A COMPARATIVE STUDY OF CONCEPTUAL DESIGN AND PROTOTYPE FOR DC-TRAD USING EV POWERTRAIN FOR RTW DC IN KT CITY

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ABSTRACT

This paper is an overview of electric vehicle (EV) conceptual model development in SIMULINK; this involves components of an EV which include driver input, motor and controller, battery and the calculation of parameters with a dashboard viewing interface in which all parameters can be monitored from the dashboard. The paper focuses on comparisons of specifications and costing of an EV and a fuel-powered vehicle on route-to-work driving cycle for Kuala Terengganu city (RTW DC for KT city). A few parameters of EV were chosen to be interpreted: time, distance travelled, average speed, average running speed, average acceleration, average deceleration, acceleration percentage, deceleration percentage, idling percentage, cruising percentage, kWh and fuel costing, battery voltage, current, state-of-charge (SOC) and power. Through this, detailed overview of EV efficiency can be concluded and proven. This paper applies four methods: parameter calculation, EV modelling, data collection on RTW DC for KT city using driving cycle tracking device and validation of EV with RTW DC for KT city. The validation of the model is successful, and the travelling with the EV is proven to be more cost-efficient compared to that with fuel-powered vehicles.
Keywords: driving cycle, electric vehicle, energy, route-to-work for Kuala Terengganu, SIMULINK.

1 INTRODUCTION

Global warming and environmental deterioration are important issues faced globally. The major factor contributing to these issues is the increase in the number of vehicles on the road; hence, emissions of hazardous gasses and substances are being considered matters of concern globally. Several investigations are being conducted to study the emission rate of vehicles; the efficiency of internal burning and combustion of heavy load vehicles are found to be in satisfactory condition; however, the latter are mostly operated at lower road speeds and this reduces overall efficiency [1]. When hazardous substance emissions and engine efficiency become crucial, the invention of and research on electric vehicles (EVs) plays an important role since, using of the latter, the pollutants can be reduced drastically. In research to assess air pollution and health impacts in Malaysia, the air pollution is mainly contributed by land transportation, industrial emissions and open-burning, and of these, 70%–75% of pollution is caused by motor vehicle emissions [2]. Moreover, the most significant cause of climate change is due to excessive carbon emissions and its detrimental effects to human health [3]. The recent developments in this area were the cause for the establishment of the driving cycle. However, Malaysia is in the initial stage of developing a fuel economy driving cycle [4–6]. The discrepancies between existing driving cycles and real-world driving behaviour are caused by a few factors, such as insufficient information, improper modelling design and inaccurate driving cycle development methodologies [7]. Many models have been developed to estimate vehicle emissions and fuel consumption of a vehicle. These models can be divided

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into two categories, namely travel-based models or fuel-based models [8]. As a step forward for validation, driving cycle tracking device (DC-TRAD) is used to collect data on route-to-work driving cycle for Kuala Terengganu city (RTW DC for KT city) and simulated in the EV model for a comparative study.

1.1 Electric vehicle

EV runs partially or fully on electricity as a replacement and an alternative for gasoline and fuel-powered vehicles. An EV is in high demand as it consists of a smaller number of moving parts for which the maintenance cost can be reduced drastically. EVs are also environment friendly as they consume less or, in cases, no fuels and gasoline at all. Modern EVs use lithium-ion battery as it has greater reliability and excellent energy retaining capability with a minimal self-discharging rate of approximately 5% on monthly basis. Battery and electrically powered vehicles are proven to have 99% fewer moving parts, which means that they require less maintenance [9]. EVs are said to be an effective solution to reduce greenhouse effects and environment disasters [10]. Transportation and energy sectors are approximately 98% dependent on fuels and gasoline. According to United States Environmental Protection Agency (EPA), greenhouse gases (GHGs) from human activities are the most significant cause observed for climate changes since the mid-20th century [11]. To overcome this, EVs are taking over this role effectively whereby fuel-powered vehicles can be replaced by EV as this reduces emissions of GHGs by 30%–50%. Moreover, data validation is an important tool to ensure that the outcome of every research is reliable and accurate so that it can be used at all times in a proactive way [12]. As a step forward, the conceptual model of an EV is here validated and verified with the established RTW DC for KT city [13].

2 METHODOLOGY

2.1 Parameter calculation

The first step towards modelling an EV is identifying the vehicle dynamics [14]. Vehicle dynamics plays an important role in energy optimization of an EV so that it meets its main purpose in terms of energy efficiency; this involves aerodynamic forces, gravitational force, acceleration forces, rolling resistance forces, tractive effect, motor power and battery.

Aerodynamics is defined as the flow of air around and inside objects. At slow speeds, the air flowing over the vehicle body may affect the acceleration, top speed, steering control and fuel efficiency. The general aerodynamic drag force is given, in N, by

$$F_{ad} = \frac{1}{2}\rho A_f C_d V(S)^2 \tag{1}$$

where

- ρ = *air density* (kg/m^3)
- A_f = *frontal area* (m^2)
- C_d = *air drag coefficient* (dimensionless)
- $V(S)$ = *vehicle speed* (m/s)

Rolling resistance is defined in the context of energy lost for a unit distance travelled by the vehicle tire and is also known as the friction or drag force acting on the tires of the vehicle whose motion is restricted due to non-elastic effects and properties of tires. The general rolling resistance force is given by

$$F_{rr}=\mu_{rr}\, mg, \tag{2}$$

where
- μ_{rr} = *rolling resistance coefficient* (dimensionless)
- m = *mass of vehicle* (kg)
- g = *gravitional acceleration* (m/s^2)

The gravitational force that may act on the vehicle is given by

$$F_g=mg\, sin\alpha \tag{3}$$

where
- α = grade angle with respect to horizon (°)

Besides driving resistance which occurs in steady-state motion, resistance also occurs during acceleration and braking. The factors which affect the acceleration resistance are the total mass of the vehicle and the inertial mass of rotating parts [15]. The acceleration resistance is given by

$$F_a = \left(m + \frac{\sum I_{rot}}{r^2_{dyn}}\right)\frac{dV(S)}{dt}, \tag{4}$$

where
- I_{rot} = *Rotational components inertia* (kg/m^2)
- r_{dyn} = *dynamic radius of tires* (m)

The total tractive force is simply the summation of all forces acting on the vehicle body and is thus given by

$$F_{te} = F_{ad} + F_{rr} + F_g + F_a \tag{5}$$

The EV motor converts electrical power into mechanical power. The motor in an EV undergoes two phases: one during driving and one during braking. When the EV accelerates, the electric power which flows into the motor is greater than the output of the motor mechanical power, whereas during deceleration, the electric power into the motor is less than the output of the motor mechanical power. Hence, motor power output and power into motor during acceleration and deceleration are specified through the following equations:

Motor power output during acceleration,

$$P_{motorout} = \frac{P_{te}}{n_g}. \tag{6}$$

Motor power output during deceleration,

$$P_{motorout} = P_{te}\, n_g. \tag{7}$$

Power into motor during acceleration,

$$P_{motorin} = \frac{P_{motorout}}{n_m}. \tag{8}$$

Power into motor during deceleration,

$$P_{motorin} = P_{motorout}\, n_m. \tag{9}$$

where

- n_m = *motor and controller efficiency* (%)

2.2 EV modelling in SIMULINK

Automobile industries drifted towards the introduction of EV. The use of EV provides an alternative platform for those industries to transport without deteriorating the environment [16]. An EV can be modelled in various ways whereby different models are interconnected for a proper working representation of the complete system. At the initial stage of development, a few parameters have to be initialized in order to set up the vehicle and driving interface, namely tires and vehicle body parameters, type of motor being used and type of battery being integrated into the system. There are a few types of motors which can be integrated into EV modelling and can be compared on the basis of usability and dependability of the units. Most EV in the market is integrated with single induction or permanent magnet motor using an automotive differential. An automotive differential is designed to drive a pair of wheels with different speeds. An induction motor is also known as asynchronous motor which is well-known for its simplicity. The rotor of the motor consists of laminated steel with short-circuited bars which are made of aluminium in the shape of squirrel cage. The magnetic field of the stator in the motor rotates at higher speed than the rotor of the motor. Frequency is induced by the slip between the rotors and stator which produces torque to drive the motor. Permanent magnet motors are efficient and require less cooling system as the count of excitation current in it is very minimal.

Regarding batteries, most EVs use lithium-ion batteries in energy storage systems. EVs do not use a single battery as mobile phones and laptops do but a stack which consists of thousands of lithium-ion cells working in series and parallel. This works in parallel since, when the vehicle is under charge, electricity is used to convert electrical energy to chemical energy, and when the vehicle is on the road, chemical energy will be converted into electrical energy and accordingly provide sufficient power for the motor of the vehicle to produce torque and rotational speed.

2.3 Data collection on RTW DC for KT city using DC-TRAD

DC-TRAD is a device invented to collect parameters required to construct a driving cycle. DC-TRAD is known for its accuracy which is up to approximately one meter radius [17]. This device is also integrated with internet of things platform which is phpMyAdmin and MySQL database in which collected data points are updated and managed in the database system instantly. The device was used to collect data on five selected RTW DC for KT city which is approved by the Ministry of Works Malaysia as the most frequently used routes by Kuala Terengganu citizens to work [18]. These routes begin from Kampung Wakaf Tembesu and end at Wisma Persekutuan Kuala Terengganu. Figures 1–5 show the selected routes.

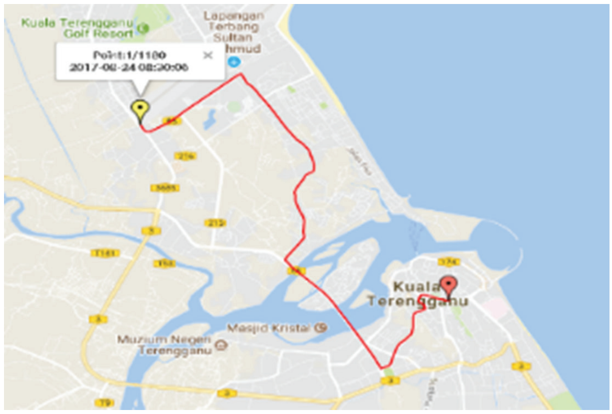

Figure 1: Route A.

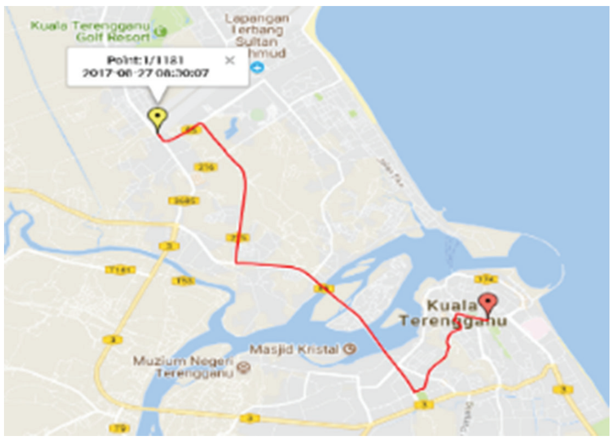

Figure 2: Route B.

Figure 3: Route C.

Figure 4: Route D.

Figure 5: Route E.

2.4 Model validation with RTW DC for KT city

Data validation is important in research as it will ensure accuracy of the collected data as well as that the latter is within acceptable range. In this research, the developed EV model was verified and validated with the established RTW DC for KT city. The collected data points were uploaded into signal builder of the model, and they act as the required data, whereas the simulated driving cycle will be the acquired driving cycle.

Besides, a few simulation parameters were also chosen to be analysed; battery state-of-charge (SOC), battery parameters (voltage, current, power), kWh charges and fuel charges incurred in Ringgit Malaysia (RM) (1 RM ~ 0.24 USD) for the driving cycle route selected. As a validation procedure, percentage errors were calculated for each parameter and discussed as well.

3 RESULTS AND DISCUSSION

3.1 EV modelling in SIMULINK

Blocks from electrical simscape and vehicle dynamics blockset were used to construct a conceptual model of an EV. All required blocksets were integrated into respective subsystems to simplify the complexity of the conceptual model which comprises driver input, motor and controller, battery and vehicle body and tires. A graphical interface which acts as the dashboard of the EV with speedometer and parameter displays was arranged in a subsystem for easy viewing experience upon model simulation. Figure 6 shows the overall conceptual design of an EV.

In the driver input subsystem, a selector switch was integrated to choose between RTW DC for KT city. A drive cycle source block from Powertrain blockset is also integrated in the switch as most of the established driving cycles can be obtained from the block for verification purposes. A longitudinal driver blockset is used as the parametric speed tracking controller which generates normalized acceleration and deceleration forces according to driving cycle raw data and velocity feedbacks. Figure 7 shows the driver input subsystem.

In motor and controller subsystem, a brushed direct current (DC) motor with permanent magnet pole was used as the electric engine of the vehicle. Permanent magnet was used in an EV rotor where the current applied to the stator rotates the rotor of the motor. Brushed and brushless permanent magnet motors are commonly used in EV applications since they are known for their efficiency in terms of operation and cost. The motor is driven with a pulse width modulation (PWM) controller [19]. Square sinusoidal PWM is used in this research to create a pulse modulation of zero and one which works with the command of reference velocity; one for acceleration and zero for deceleration [20]. Figure 8 shows the motor and controller subsystem. A solver configuration block was also included in the model

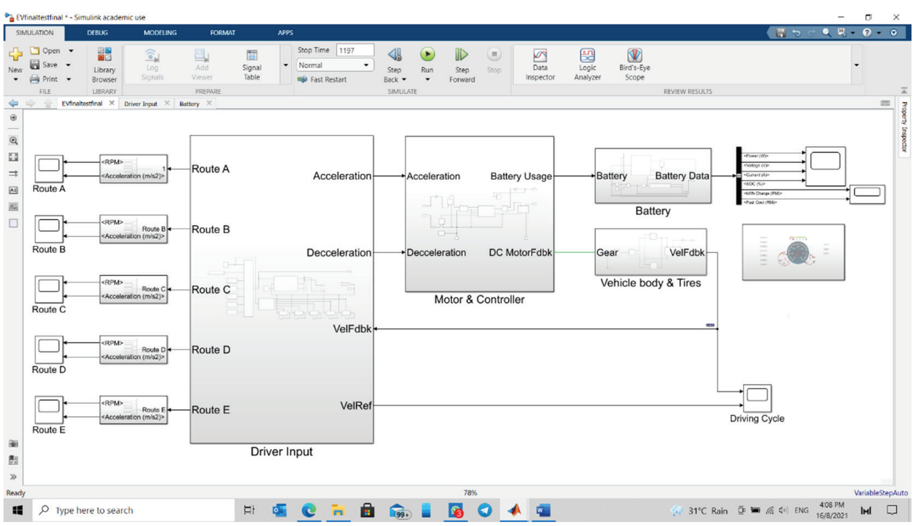

Figure 6: Conceptual model of EV in SIMULINK.

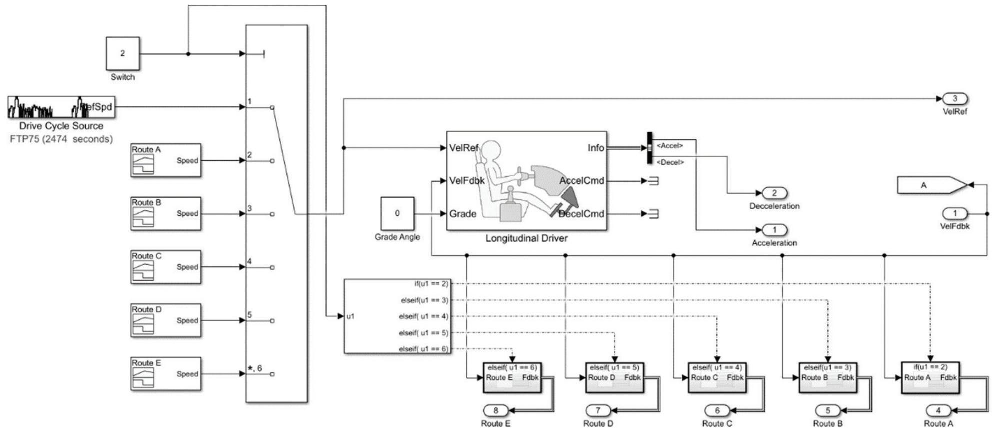

Figure 7: Driver input subsystem.

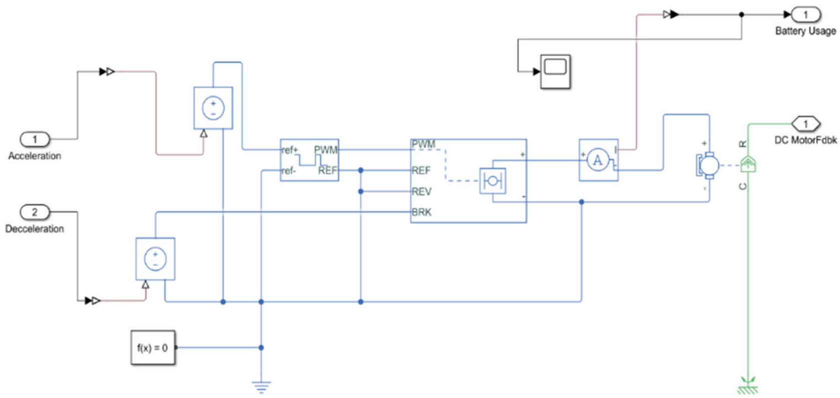

Figure 8: Motor and controller subsystem.

with ode23t solver. The solver configuration block ensures and specifies the solver parameters to be configured and that is needed to execute the model properly with minimal zero hitting and crossing and also to ensure there are not any errors encountered during the simulation.

In the PWM controller circuit, an internal power source was selected to be used with 300 VDC of power, 12×10^{-9} Ω total bridge resistance and a 0.05 Ω freewheeling diode resistance. To calculate the power consumption, battery SOC and kWh charges, a generic battery model was implemented which configures most popular battery types such as lithium-ion cells with automatic nominal parameter settings. The generic battery model was also configured in a similar way as a DC motor with 300 VDC voltage and with 100 Ah rated battery capacity. The initial battery SOC was configured at 100% with 30 seconds of battery response time. Figure 9 shows the battery model.

The total kW consumed was calculated by means of integration of power, and a typical car of Malaysia (Proton Saga) travels 9 km/L in heavy traffic [21]. The price per kW of electricity in Malaysia is at the cost of RM0.408 [22]. Thus, the total price incurred for kWh for the trip

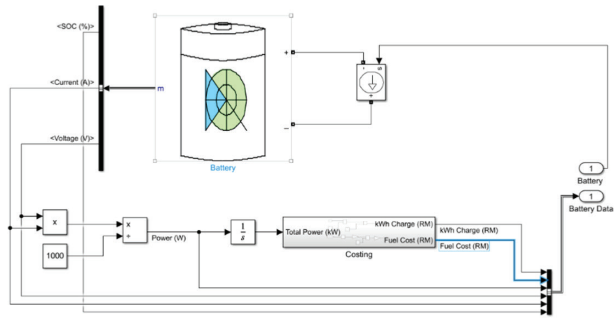

Figure 9: Battery subsystem.

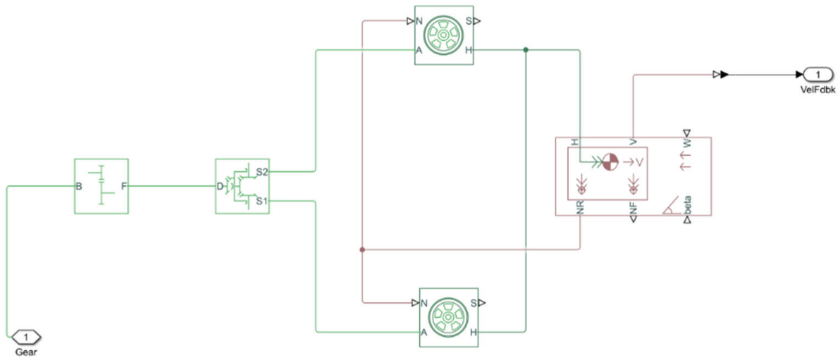

Figure 10: Vehicle and tire subsystem.

for each route was calculated as per eqn (10). The current petrol price of RON95 is placed at RM2.05/L [23]. With this, the fuel consumption price was calculated as per eqn (11).

$$kWh\ Price = kWh * 0.408 \tag{10}$$

$$Fuel\ Price = \frac{Total\ Distance\ (km)}{9} * 2.05 \tag{11}$$

A vehicle body block from simscape blockset was used, which consists of a two-axle vehicle body with longitudinal motion. Parameters such as body mass, aerodynamic drag, road grade angle and weight distribution between axles were configured in the block. Since a rear drive vehicle was implemented, two units of wheels were configured to the NR port of the vehicle body. A differential block was used with the aid of a simple gear to drive the axle of the tires. The differential block is commonly used as an additional bevel gear transmission between driveshaft and the carrier. Figure 10 shows the vehicle and tire subsystem. In addition, regenerative braking plays an important role in EV as the drive is fully dependent on electricity. Therefore, small charges and currents generated and released by the transmission of the rotor and stator of the motor is stored in the battery to be used and consumed by small power accessories such as lamps and audio systems of the vehicle.

3.2 Model validation with RTW DC for KT city

Results of required and acquired data points are as per Tables 1, 2, 3, 4 and 5.

Table 1: Route A parameters.

Item	*Required*	*Acquired*	*Variance*	*Error (%)*
Time (s)	670.000	670.000	0.000	0.000
Distance travelled (km)	13.500	13.330	0.170	1.259
Average speed (m/s)	18.074	17.230	0.844	4.672
Average running speed (m/s)	18.981	19.234	0.253	1.333
Average acceleration (m/s^2)	0.979	0.952	0.027	2.729
Average deceleration (m/s^2)	1.123	1.098	0.025	2.195
Acceleration percentage (%)	46.270	45.980	0.290	0.627
Deceleration percentage (%)	40.300	41.090	0.790	1.960
Idling percentage (%)	4.630	4.780	0.150	3.240
Cruising percentage (%)	8.810	8.990	0.180	2.043

Table 2: Route B parameters.

Item	*Required*	*Acquired*	*Variance*	*Error (%)*
Time (s)	826.000	826.000	0.000	0.000
Distance travelled (km)	15.120	15.300	0.180	1.190
Average speed (m/s)	12.000	11.700	0.300	2.498
Average running speed (m/s)	12.918	12.800	0.118	0.912
Average acceleration (m/s^2)	0.976	1.003	0.027	2.760
Average deceleration (m/s^2)	1.051	1.198	0.147	13.987
Acceleration percentage (%)	42.250	41.900	0.350	0.828
Deceleration percentage (%)	39.350	38.600	0.750	1.906
Idling percentage (%)	6.300	6.110	0.190	3.016
Cruising percentage (%)	12.110	12.100	0.010	0.083

As per simulation of route A, B, C, D and E, 95% of the acquired data are within a range of below a 5% error compared with the required data. Five percent of acquired data, highlighted in red, is out of range; as the simulation result was measured in mm/s, this is relatively small and can be neglected. Looking in detail at each driving cycle, the data recorded which is out of range is at the point of deceleration when the required data records near zero m/s and the acquired data records slightly higher which is recorded in mm/s. This is due to the inertia force on the vehicle since inertia is defined as the tendency to remain still unless an external force is applied. Inertia thus resists changes to the speed and velocity of the vehicle [22]. In

Table 3: Route C parameters.

Item	*Required*	*Acquired*	*Variance*	*Error (%)*
Time (s)	788.000	788.000	0.000	0.000
Distance travelled (km)	8.330	8.120	0.210	2.521
Average speed (m/s)	11.958	11.772	0.186	1.553
Average running speed (m/s)	13.160	13.240	0.080	0.607
Average acceleration (m/s^2)	0.830	0.798	0.032	3.866
Average deceleration (m/s^2)	0.999	0.928	0.071	7.107
Acceleration percentage (%)	43.910	43.122	0.788	1.795
Deceleration percentage (%)	36.420	37.540	1.120	3.075
Idling percentage (%)	10.410	10.432	0.022	0.211
Cruising percentage (%)	9.260	9.276	0.016	0.173

Table 4: Route D parameters.

Item	*Required*	*Acquired*	*Variance*	*Error (%)*
Time (s)	737.000	737.000	0.000	0.000
Distance travelled (km)	15.010	15.200	0.190	1.266
Average speed (m/s)	17.546	17.230	0.316	1.800
Average running speed (m/s)	17.960	17.880	0.080	0.446
Average acceleration (m/s^2)	0.509	0.510	0.001	0.105
Average deceleration (m/s^2)	0.616	0.590	0.026	4.294
Acceleration percentage (%)	27.270	26.220	1.050	3.850
Deceleration percentage (%)	23.020	23.140	0.120	0.521
Idling percentage (%)	13.030	13.143	0.113	0.867
Cruising percentage (%)	36.500	36.430	0.070	0.192

this proposed EV model, a rotor moment of inertia of 0.1 g/cm^2 was configured. The rotor inertia is inversely proportional to deceleration whereby, as the inertia increases, the deceleration decreases and the period for accelerative force to take over the vehicle control is shortened. Considering the driving cycles of all routes and calculated parameters, the model of EV is thus verified and validated as the simulated driver can follow the reference velocity closely with minimal zero crossing and hit crossing effects without compromising the acceptable percentage error which is below 5%.

Furthermore, as a generic battery model was integrated into this model, battery voltage, current, power and SOC data were also obtained. Battery size, discharge rate and SOC play an important role in a typical vehicle. In the proposed model, a battery size of 300 VDC with a 100 Ah discharge rate was chosen as most of the EV in market come with this rated battery size. Table 6 shows the battery specification analysis tabulation for routes A, B, C, D and E.

Table 5: Route E parameters.

Item	*Required*	*Acquired*	*Variance*	*Error (%)*
Time (s)	898.000	898.000	0.000	0.000
Distance travelled (km)	13.800	13.750	0.050	0.362
Average speed (m/s)	13.166	13.430	0.264	2.007
Average running speed (m/s)	13.527	13.230	0.297	2.198
Average acceleration (m/s^2)	0.685	0.710	0.025	3.578
Average deceleration (m/s^2)	0.797	0.712	0.085	10.665
Acceleration percentage (%)	43.430	43.410	0.020	0.046
Deceleration percentage (%)	37.420	37.912	0.492	1.315
Idling percentage (%)	3.230	3.130	0.100	3.096
Cruising percentage (%)	15.920	16.100	0.180	1.131

Table 6: Battery specification analysis.

Item	**Unit**	**Route A**	**Route B**	**Route C**	**Route D**	**Route E**
Peak power	kW	240.20	308.10	297.45	213.50	302.33
Peak current	A	780.40	910.15	960.34	708.80	970.23
Peak voltage	V	367.80	370.60	361.60	364.70	364.50
Battery SOC	%	95.00	93.67	95.22	94.02	95.00
kWh charge	RM	1.72	2.26	1.73	2.31	1.98
Fuel charge	RM	3.70	4.31	3.33	4.48	4.05

The maximum charging capacity of a battery was set at 350 V with internal resistance of 0.03 Ω to maintain the performance of the battery at nominal operation. This is defined as float voltage whereby the battery will be charged above the nominal voltage to ensure backup power when it is unused and to make up for the self-discharge of the battery. Float voltage is also understood to be mostly affected by the surrounding temperature. Therefore, a float voltage of 60 V was set into a generic battery model with an overall 10% slip. There were few major spikes in motor power which last for a second for each route; this is known as an overloading of the motor. In terms of battery SOC, routes B and D used up the maximum amount of battery charge as the distance travelled in these routes was the longest, which is 15.12 km and 15.01 km, respectively, whereas route C used up the least amount of battery in which upon simulation completion, there was 95.22% of battery SOC left with the least distance travelled which is 8.33 km. On the other hand, scope for regenerative braking can be seen in the battery SOC since there are several recharging states of battery due to braking effects. The kinetic energy which is produced during braking is stored back into the battery of the vehicle so that it can be reused for acceleration and deceleration commands and for other vehicle accessories. Battery charge which is stored in the battery due to braking is relatively small, that is, within the range of 0.2–0.7 V. Besides, the costing for each route was also calculated and analysed accordingly. Overall, the cost of travelling in all routes is relatively cheaper using an EV compared to that of fuel-powered vehicles which is approximately two times higher than that of an EV.

4 CONCLUSION

To conclude, since SIMULINK has been a great platform for simulation uses in automotive industry, it was adopted in this research to design a conceptual model of an EV by which data were collected by using DC-TRAD on RTW DC for KT city, and subsequently, the efficiency of a fuel-powered vehicle and an EV on the selected routes was analysed. The proposed conceptual model has been validated and verified since the error in all calculated parameters is within acceptable range, that is, below 5% except for battery current and power due to the absence of relative resistance to limit the amount of current flowing into the electric motor and overload protection relay for the electric motor as a safety measure. By comparing the cost of travelling for all the routes, an EV is shown to be more efficient since the respective cost of travelling is two times lower compared to the cost of fuel.

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