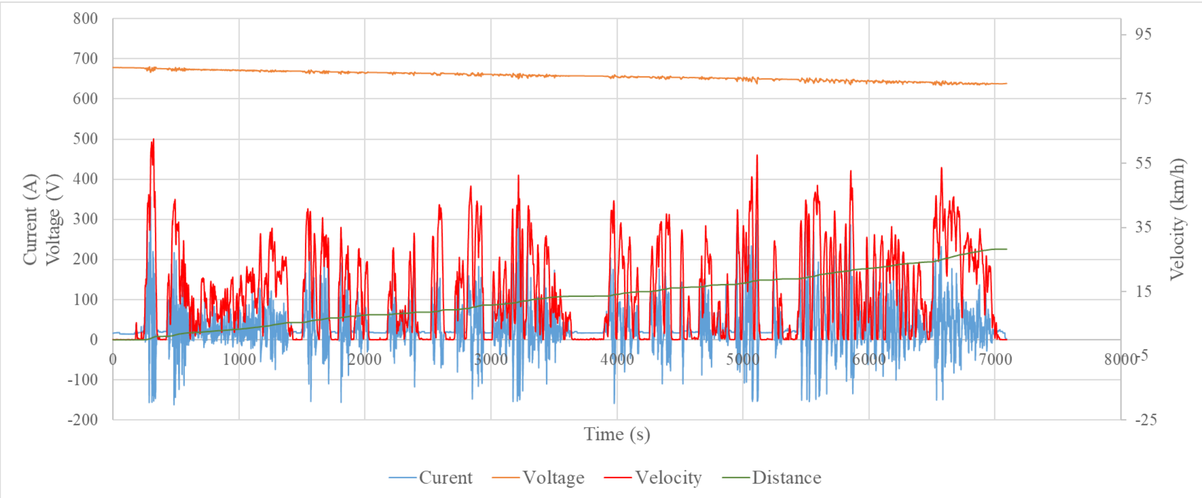
Figure 3: Traffic conditions of two routes between (a) weekdays and (b) weekend.

From Figure 3, a clear different in traffic conditions between weekdays and weekend can be observed. On weekdays, the traffic on route 137 was relatively heavy during rush hours both in the morning and the evening, whereas the traffic on route 36 was congested almost all day. On weekend, on the other hand, the traffic on both routes was better than on weekdays, especially on route 137 in which the average speed of the electric bus before 8am could reach 20 km/h. However, from late morning onwards, the traffic was more congested as people started to travel from their homes to other places, such as department stores and supermarkets, etc.

The energy consumption was calculated using instantaneous voltage and current readings from the battery using equation (1). The time series data of voltage, current, velocity and distance is shown in Figure 4. For the measurement of electricity current, the positive values represent the energy discharging from the battery and the negative values show that the battery is being recharged using dissipated energy from the regenerative braking system. The data of instantaneous energy consumption together with the velocity is also plotted and shown in Figure 5. Similar to electric current data, the energy consumption is positive when the electrical energy is used to move the bus and it is negative when the energy is recharged back to battery from braking system.



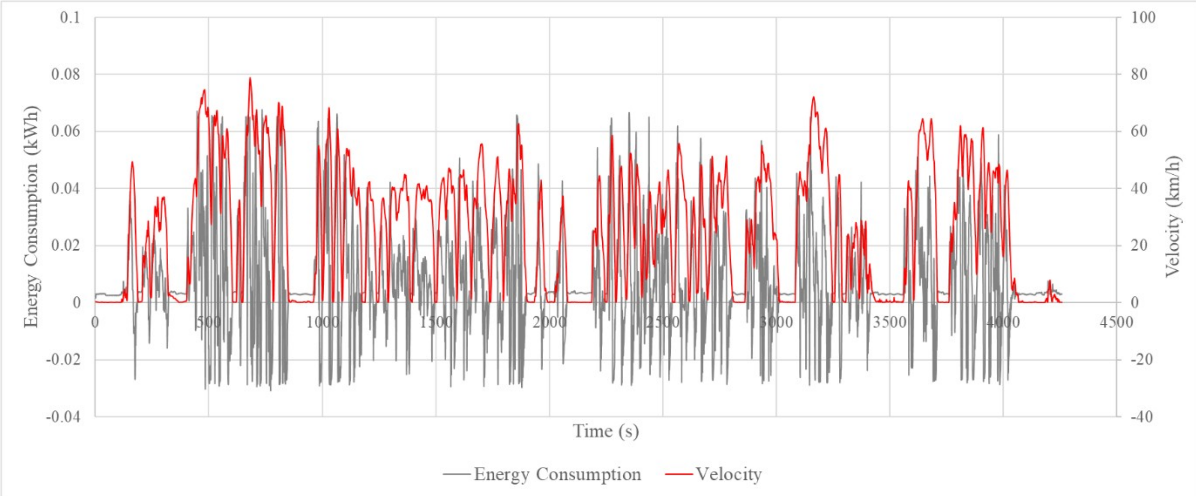
(a) Route 137 (average speed = 25.23 km/h)



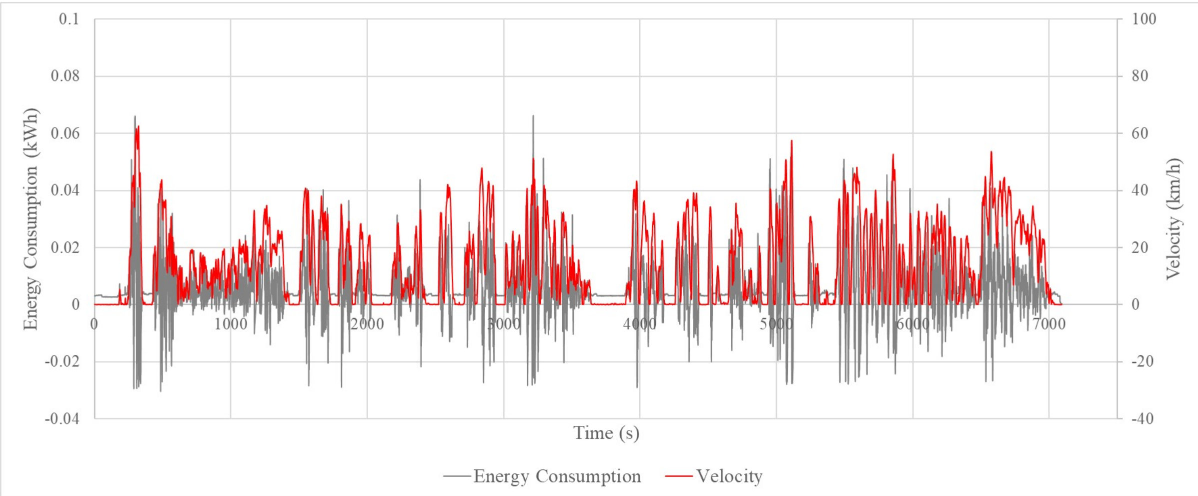
(b) Route 36 (average speed = 14.33 km/hr)

Figure 4: Samples of electrical current, voltage, velocity and distance data of (a) route 137 and (b) route 36.

The Figure 4 shows the samples of data extracted from the trips with highest average speed of each route. Although the total distance of the 2 routes are similar, the time taken between dispatching the bus and the bus returning to the depot is significantly different. This implies that the stopping time of the bus on route 36 is higher than route 137, and, as the electric bus stops more frequent on route 36, the acceleration from stopping also occurs more frequent. Therefore, the total electrical energy consumed by the bus is higher for route 36 compared with route 137.



(a) Route 137



(b) Route 36

Figure 5: Samples of energy consumption and velocity data of (a) route 137 and (b) route 36.

In order to clearly evaluate the effects of traffic conditions on energy consumption of the electric bus, the energy consumption data of each trip was accumulated and plotted against the average speed of that trip as shown in Figure 6. As the average speed increases, the energy consumption reduces in a non-linear fashion expressed by equation (2) obtained from curve fitting. It is suggested from Figure 6 that the electric bus should not be used in congested route as the energy consumption can be tripled compared to moderate or light traffic conditions. However, it should be noted that this relationship between average speed and energy consumption may be different from equation (2) as more data at higher average speed could be obtained. It is expected that the energy consumption will reach a lowest point at a particular speed and, then, the energy consumption may increase at high average speed such as in highway mode. This is because the electric bus does not decelerate very often; therefore, no recovery energy could be obtained from regenerative braking system although the energy is not much dissipated during acceleration as well. However, a more detailed experiment at high average speed is needed to confirm the above statement.

$$E_c = 6.4497 v_{avg}^{-0.579} \tag{2}$$

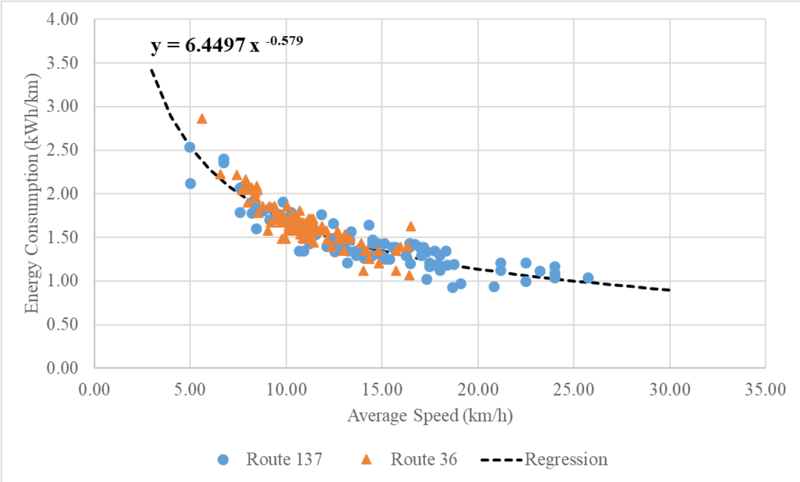


Figure 6: Energy consumption of the electric bus at different average speed.

In addition to the performance and energy consumption results, the charging characteristics was investigated. The electric bus was charged using the 200 kW charger, which its specifications are provided in Table 4. The voltage, current and energy information during charging is presented in Figure 7. The charging characteristics can be separated into 3 stages. The first stage is when the output current is maximum and is hold constant to quickly charge the bus. Then, as the voltage increases and approaches the maximum value, the charger slightly decreases the current until the battery is nearly at full charge, the charger cuts off the current transmitted to the battery to prevent overcharge.

Table 4: Specifications of the charger.

Items	Details
Charging Plug	CCS Combo Type 2 x 2 sockets
Rated Input Voltage	380 VAC ± 10%
Input Current	Max. 335 A
Input Power Capacity	Max. 225 KVA
Rated Output Voltage	DC 200 – 850 V
Rated Output Current	DC 0 – 134 A x 2 channels (in 100 kW, 750 V)
Dimension (W x H x D)	0.85 x 1.85 x 1.15 m

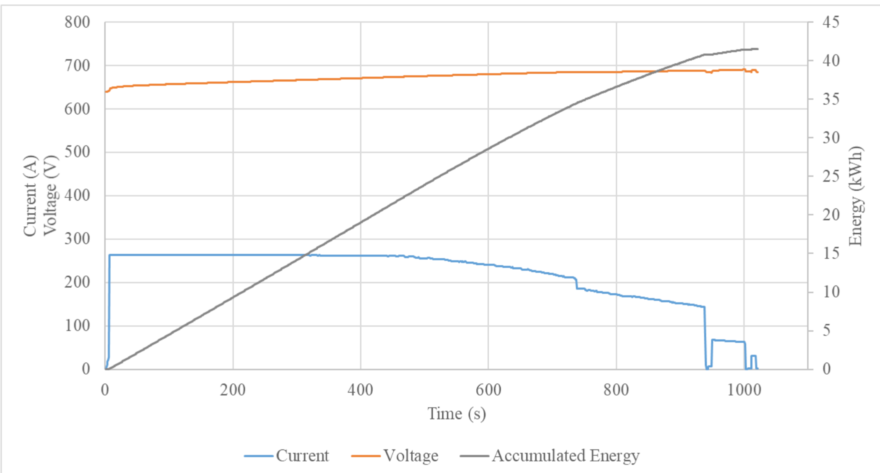


Figure 7: Charging characteristics.

4 Conclusion

This study aims to evaluate the effects of Bangkok traffic conditions on energy consumption based on real road test results from 2 routes, route 137 and route 36. The traffic conditions of the two routes were relatively similar on both weekdays and weekend. On weekday, the traffic was congested during the rush hours in the morning and evening, while, on weekend, the traffic condition was moderately congested from 10am onwards. The energy consumption of the electric bus significantly changes with the traffic conditions in a non-linear fashion. As the low average speed (heavy traffic condition), the energy consumption is high. Its values decreases as the traffic condition is lighter. The difference in energy used to operate the bus is up to 3 times when compared between congested and moderate or light traffic conditions. Moreover, more data at higher average speed is needed to accurately formulate the relationship between energy consumption and traffic conditions in Bangkok.

Acknowledgments

This research was financially supported by the "Development and Promotion of Electric Bus in Thailand" through the Ministry of Trade Industry & Energy (MOTIE) and Korea Institute of Energy Technology Evaluation and Planning all rights reserved (KETEP). In addition, the project was jointly supported by The Thailand Research Fund (TRF), contract No. RDG6050041. The authors would also like to thank Edison Motors Co., Ltd. and the Bangkok Mass Transit Authority (BMTA) for bus operation support.

References

[1] GIZ, *Urban Transport and Energy Efficiency*, 2012.

[2] Bloomberg New Energy Finance, *Electric Buses in Cities – Driving Towards Cleaner Air and Lower* CO_2, Bloomberg Finance L.P. 2018., March 29, 2018.

[3] International Energy Agency, *Global EV Outlook 2018 - Towards cross-modal electrification*, OECD/IEA, 2018.

[4] Barnitt R, Gonder J., *Drive cycle analysis, measurement of emissions and fuel consumption of a PHEV school bus*. SAE International 2011-01-0863, 2011.

[5] Wu X, Zhang S, Wu Y, Li Z, Ke W, Fu L, et al. *On-road measurement of gaseous emissions and fuel consumption for two hybrid electric vehicles in Macao*. Atmos Pollut Res 6:858 – 66, 2015.

[6] Paffumi E, de Gennaro M, Martini G, Manfredi U, Vianelli S, Ortenzi F, et al. *Experimental test campaign on a battery electric vehicle: on-road test results (Part 2)*. SAE Int J Altern Power 4(2):277 – 92, 2015.

[7] Zhou B, Wu Y, Zhou B, Wang R, Ke W, Zhang S and Hao J, *Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions*. Energy 96: 603 – 613, 2016.

Authors

Kitchanon Ruangjirakit received his M.Eng and Ph.D. in Aeronautical Engineering from Imperial College London, UK in 2008 and 2014, respectively. Currently, Dr.Ruangjirakit is a lecturer at Department of Mechanical Engineering, King Mongkut's Univeristy of Technology Thonburi, Bangkok, Thailand. His main research interests focus on composite materials, design of lightweight automotive structure and energy consumption in electric vehicles.

Yossapong Laoonual studied his first degree in Mechanical Engineering at Sirindhorn International Institute of Technology (SIIT), Thammasat University, Thailand. Between 1999 and 2006 he received Thai Government Scholarship to study in the UK where he continued his master's degree in Mechanical Engineering at the University of Manchester Institute of Science and Technology (UMIST), now University of Manchester, UK, followed by Imperial College London to gain his Ph.D. in Mechanical Engineering. He is currently an assistant professor at the Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi (KMUTT). He is also one of founding members of Electric Vehicle Association of Thailand [EVAT) and currently the first elected President from 2015.

Poj Tangamchit received his Ph.D. degree in Electrical and Computer Eng. (2003) from Carnegie Mellon University, USA. He is currently an associate professor at the department of Control System and Instrumentation Engineering at King Mongkut's University of Technology Thonburi, Bangkok, Thailand. His research involves AI, robotics, and ITS.

Ocktaeck Lim received his B.S. and M.S degrees in Mechanical Engineering from Chonnam National University, Korea, in 1998 and 2002, respectively. He received his Ph.D. degree from Keio University in 2006. Dr. Lim is currently a Professor at the School of Automotive and Mechanical Engineering at Ulsan University in Ulsan, Korea. Dr. Lim's research interests include Internal Combustion Engines, Alternative Fuel and Thermodynamics.