Implementation and Validation Modelling of Energy Demand of Electric Buses for Local Public Transport

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***Abstract*— In recent years, a focused attention towards the conversion of conventional fleets in local public transport to fully electric fleets have gained momentum, instilled by awareness about the environment and significant trend of urbanization. Public transport operators in major cities all over the world have engaged themselves in fulfilling this change. An efficient electrification process is still a challenge for most operators. This paper aims to propose an energy demand model for an electric bus vehicle to monitor and verify the energy consumption. The real drive cycles of actual electric buses are used to simulate the energy demand characteristics and the battery state of charge of the vehicle. Real-time collected local data are used as input for the simulation model and discharge energy, regenerated energy and battery state of charge are computed. The simulated results are then validated with the real data available. The results are then used to consider an improvement for charging infrastructure.**

Keywords—local public transport, simulation, electric bus energy demand, vehicle scheduling, Simulink, state of charge, charging infrastructure.

I. Introduction

The ever-increasing focus towards environmental issues have pushed the cities and local governments to improve the electrification of vehicles in Local Public Transport (LPT) by advancement in electric powertrain and battery technologies. In recent years, development of smart charging solutions and decreasing battery prices have enabled the local Public Transport Operators (PTOs) to proceed with the conversion of conventional vehicles into a full-electric bus fleet [1-2]. This is mainly centered around the metropolitan areas of the world mainly because of the trend of increasing urbanization. Until recently, accepting this evolution has been difficult due to the high upfront investment and limited range of electric vehicles. The technological advancement and several government policies have allowed a successful implementation of the transition to full-electric bus fleet in major cities.

Actually, there are examples of European cities that have started employing their technology towards a practical implementation, promoting and inspiring several cities around the world to face this change. Some remarkable examples are cities of Vienna, London, and Eindhoven, the first few cities in Europe to begin subnetwork operations at very early stages [3-5]. Currently several cities are transforming part of their network operated with electric vehicles. However, the Battery Electric Bus (BEB) technology, charging infrastructure and vehicle scheduling depend on the local scenario. Thus, every PTO must adapt the electrification process to achieve the targets.

This paper aims to develop a simulation model of energy demand which computes the energy requirements for service operations. The model includes a parameterized vehicle and is based on the existing local driving scenarios, also providing the assessment of opportunity charging solutions.

II. General Overview

The service scheduling influences the technical design of vehicles and infrastructure and defines the entire framework of the scenario; this is established by the driving range and the dwell time durations at potential charging locations [5]. On the other hand, vehicle scheduling is limited by technical constraints of the BEBs and charging infrastructure, as depicted in Figure 1.

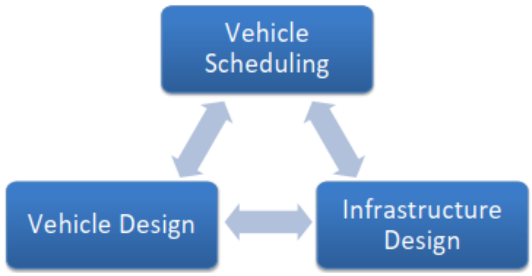


Fig. 1. Interdependence of BEB system design processes

An efficient BEB system design must consider:

- the development of a mathematical model for a full-electric vehicle,
- an accurate model of the energy consumption of BEBs considering the route topology, weather conditions, and traffic flow,
- the operational requirements of power distribution networks,
- the definition of the optimal configuration of both on-board battery packs and chargers [6].

Therefore, a model for calculating BEB energy demand on specific routes has been created to evaluate the vehicle energy demand and infrastructure improvements. Since the energy demand depends on the route characteristics as well as on the technical configuration of the vehicle, general data about the existing local scenarios have been recorded through Phyphox phone application [7]. The sampled data is constituted by the real-time speed and altitude profiles.

III. Energy Demand Model

The proposed model for BEB energy demand has been developed in MATLAB-Simulink and considers reference real driver cycle and altitude profile for the selected route as input. The characterization of the vehicle considers the motors, battery, brake, and driveline subsystems [8]. The proposed Simulink model consists of 6 subsystems that describe the vehicle energy consumption on a reference route.

A. Longitudinal Driver

The model implements a Longitudinal Driver block as a PID speed-tracking controller. Based on real-time slope, speed reference and feedback signals, the block generates the dynamic normalized response of a driver, with acceleration and braking commands varying from 0 to 1.

B. Braking System

The Braking System block gives the friction braking force and the regenerative braking command as output, based on the brake pedal position as input from the Longitudinal Driver. The braking command is converted into desired braking force since the tyre-road adhesion coefficient is known. The desired braking force is then split into the friction braking force and the regenerative brake force [9]. Finally, the regenerative brake force is converted into regenerative torque through the gear ratio and wheel radius.

C. Motor System

The accelerator pedal position from the driver block acts as an input also to Motor System block, which produces a corresponding positive torque for each time instant. The torque is taken according to (1).

$$C_m = min\left(0{,}8C_{rated}; \frac{P_{rated}}{\omega}\right) \tag{1}$$

The allowable regenerative torque limit is defined and used as a lower bound to convert the regenerative brake torque into the actual regenerative torque. Net motor torque for each time step is then obtained through (2).

$$C_{m,net} = C_m - C_{regenerated} \tag{2}$$

During the regenerative braking phase, the mechanical power coming from the driveline is converted into electric power by the electric motor, acting as a generator. The electric motor power requested by the battery and the net motor torque transmitted to the driveline are the output of the block.

D. Battery System

The Battery system block receives as input the total power of discharge, constituted by the electric motor power required by the electric motor and the auxiliary power absorbed by the other systems. The battery is represented by an ideal voltage source defined as the open-circuit voltage V_{OC} in series with its internal resistance R_i. According to (3), the real discharge power of the battery is equal to the difference between ideal discharge power and power losses linked to the internal resistance of the battery.

$$\begin{aligned} P_{discharge,real} &= P_{discharge,ideal} - P_{discharge,loss} \\ P_{discharge,real} &= V_{oc} \cdot I_{discharge} - R_i \cdot I_{discharge}^2 \end{aligned} \tag{3}$$

Thus, the discharge current is given by (4).

$$I_{discharge} = \frac{V_{OC} - \sqrt{{V_{OC}}^2 - 4R_{i,discharge}P_{discharge,real}}}{2R_{i,discharge}} \tag{4}$$

Hence, it is possible to evaluate the State Of Charge (SOC) of the battery as a function of the rated energy content of the battery E_{bat}, according to (5). The SOC provides the actual battery status, where 0% indicates battery completely discharged and 100% battery full charged. Since considering 0% dramatically reduces the battery efficiency, the acceptable SOC lower limit is set to 20% [10].

$$SOC_{bat} = \frac{-\int_0^t V_{oc} I_{discharge} \cdot dt}{E_{bat}} \cdot 100 \tag{5}$$

E. Driveline System

The Driveline System block sees as input the net motor torque from the electric motor, the friction brake force from the braking system, and the instantaneous simulated speed of the vehicle. The tractive force transmitted to the tyres is then computed by multiplying with the ratio between the gear ratio and the wheel radius. The difference between positive tractive force and friction brake force from the brake system block constitutes the net tractive force acting on the bus.

F. Longitudinal Vehicle Dynamics

The Longitudinal Vehicle Dynamics block receives the net tractive force acting on the vehicle as an input and compares it with the sum of the resistances opposing to the bus motion. For each time step, the rolling resistance R_r, the aerodynamic resistance R_{aero}, and the slope resistance R_g are computed using (6), (7), and (8) respectively and the inertial force, as shown in Figure 2. The maximum vehicle mass has been considered.

$$R_r = K_r mgcos\theta \tag{6}$$

$$R_{aero} = \frac{1}{2}\rho_{air} C_{aero} A v^2 \tag{7}$$

$$R_g = mgcos\theta \tag{8}$$

where:

- K_r is the rolling resistance coefficient
- ρ_{air} is the air density
- A is the front surface of the vehicle

- v is the instantaneous vehicle speed
- θ is the instantaneous slope angle

The block calculates the acceleration of the vehicle and the simulated speed, which are then feedback to the driver, brake, and driveline blocks in a closed loop.

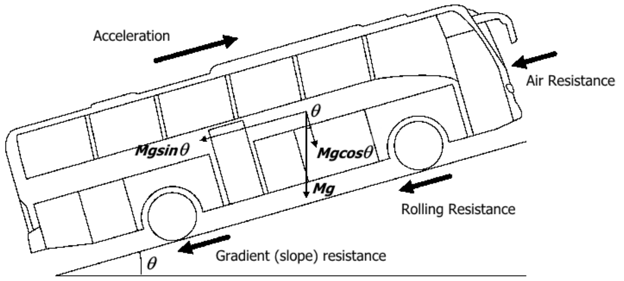


Fig. 2. Longitudinal Forces on a bus in motion.

IV. CASE STUDY: A REAL BUS ROUTE

The case study considers a real route in Northern Italy served by BEB vehicles. The route is 8,6 km long and depicted in Figure 3. Almost all the vehicles running on this route are full-electric buses.

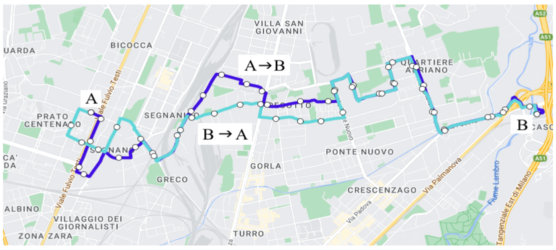


Fig. 3. Map of the route chosen for analysis, 29 stops, length 8.5 km (blue path) and 8.7 km (light blue path)

The technical characteristics of vehicle are briefly reported in Table I, while Table II collects all additional simulation parameters [11-15].

TABLE I. VEHICLE TECHNICAL CHARACTERISTICS

	Units	Model series 1	Model series 2
Length	[m]	1200	1200
Width	[m]	2550	2550
Height	[m]	3300	3300
Tare	[kg]	13350	13885
Useful load	[kg]	5650	5115
Permissible Mass	[kg]	19000	19000
Total seats	[-]	83	76
Useful capacity	[kWh]	216	316
Nominal capacity	[kWh]	254	396
Max power		2x125 kW	
Nominal tension		3x400 V	
Charging system	[-]	DC 2 sockets (one each side) plug-in CCS Combo2	
Opportunity Charge Protocol	[-]	Upside-down pantograph	

TABLE II. SIMULATION PARAMETERS

Parameters	Units	Value
Tyre-road adhesion coefficient	[-]	0.85
Regenerative braking threshold velocity	[km/h]	15.5
Regenerative braking factor	[-]	0.7
Air density	[kg/m^3]	1.23
Aerodynamic drag coefficient	[-]	0.79
Rolling resistance coefficient	[-]	0.01
Gravity acceleration	[m/s^2]	9.81
Auxiliary energy consumption	[kWh/km]	1.41

Speed and altitude profiles have been recorded for various roundtrips at different hours of the day (peak and off-peak hours) and on different days of the week (working and weekend days). For each simulation, one roundtrip data has been considered with 4 minutes of dwell time at the terminal stop as recorded. The simulation aims to evaluate the discharge energy, regenerated energy, and battery SOC. The observations from the simulation results are shown in Table III for the working days and weekends.

TABLE III. WORKING DAY AND WEEKEND ROUNDTRIP SIMULATION RESULTS

	Roundtrip Duration [s]	$E_{discarge}$ [kWh]	$E_{regenerated}$ [kWh]	Regeneration [%]	SOC [%]
Working days					
Peak	4965	30.67	6.89	22.46	91.38
Off-Peak	4353	28.65	6.75	23.56	92
Weekend days					
Peak	3631	38.61	11.89	30.80	90.31
Off-Peak	3217	41.38	13.58	32.81	89.92

On working days, the energy discharged is higher during peak hours, as to cover the same distance, more time is spent. On weekend days, a higher energy consumption is observed as the bus has higher maximum speeds for longer durations. Higher regeneration percentage is observed during off-peak hours in both cases, because with higher speeds the duration of braking is longer and stronger than in the cases of peak hours, which leads to higher regeneration. During roundtrip operations, the battery consumption is about 8-11%, being higher during peak hours. It can be concluded that a bus can cover 8-10 roundtrips with a full charge of battery.

V. VALIDATION OF MODEL AND ANALYSIS OF RESULTS

To validate the data obtained from the developed model, real data of the BEBs operating on the route on five working days have been obtained for 5 consecutive days. The data consist of the Bus ID, Date of service, Start-of-service time, End-of-service time and Discharged energy, Regenerated energy, and Battery SOC. Also, the time of exiting from and returning to the depot have been considered. Test data have been prepared as shown in Table IV after choosing six buses (named BEB-1 to BEB-6) whose start, and end-of-service times cover the service durations of each bus running on working days. The discharge energy, regenerated energy and battery used test data have been prepared by averaging the data of all the buses for 5 days, corresponding to a similar duration of service and number of peak and off-peak roundtrips taken.

TABLE IV. PREPARED TEST DATA FOR VALIDATION

Bus No.	Start of Service Time [hh:mm:ss]	End of Service Time [hh:mm:ss]	$E_{discarge}$ [kWh]	$E_{regenerated}$ [kWh]	Battery Used [%]
BEB -1	09:39:00	12:23:00	61	15	26
BEB -2	06:12:00	10:18:00	90	20	37
BEB -3	12:45:00	22:16:00	208	49	59
BEB -4	16:43:00	19:52:00	65	15	16
BEB -5	05:47:00	10:03:00	91	21	26

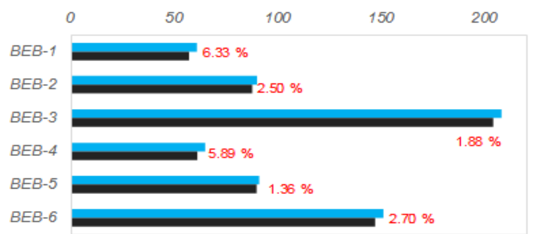
Bus No.	Start of Service Time [hh:mm:ss]	End of Service Time [hh:mm:ss]	$E_{discarge}$ [kWh]	$E_{regenerated}$ [kWh]	Battery Used [%]
BEB -1	09:39:00	12:23:00	61	15	26
BEB -6	13:03:00	20:07:00	151	38	45

For the prepared test data, simulation scenarios have been created as shown in Table V based on the combination of peak and off-peak roundtrips during their service time. The duration on-line is the time spent on the path specified for the route. The duration off-line corresponds to the time spent in dwelling at the initial stop after each roundtrip and the time taken to go from and back to the depot.

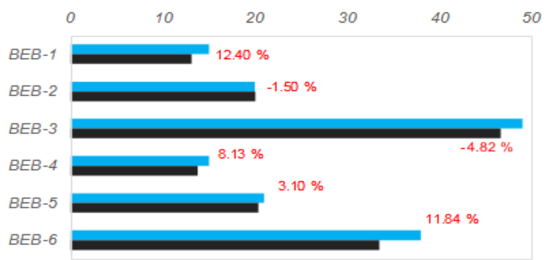
TABLE V. PREPARED SIMULATION SCENARIOS OF TEST DATA

Bus No.	Duration of Service [min]	No. of Peak round trips	No. of Off-Peak round trips	Duration On-line [min]	Duration Off-line [min]
BEB-1	164	0	2	145	19
BEB-2	246	1	2	227.75	18.25
BEB-3	571	2	5	528	43
BEB-4	189	2	0	165.5	23.5
BEB-5	256	2	1	238	18
BEB-6	424	2	3	383	41

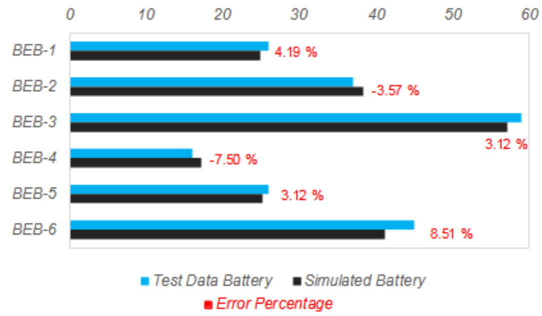
After performing simulations for the 6 BEBs, the simulated results have been compared with the test data and depicted in Figure 4.



(a)



(b)



(c)

Fig. 4. Error between real and simulated data: (a) discharged energy, (b) regenerated energy, (c) battery used.

The simulation results are close to the test data with errors within 6% for discharge energy, 12.5% for regenerated energy and 8.5% for the battery used data. The sources of error are related to the non-availability of the velocity profile and driving behavior for the duration off-line. Moreover, the simulation data are a combination of roundtrips that belong either to peak hours or off-peak hours whereas in reality, there are few roundtrips which lie both in peak and off-peak region. Thus, upon comparison with minimal errors, it can be concluded that the Simulink model has been validated.

VI. IMPLEMENTATION OF INFRASTRUCTURE

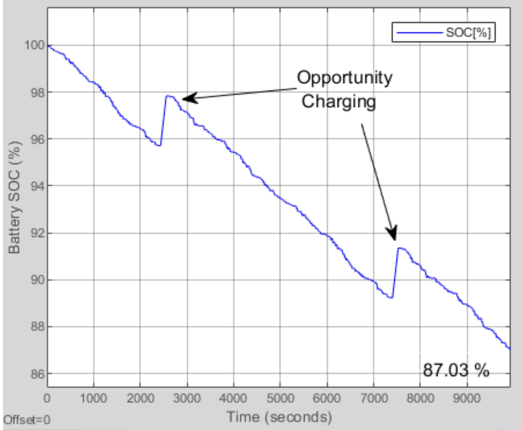
The model hereby presented has been then used to simulate all the running behaviour of each BEB vehicle running during a whole day of observation, according to the timetable of the route considered. The model estimates the Battery SOC and battery used for each running bus. After the first simulated run covering the morning shifts, several BEBs show a considerable amount of battery stored. Setting a SOC=20% as lower limit, a second simulation has been performed, in order to exploit the remaining SOC after the first simulated service and taking as initial SOC for the second simulations the battery SOC at the end of the first runs. After a second service, the remaining SOC results well above 20%. Therefore, the virtual BEB model is used to provide a third service on the route considered.

On further observation, if the BEBs running for two services is employed for a third service, the remaining SOCs lie below the SOC lower limit, as shown in Table VI.

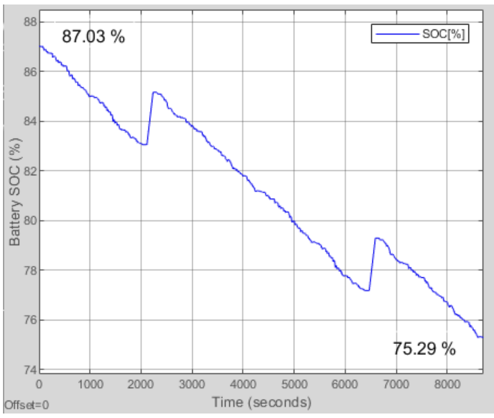
TABLE VI. THREE SERVICE BEB SIMULATION-BATTERY SOC

Bus No.	Start of Service Time [hh:mm:ss]	End of Service Time [hh:mm:ss]	SOC [%]
Service 1	05:57:00	09:30:00	82.80
Service 2	09:39:00	12:23:00	66.83
Service 3	13:22:00	22:12:00	9.67

An implementable solution is constituted by an Opportunity Charging. This is represented by a 200 kW fixed charger for inverted-pantograph already installed on other routes. This solution has been implemented through the BEB vehicle model considering 4 minutes of dwell time at the terminal stop, with 1 minute for charging connection/disconnection and 2 minutes for charging at 200 kW. The simulation has been carried out separately for the three services and results are shown in Figure 5 and reported in Table VII.



(a)



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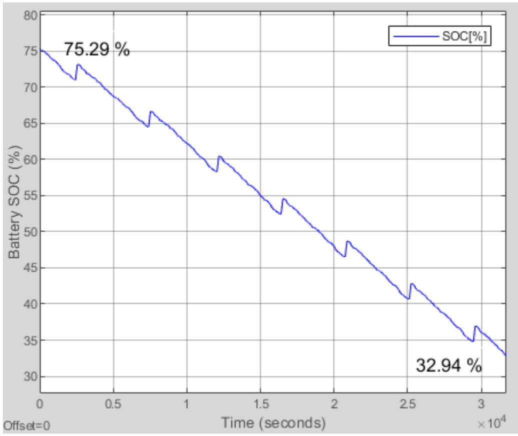

(c)

Fig. 5. BEB Simulations with Opportunity Charging for (a) service 1, (b) service 2 and (3) service 3.

TABLE VII. THREE SERVICE BEB SIMULATION - BATTERY SOC WITH OPPORTUNITY CHARGING

Bus No.	Start of Service Time [hh:mm:ss]	End of Service Time [hh:mm:ss]	SOC with Opportunity Charging [%]
Service 1	05:57:00	09:30:00	87.03
Service 2	09:39:00	12:23:00	75.29
Service 3	13:22:00	22:12:00	32.94

VII. CONCLUSIONS

An energy demand model for BEBs used in LPT has been developed to provide smart charging solutions based on the energy requirement of the vehicles employed on route. The model has been tuned and validated on real data already available for daily working day service or sampled through Phyphox mobile app. The model has proved to be efficient in replicating the real behaviour with minimal errors. At the same time, it helps in improving the existing public transport infrastructure by collecting real-time data and implementing the model on existing route networks. Similar study can be extended also for other non-electrified routes of the network, contributing to develop an efficient electrification to fully electrify the LPT network. Moreover, this work provides an initial step towards electrification process planning for any city having an existing network of LPT and can be used for analysing any route with conventional bus service, using the model to estimate the energy demand of an equivalent BEB and providing help in both choice of vehicles with proper specifications and its appropriate number for starting their services.

REFERENCES

[1] A. O' Donovan, J. Frith, and C. McKerracher, “Electric Buses in Cities: Driving Towards Cleaner Air and Lower CO2,” Bloomberg New Energy Finance, Mar. 2018.

[2] IEA, “Global EV Outlook 2019: Scaling-up the transition to electric mobility,” 2019.

[3] P. Bruge, ZeEUS Launch in Bonn: six e-buses to commence regular service: UITP. Brussels, 2016.

[4] M. Young, The Technical Writer’s Handbook. Mill Valley, CA: University Science, 1989.

[5] M. Rogge, D. U. Sauer, A. Larsen, “Electrification of public transport bus fleets with battery electric buses: development of a software toolchain for the changeover planning of entire bus fleets with consideration of technical and operational constraints”, Aachen: ISEA (2020, 2021). https://doi.org/10.18154/RWTH-2021-02146.

[6] Technical Report R4 Submitted to IESO Conservation Fund, “Optimization toolbox for Public Bus Transit Electrification”, Smart Grid Research Lab, Department of Electrical Engineering & Computer Science, Lassonde School of Engineering, YORK UNIVERSITY, March 2020.

[7] Phyphox-Physical Phone Experiments. Available online: https://phyphox.org/

[8] MATLAB and Simulink Racing Lounge: Vehicle Modeling—File Exchange—MATLAB Central. Available online: https://it.mathworks.com/matlabcentral/fileexchange/63823-matlab-and-simulink-racing-lounge-vehicle-Modeling.

[9] Heydari, S.; Fajri, P.; Rasheduzzaman, M.; Sabzehgar, R. Maximizing Regenerative Braking Energy Recovery of Electric Vehicles Through Dynamic Low-Speed Cutoff Point Detection. IEEE Trans. Transp. Electrif. 2019, 5, 262–270.

[10] Emmanouil D. Kostopoulos, George C. Spyropoulos, John K. Kaldellis, Real-world study for the optimal charging of electric vehicles, Energy Reports, Volume 6, 2020, Pages 418-426, ISSN 2352-4847, https://doi.org/10.1016/j.egyr.2019.12.008.

[11] Q. Chen, S. Kang, H. Chen, Y. Liu and J. Bai, "Acceleration Slip Regulation of Distributed Driving Electric Vehicle Based on Road Identification," in IEEE Access, vol. 8, pp. 144585-144591, 2020, doi: 10.1109/ACCESS.2020.3014904.

[12] Leone, C.; Piazza, G.; Longo, M.; Bracco, S. Electrification of LPT in Algeciras Bay: A New Methodology to Assess the Consumption of an Equivalent E-Bus. Energies 2021, 14, 5117. https://doi.org/10.3390/en14165117.

[13] Varocky, B. J., Nijmeijer, H., & Besselink, I. J. M. (2011). Benchmarking of regenerative braking for a fully electric car. (D&C; Vol. 2011.002). Eindhoven University of Technology.

[14] Khanipour, A. , Ebrahimi, K., Seale, W. (2007). 'Conventional Design and Simulation of an Urban Hybrid Bus '. World Academy of Science, Engineering and Technology, Open Science Index 4, International Journal of Mechanical and Mechatronics Engineering, 1(4), 146 – 152.

[15] T. Paul and H. Yamada, "Operation and charging scheduling of electric buses in a city bus route network," 17th International IEEE Conference on Intelligent Transportation Systems (ITSC), 2014, pp. 2780-2786, doi: 10.1109/ITSC.2014.6958135.