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Energy consumption analysis for electric campus tram design based on real university driving cycle pattern in Thailand

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Abstract. Rising population in suburban area have led to an increasing demand for commuter buses. Coupled with a desire to reduce pollution from daily routine of traveling and transportation, the electric vehicle has become more interesting as an alternative placement for internal combustion engine vehicles. However, in comparison to those conventional vehicles, Electric vehicles have an issue of limited driving range. One of main challenges in designing EV is to estimate the size and power of energy storage system, i.e. battery pack, for any specific application. A reliable information on energy consumption of vehicle of interest is therefore necessary for a successful EV implementation in terms of both performance and cost. However, energy consumption usually depends on several factors such as traffic conditions, driving cycle, velocities, road topology, etc. This paper presents an energy consumption analysis of electric campus tram based on university driving cycles in Thailand. First, the driving data of NGV trams operating in a campus of university situated in suburban of Bangkok were collected and used as a reference. The real driving cycle data i.e. velocity and vehicle global position (latitude, longitude, including road slope) were collected through a GPS-based equipment, V Box (VB20SL3, Racelogic Ltd). The driving data from a campus tram for different service routes were gathered to compute the energy consumption using Matlab/Simulink. The calculated energy consumptions were discussed for analyzing the proper EV performance with available preliminary specifications and planning in each route.

1. Introduction

Climate change and the conditions for the use of fossil resources are causing countries to change their climate and energy policies. The introduction of emissions-free zones in town will speed up the expansion of electro mobility. Some challenges of electric vehicle such as limited range and speed, sparse of electric charging station, long recharge time, etc. are related to an energy storage system design (energy and power), i.e. battery packs, for any specific application. [1] A reliable information on energy consumption is therefore necessary for a successful EV implementation in terms of both performance and cost. Knowledge of vocational drive cycle is important for improving the electric vehicle performance and design purposes. Driving cycle is the series of points representing the speed of the vehicle versus time. It is important for a fleet to match routes to technology to achieve maximum benefits. Standard driving cycles such as NEDC, WLTC, NYC, etc. were simulated by ADVISOR program in order to compare energy consumption with vehicle configurator models. [2-4] Energy consumption, cost-benefit analysis (CBA) and energy management strategy of either school or conventional bus were analyzed based on actual collected driving data in the specific area founded that the energy consumption was depending on the driving cycle. [2,5] From the driving profile, intelligent energy management also needs to know the roadway type, driving style in driving trend, the driving situation, and several characteristic parameters of the driving pattern. [6-8] On board vehicle power and energy management should be functions of real driving requirements. [9] Understanding actual vehicle usage is critical not only in design, but also in deployment because electric vehicle energy consumption depends on many external factors such as road topology, traffic, driving style, etc.

In this study, an energy consumption calculation was investigated based on a campus tram driving pattern in Thailand to achieve a suitable performance of electric vehicles in specific vehicle type and area. The aim was to collect and analyze the actual driving cycles in different routes data by using Global Positioning System (GPS) device. Four different tram routes were selected for a driving data collection in this work. The whole driving data in each route was separated to microtrips for randomly selection to construct equivalent driving pattern representations. Cycle time errors in each speed range were calculated for determining the best fit by having the least sum of error from ten candidates of generated driving cycle in each route. Data management, driving data separated to microtrips and driving data construction process were computed by Matlab/Simulink. The energy consumption considered in this work was the energy consumption on a battery-to-wheel based on basic vehicle dynamic equations. The energy consumption and energy efficiency were discussed for the EV performance with available preliminary specifications and planning in each route.

2. Method

2.1 Data Collection

In order to estimate energy consumption from a real university driving cycle pattern in Thailand, four different routes of tram operating in the same campus area were surveyed. Operating data including vehicle speed and time were acquired by the positioning-measurement instrument V Box (VB20SL3, Racelogic Ltd.). The details of driving data measurement are shown in Table 1. Driving data were collected from trams that were in operation between 7:00 a.m. – 8:00 p.m from Monday to Friday to represent a range of weekday service driving pattern. An investigation was conducted during July 12-26, 2017. The service trams of interest were powered by a gasoline engine with 29 passenger seats.

Table 1. Data collection setup details

Type of vehicle	Tram, internal combustion engine (NGV, gasoline)
Route	4 Routes: 1, 2, 3 and 4
Total number of vehicles in fleet	16
Configuration	
Number of seats	29 (with standing allowed)
Measurement Equipment	V Box (VB20SL3, Racelogic Ltd.) 
Acquired Data	Speed, Latitude, Longitude, Time, Brake Trigger

2.1.1 Operation Routes

The four different tram routes investigated in this study are displayed in Figure 1. The total number of cycle and total driving distance of tram collected for this study were 47 cycle and 190 km, respectively. The details of each route are shown in Table 2.

a) Route 1 b) Route 2 c) Route 3 d) Route 4

Figure 1. Tram operation routes

Table 2. The total number of cycle and distance collected in each tram route.

Tram Route	**1**	**2**	**3**	**4**	**Total**
Number of Cycle	8	12	20	7	47
Distance (km)	25.34	60.99	78.59	25.08	190

2.2 Driving Cycle Pattern Development

Driving cycle is a series of data points representing the speed of vehicle versus time profile and is developed for certain road, route, specific area or city. It is widely used in many applications for vehicle manufacturers, environmentalists and traffic engineers. In this study, the relation of driving cycle and energy consumption was a subject of interest for designing energy storage. First, the tram characteristics data was collected. The surveyed tram routes had many operating parameters e.g. time per cycle, number of passengers, and travel distance, etc. Collected data was simulated in order to generate the driving cycle pattern. The resulting energy consumption based on these different parameters would be important for the suitable design purpose.

2.2.1 Campus Tram Driving Pattern Characteristics

In order to distinguish between each service route, the operating characteristics of each tram route were represented by the value of average speed (V_{avg}), maximum velocity (V_{max}), and time per one cycle. The operating characteristics from four different service routes are shown in Table 3. Each value was obtained by averaging the relevant values from each individual cycle collected for each service route. The averaged time per cycle was then used as a main constraint for a driving cycle development for each service route as will be explained in following section.

Table 3. The operating characteristics of service tram per cycle for each route.

Tram Route	1	2	3	4
V_{avg} (km/hr)	12.63	13.45	13.46	13.36
V_{max} (km/hr)	35.16	33.08	30.54	28.85
Time per one cycle (s)	848	1113	1353	874

2.2.2 Microtrip: data segmentation

The speed-time data obtained from real-world trams operating in the university were divided into small parts of driving data i.e. Microtrips. Microtrip is a small portion of driving data that could be separated by periods of idle. The segmentation process was carried out on all collected cycles to form a database of microtrips for each service route. These databases were then used in a randomly selection process of microtrips to construct a tram driving cycle representative for each route. The process details for the driving data separation into microtrips can be described as in Figure 2. Microtrips were categorized according to a range their corresponding averaged velocity fell into. Three velocity ranges, equally divided from 0 to 30 km/h, were used in this study based on an initial observation during a survey. Additionally, the example of microtrips segmentation is illustrated in Figure 3.

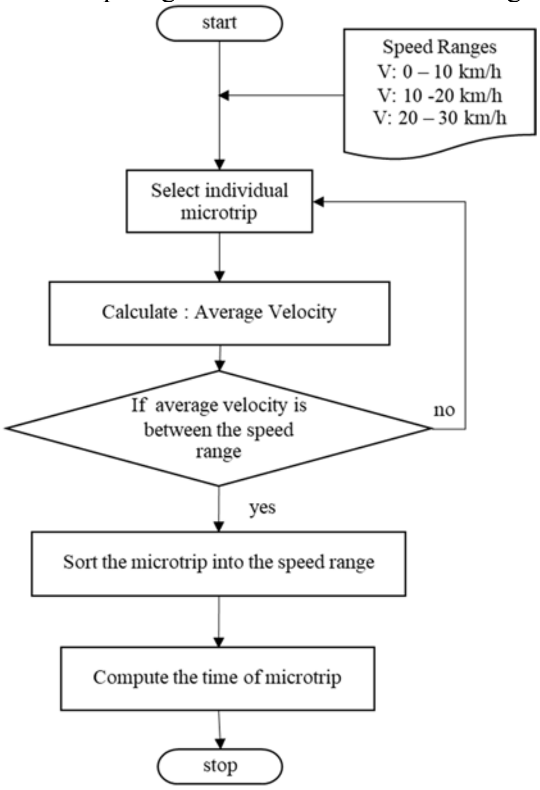

Figure 2. Microtrips construction process

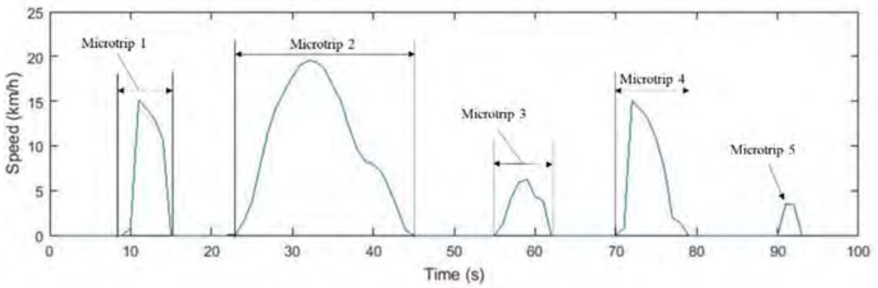

Figure 3. Example of microtrips segmentation from a speed-time data

2.2.3 Driving Cycle Pattern Construction

Each route of service trams surveyed in this study had a certain operating pattern because of the nature of their operation i.e. bus stops and certain type of road features which made the trams stopped such as t-junction, washboard road, pedestrian crossing, etc. As a result, the influence of the driver behaviour's on collected driving data was minimum. In this study, driving cycle patterns were constructed by using an averaged time per cycle for each route reported in Table 3, or an averaged time limit (T_{lim}), as a main criteria such that a total time of the constructed driving cycle must be within 10% difference from that of the time limit. Furthermore, the driving cycle pattern was constructed sequentially according to the speed ranges as explained in an earlier section. For a construction process in each speed range, the time limit was assigned by using a weight factor related to a proportion of number of collected microtrips in that speed range to the total number of microtrips in the database. The procedure of driving cycle construction is shown graphically in Figure 4.

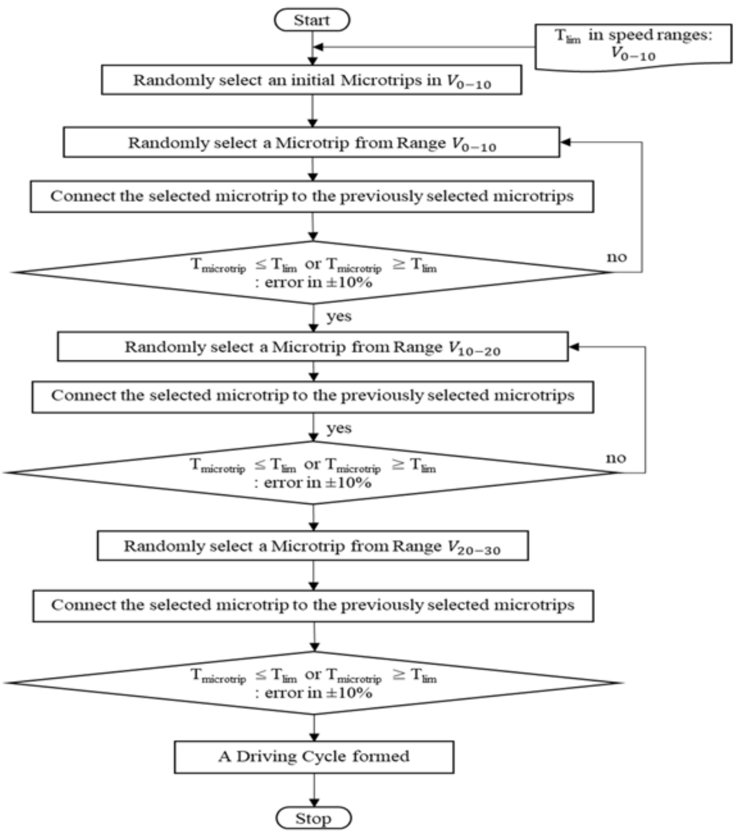

Figure 4. Driving Cycle Construction Procedure Flow Chart

2.2.4 Generated Tram Driving Cycle

As can be seen from the previous section a driving cycle in each service route was formed by a random selection of microtrips from all collected driving data. The example of generated tram route driving cycle is illustrated in Figure 5. In this study, ten candidates of such driving cycles were generated for each route. In order to select the best representative driving cycle, the percentage of the error between $T_{microtrip}$, i.e. microtrip time, and T_{lim} in each speed ranges were considered.

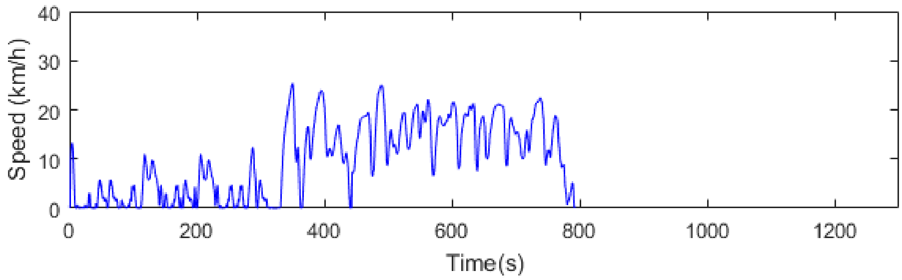

Figure 5. Example of tram generated driving cycle

The generated driving cycle were calculated the errors between $T_{microtrip}$, T_{lim} and weight factor were considered in the condition. The resulting error from each speed range, i.e. E1, E2 and E3, were the function of discrepancy between $T_{microtrip}$ and T_{lim} including weight factor by number of microtrips for each speed range presented in the database. The equation of the errors calculation in each speed ranges are given by:

$$E_1 = \left| \frac{T_{\lim} - T_{microtrip}}{T_{\lim}} \right| \times W_{0\text{-}10} \times 100\ (\%) \quad (1)$$

$$E_2 = \left| \frac{T_{\lim} - T_{microtrip}}{T_{\lim}} \right| \times W_{10\text{-}20} \times 100\ (\%) \quad (2)$$

$$E_3 = \left| \frac{T_{\lim} - T_{microtrip}}{T_{\lim}} \right| \times W_{20\text{-}30} \times 100\ (\%) \quad (3)$$

where $W_{0\text{-}10}$, $W_{10\text{-}20}$ and $W_{20\text{-}30}$ are weight factor for each speed range 0 – 10 km/h, 10 – 20 km/h, and 20-30 km/h, respectively. In other word, the contributions to the total error (E) were due to the percentage of number of microtrip in each speed range for each route. Finally, the sum of error including weight factor was determined as followed:

$$E = E_1 + E_2 + E_3\ (\%) \quad (4)$$

3. Energy Consumption Calculation

The energy consumption was calculated from the fundamental theory of vehicle dynamics. In this study, the electric power was assumed to be equal to the power to produce a tractive force. The energy involving air conditioning, auxiliary components, and regenerative brake were ignored. The tractive force is described by the following equation:

$$F = R_a + R_r + R_{cl} \quad (5)$$

where F is tractive force (N), R_a is the aerodynamic resistance (N), R_r is the rolling resistance (N) and R_{cl} is grade resistant (N). R_a, R_r and R_{cl} were calculated when a tram was traveling at constant velocity, v (m/s^2), C_d is coefficient of drag, ρ is air density (kg/m^3), A is frontal area of the vehicle (m^3), f_r is rolling resistance constant, g is gravity acceleration (g = 9.81 m/s^2), m is a mass of vehicle (kg) and θ is the road grade (degree). Finally, the tractive force (F) is found in equation (9) by combining equation (6), equation (7), and equation (8).

$$R_a = C_d \frac{\rho}{2} A v^2 \quad (6)$$

$$R_r = f_r mg \cos\theta \quad (7)$$

$$R_{cl} = mg \sin\theta \quad (8)$$

$$F = C_d \frac{\rho}{2} A v^2 + f_r mg \cos\theta + mg \sin\theta \quad (9)$$

To calculate energy consumption, the power for vehicle traveling at velocity (v) was required. Required power, denoted P (Watt), can be determined from the relationship between F and v in equation (10).

$$P = F \cdot v \quad (10)$$

In this study, the energy consumption was calculated by using geometric parameters of 9-meter EV bus prototype and other constants as shown in Table 4.

Table 4. Parameters for energy consumption calculation

General characteristics of Vehicle (Medium-sized Bus)	
Parameters	**Value**
Curb weight(kg)	9000
Vehicle frontal area(m^2)	7.5
Rolling Resistance	0.015
Drag coefficient	0.7
Air Density(kg/m^3)	1.14
Gravity Acceleration(m/s^2)	9.8

The values from Table 4 were used for calculating power in equation (10). The control variables were velocity and roadway grade. The tram driving cycles generated as described in the previous section were used as a calculation input for each service route. A vehicle weight was a sum of the curb weight and the averaged passenger weight recorded in each service tram route. Matlab Simulink was used to calculate the energy consumption by using the workflow as described in Figure 6.

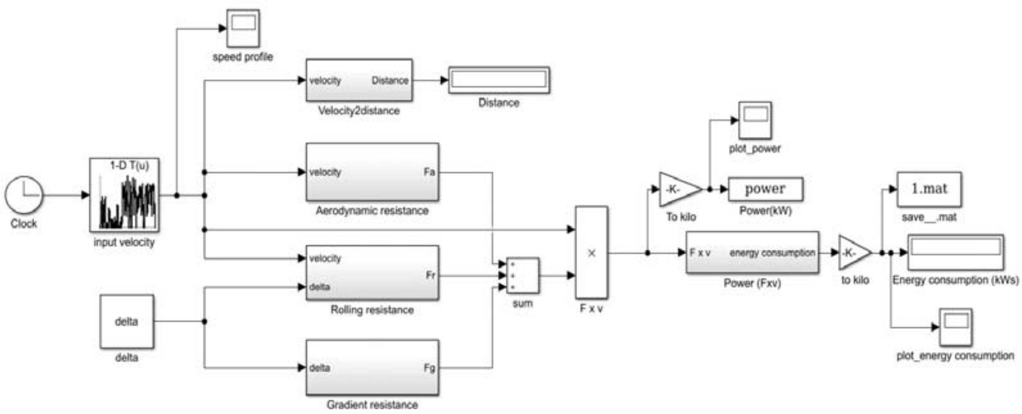

Figure 6. Matlab Simulink for Energy Consumption Calculation

4. Results and discussion

4.1 Driving Cycle Development

As explained in section 2, after the collected driving data were separated into microtrips (Figure 2-3), they were arranged into different speed ranges by the corresponding averaged velocity of each microtrip. The driving characteristic of the trams after the microtrip segmentation for service route 1-4 are shown in Table 5-8 respectively. The results consisted of average velocity (V_{avg}), maximum velocity (V_{max}), standard deviation of velocity (V_{sd}), average time of each microtrip, and number of microtrips.

Table 5. Route 1 Driving Characteristics.

Velocity Ranges	V_{avg} (km/hr)	V_{max} (km/hr)	V_{sd}	Time (s)	Number of Microtrips
0 ≤ v < 10	1.43	3.21	1.17	8.17	35(39.33%)
10 ≤ v < 20	15.18	25.87	6.73	112.09	53(59.55%)
20 ≤ v < 30	21.29	35.16	7.54	193.00	1 (1.12%)

Table 6. Route 2 Driving Characteristics.

Velocity Ranges	V_{avg} (km/hr)	V_{max} (km/hr)	V_{sd}	Time (s)	Number of Microtrips
0 ≤ v < 10	2.70	6.75	2.57	11.36	64 (27.71%)
10 ≤ v < 20	16.86	28.51	7.70	90.94	149 (64.5%)
20 ≤ v < 30	20.79	33.08	7.86	140.56	18 (7.79%)

Table 7. Route 3 Driving Characteristics.

Velocity Ranges	V_{avg} (km/hr)	V_{max} (km/hr)	V_{sd}	Time (s)	Number of Microtrips
0 ≤ v <10	2.98	6.78	2.65	8.14	44 (16.67%)
10 ≤ v <20	16.72	29.14	7.67	104.81	212 (80.3%)
20 ≤ v <30	20.68	30.54	6.58	148.13	8 (3.03%)

Table 8. Route 4 Driving Characteristics.

Velocity Ranges	V_{avg} (km/hr)	V_{max} (km/hr)	V_{sd}	Time (s)	Number of Microtrips
0 ≤ v < 10	4.00	8.80	3.40	11.28	72 (57.6%)
10 ≤ v < 20	15.85	25.99	6.82	98.54	52 (41.6%)
20 ≤ v < 30	20.24	28.85	7.12	87.00	1 (0.8%)

Furthermore, in each route from Table 5-8, the proportion of number of microtrips presented in each speed range was used to calculate the corresponding time constraint (T_{lim}) which was then used to carry out the driving cycle construction process as explained in section 2.2.3. It could be seen that the highest number of microtrips were in the 10 – 20 km/h speed range for service route 1-3, while it was in the 0 – 10 km/h range for route 4. The resulting driving cycles were then constructed as explained in Figure 4. Ten candidates of generated driving cycle were chosen by the lowest sum of error which had taken into account the weight factor as explained in section 2.2.4. The obtained values of E_1, E_2, E_3 and E from all ten candidates of driving cycle representative in each route are summarized in Table 9 – 12.

Table 9. Percentage of time error in each speed range of generated driving cycle candidates to the averaged cycle time from actual driving data of route 1.

Ranges	Sum of the errors	Route 1									
		(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
0 ≤ V < 10	E1	0.41	0.29	0.41	0.53	0.53	0.53	0.41	0.65	0.76	0.17
10 ≤ V < 20	E2	0.35	1.65	0.12	1.77	4.83	4.95	3.42	1.77	2.24	0.71
20 ≤ V < 30	E3	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
Total	**E**	**1.89**	**3.07**	**1.65**	**3.42**	**6.49**	**6.60**	**4.95**	**3.54**	**4.13**	**2.00**

Table 10. Percentage of time error in each speed rage of generated driving cycle candidates to the averaged cycle time from actual driving data of route 2.

Ranges	Sum of the errors	Route 2									
		(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
0 ≤ V < 10	E1	0.75	0.57	0.12	0.39	0.66	0.39	0.48	0.75	0.12	0.48
10 ≤ V < 20	E2	4.03	0.26	0.53	6.37	6.10	0.53	5.92	1.70	6.64	8.71
20 ≤ V < 30	E3	0.29	5.91	6.44	4.29	3.03	0.07	0.33	5.55	0.42	4.47
Total	**E**	**5.08**	**6.74**	**7.10**	**11.05**	**9.79**	**0.99**	**6.74**	**8.00**	**7.19**	**13.66**

Table 11. Percentage of time error in each speed range of generated driving cycle candidates to the averaged cycle time from actual driving data of route 3.

Ranges	Sum of the errors	Route 3									
		(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
0 ≤ V < 10	E1	0.26	0.11	0.63	0.48	0.48	0.11	0.63	0.11	0.11	0.11
10 ≤ V < 20	E2	1.88	7.58	2.55	6.39	3.44	5.58	3.22	1.07	5.06	1.74
20 ≤ V < 30	E3	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03
Total	**E**	**5.17**	**10.72**	**6.21**	**9.90**	**6.95**	**8.72**	**6.87**	**4.21**	**8.20**	**4.88**

Table 12. Percentage of time error in each speed range of generated driving cycle candidates to the averaged cycle time from actual driving data of route 4.

Ranges	Sum of the errors	Route 4									
		(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
0 ≤ V < 10	E1	1.76	1.19	2.34	1.31	1.88	2.57	2.11	2.79	2.79	1.08
10 ≤ V < 20	E2	3.84	1.10	1.21	1.10	1.44	2.13	2.01	0.98	0.41	1.10
20 ≤ V < 30	E3	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Total	**E**	**6.41**	**3.09**	**4.35**	**3.20**	**4.12**	**5.49**	**4.92**	**4.58**	**4.00**	**2.97**

The most appropriated representative driving cycles for each service route were the one with the least sum of errors. As a result, from Table 9-12, candidate driving cycle number (3), (6), (8), and (10) were chosen for service route 1, 2, 3, and 4 respectively. The details of the resulting error in each speed range together with the sum of error for the selected representative driving cycles for each route of tram service are summarized in Table 13. Additionally, the chosen representative driving cycles of each tram route are displayed in Figure 7.

Table 13. The error obtained in each speed range and the sum of error of the chosen representative driving cycles of each tram service route.

Route	Candidate Number	Error in Speed Ranges			The sum of error
		$0 \leq V < 10$	$10 \leq V < 20$	$20 \leq V < 30$	
Route 1	(3)	0.41	0.12	1.12	1.65
Route 2	(6)	0.39	0.53	0.07	0.99
Route 3	(8)	0.11	1.07	3.03	4.21
Route 4	(10)	1.08	1.10	0.80	2.97

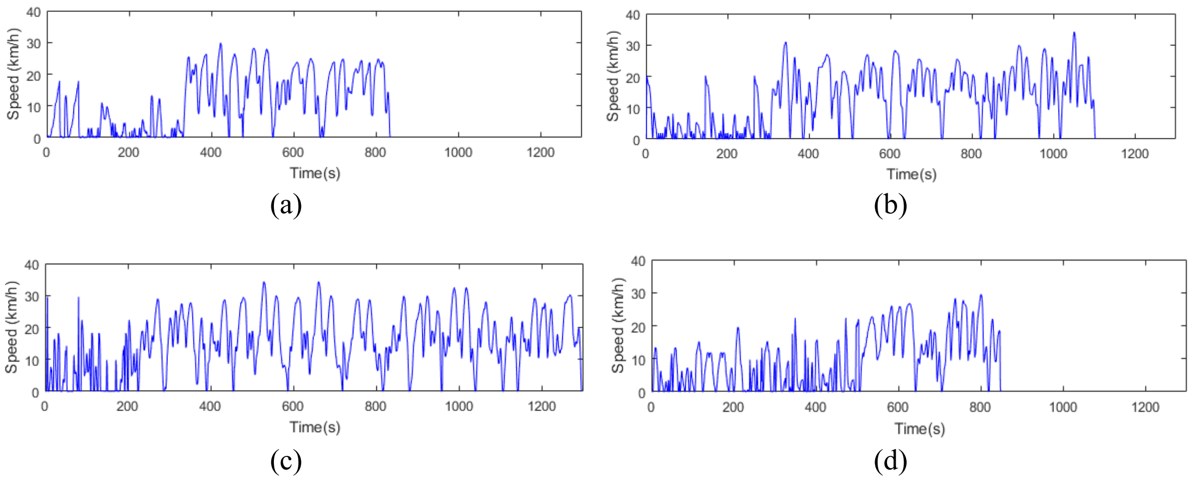

Figure 7. The chosen representative driving cycles for surveyed service trams (a) route 1, (b) route 2, (c) route 3, and (d) route 4

Table 14. The driving cycle characteristics of the representative driving cycle in each tram service route.

Tram Route		**Route 1**	**Route 2**	**Route 3**	**Route 4**
V_{avg}	**(km/hr)**	11.49	13.16	15.36	9.86
V_{max}	**(km/hr)**	29.82	34.21	34.32	29.52
Time	**(min)**	13.90	18.37	21.60	14.13
Distance	**(km)**	2.661	4.029	5.531	2.322

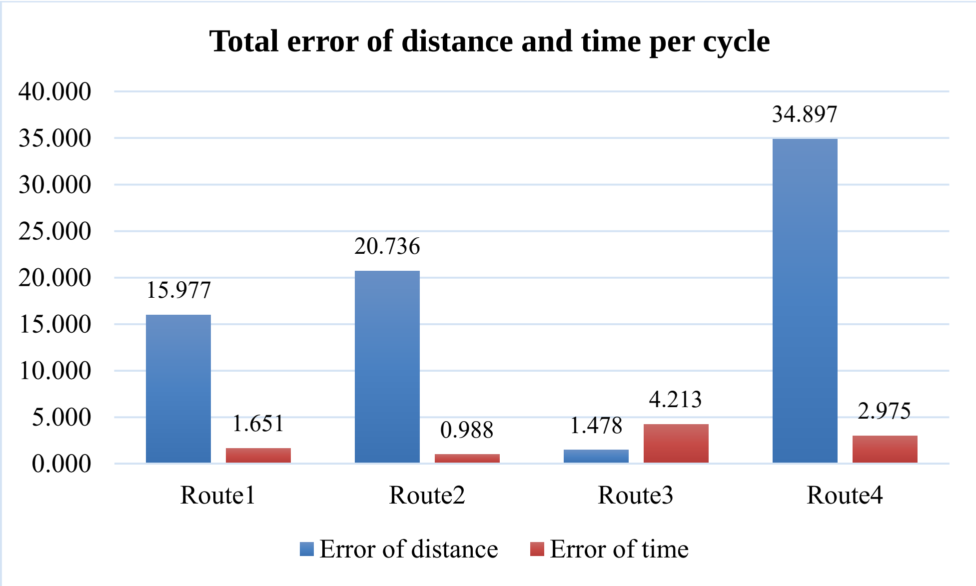

Figure 8 . The corresponding time and distance error for the generated driving cycles

The driving cycle characteristics of the generated tram driving cycles in each route are shown in Table 14. From these results, the corresponding errors between the actual and generated driving patterns could be calculated in term of travel time and distance as shown in Figure 8. It could be seen that, in general, the errors in distance were at a higher order than those of time. This was expected due to the fact that the travel time was considered in the driving cycle construction process. For the travel time per one service round, the sum of error was highest at 4.2% for route 3 which was the one with the most driving data collection. On the other hand, the distance error of route 3 was lowest at 1.5%. This showed that the number of collected data could significantly affect the error obtained from the construction process. This could be because of the total number of microtrips available for a random selection during the representative driving cycle construction.

4.2 Energy Consumption

The energy consumption was calculated as function of driving speeds obtained from the generated representative driving cycles. The values of energy consumption per cycle of the generated driving cycle for four different service routes calculated by Matlab Simulink program are shown in Table 15.

The minimum and maximum numbers of passengers considered in the calculations were six and thirty passengers. The minimum passenger was an averaged passenger per cycle as collected whereas the maximum number was including standing passengers as a worst-case scenario. It could be seen that an increase of roughly 15% in energy consumption was predicted for all routes with an increase in mass i.e. passengers. This indicated a significance of number of passenger or gross vehicle weight on the energy consumption estimations.

Table 15. The estimated energy consumption and energy efficiency in each tram route per one cycle

Route	Energy consumption (kWh)		Energy efficiency (kWh/km)	
	6 passengers	30 passengers	6 passengers	30 passengers
Route1	1.081	1.246	0.406	0.468
Route2	1.642	1.891	0.408	0.469
Route3	2.275	2.617	0.411	0.473
Route4	0.9348	1.078	0.401	0.462

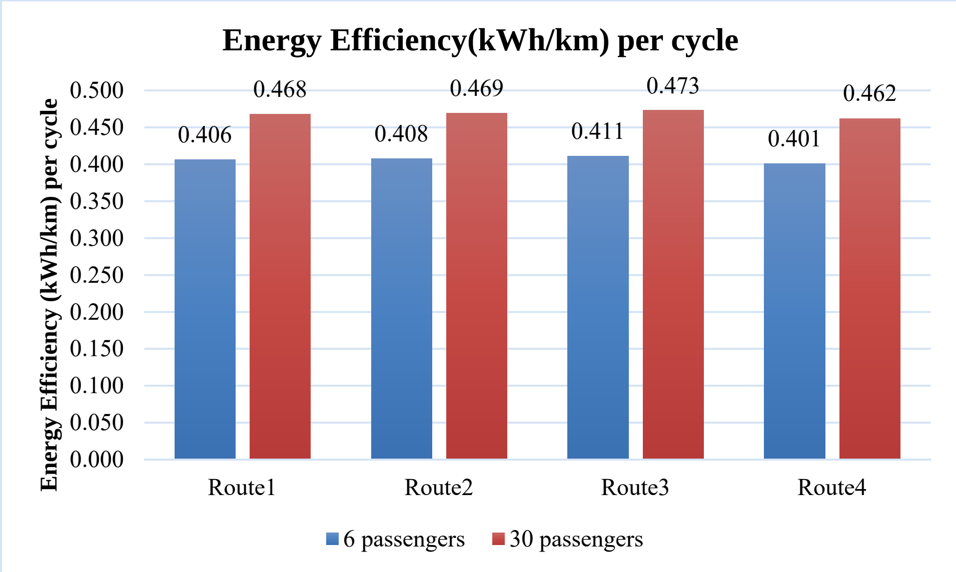

Figure 9. Energy efficiency (kWh/km) per cycle

The impact of driving cycle is presented in Figure 9 where the energy consumption and energy efficiency is showed as function from the generated driving speed in operation. The energy efficiency, in kWh/km, of all routes was found to be almost equivalent. Therefore, it could be assumed that the energy efficiency of 0.473 kWh/km, i.e. the maximum value, could be the representative energy consumption for all electric tram designs in this study.

5. Conclusions

In this paper, the energy consumption estimations of campus trams were carried out via calculations from actual driving data in university including velocity, vehicle position (latitude, longitude), and time. The energy consumption was calculated based on the fundamental theory of vehicle dynamics and the basic relationships between power and force. Four different tram service routes, operating in the same area, were investigated.

In this study, the main parameter of driving cycle construction for energy consumption calculation was operating cycle times. They were used in the driving cycle construction process as means to select the suitable candidates through a comparison of their corresponding error. This was likely the reason of a relative lower sum of error in the cycle time compared to those of the distance. The analysis indicated that the energy consumption was depending on a driving pattern. The estimated maximum error of time per cycle and distance was 4.213% and 34.897 % respectively. A weight of passengers was also found to affect to the energy consumption. An increase of 13.14% was predicted when the number of passengers were changed from six to thirty.

Between all four tram routes surveyed in this study, the energy efficiency results were not significant different because the driving data were collected from the same operating area, with the same vehicle type, and similar driving behaviour controlled by presence of bus stops along with other road features. Therefore, the energy efficiency of 0.473 kWh/km was estimated as the representative energy consumption for all electric tram designs based on this study. Nonetheless, the total amount of energy required for the energy storage system in the electrification design of the four tram routes would be significantly different because of the variant characteristics of V_{avg}, V_{max}, time per cycle, and operating distance between the driving patterns of each route.

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