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Comparative Results of a Developed Vehicle Dynamic Model for a Sedan Electric Vehicle

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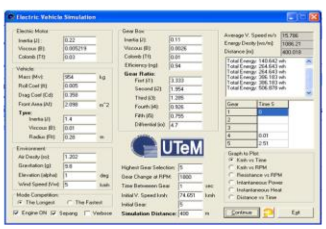
Graphical abstract



Abstract

The interest in electric vehicles (EVs) is significantly increased due to the awareness of internal combustion engine (ICE) effects towards the environmental and sustainability issue. In developing EVs projects, computer modelling of the vehicle dynamic and simulation can be utilized to estimate the battery power requirement and predict the optimum cruising strategies which in return will shorten the design development process and reduce the cost of prototyping. This paper presents the effectiveness of the vehicle dynamic simulation model of a converted internal combustion engine vehicle PROTON SAGA sedan into a fully EV called EVerGREEN. The simulation model is set to analyse the effect of the vehicle dynamic parameters such as vehicle resistance and the motor characteristics in predicting the optimum driving profile. The development of the electric vehicle EVerGREEN is shortly presented together with the vehicle dynamic model. The driving performance is measured based on a real road test at F1 Sepang International Circuit and the results are validated by comparing between the simulation model and the actual drive test. Simulation and experimental results are shown to verify the effectiveness of the proposed model which shows a good agreement between them. Further works in enhancing the model effectiveness could be implemented by incorporating the battery characteristics and hence would provide better energy management for the vehicle.

Keywords: Electric vehicle, vehicle dynamic, optimum cruising, road test.

■1.0 INTRODUCTION

Nowadays, the interests on electric vehicle (EV) development are significantly increased due to the rapid rise of the gasoline price and combined with the concern of society on the environmental issue [1]. These factors boost the research and development of EV. Typically, there are three types of EV development known as commercial EV, commercial Hybrid EV and re-engineered or conversion EV.

This article briefly introduces the step of converting a conventional ICE sedan passenger car into fully electric vehicle that solely uses the batteries as a power source. Basically, the original concept of the EV is similar to the conventional ICE vehicles, but the conventional combustion engine is replaced by an electric motor.In addition to batteries, some basic equipment is required to accomplish the task, such as an electric motor, the controller, throttle, relays, and switches.

This conversion EV as shown in Figure 1 is designed and constructed to participate in the Proton Green Mobility Challenge (PGMC) 2012 that held at F1 Sepang International Circuit. The EV is successfully tested on four challenges namely farthest distance, quarter mile acceleration, fastest two laps and the maximum speed.In this project, the EV development consists of several tasks namely motor-transmission coupling, electric motor control, battery management, monitoring system and thermal management.

This paper discusses the modelling and implementation of a sedan EV using C++ programming language and compares its resultsfor a considered road test circuit. The developed model is designed to provide a high degree of reliability in term of energy optimization and efficiency. This allows a user to study various factors on vehicle dynamic, electric motor characteristics and road profile in predicting energymanagement strategies and allowing the user to quicklychange the parametersgraphically [8]. This paper isstructured as follows: In Section 2, the process of electric vehicle development is presented. InSection 3, the vehicle dynamic model based on mathematical equations is described in more detail. Section 4 presents the effectiveness of the simulation model in comparison to the experimental results in Section 5. Section 6 concludes the paper and highlights the possible improvement of the model.

Figure 1 Developed sedan electric vehicle

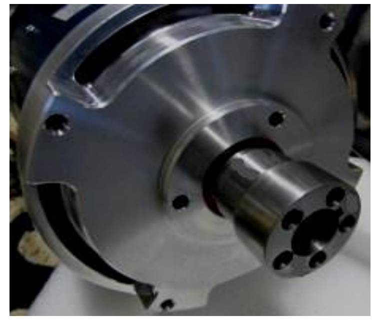


Figure 2 Shaft coupler

■2.0 ELECTRIC VEHICLE DEVELOPMENT

The motor-transmission coupling requires a precision mechanical work commencing from the design process to the assembling jobs. The coupling plate consists of two parts: adapter plate and shaft coupler. The material chosen isaluminum due to its lightweight nature and ability to withstand high starting torque produced by electric motor. The shaft coupler is used to mount the clutch and flywheel to the shaft of the induction motor [9]. The adapter plate is served to house the motor to the transmission bell housing. The balancing and the alignment are the important factors to eliminate any vibration due to the unbalanced force during rotation. Figures2 and 3 show the shaft coupler and adapter plate used for the coupling works. Additional support is also introduced to absorb vibration during movement due to uneven terrain. The original clutch and transmission unit are still in place to provide flexibility for the user to have a similar gear ratio during a conventional driving mode.

The completed coupling unit with electric motor controller is then examined in the laboratory to verify its functionality. High current power supply is used instead of battery pack to ensure the current limit is under control. It is also important to avoid unnecessary damage due to the wiring mistake and short circuit on the first implementation. The motor controller parameter is set to default setting and the other available motion control technique in [2] can be implemented after the challenge is completed. In addition, an electric vacuum pump is needed in providing an adequate pressure to the braking system as required for the safety reason. Several test drive is necessary to collect data on the power flow, thermal dissipation, battery consumption and mechanical aspect of the car. The captured data combined with the data from the manufacture is used for improvement and to plan the driving strategy. This kind of data may also be used to predict the performance of the developed EV [3,4,11].

The monitoring system is developed to continuously monitor and capture the important data to be analysed later. It is also used to assist the driver on the safety aspect and has the ability to cut off the main power supply in the case of emergency. The monitoring system with Graphical User Interface (GUI) is utilized to display all the necessary information in real time to the driver as shown in Figure 4 [4]. Any error occurs will be highlighted to the driver with the pre-programmed suggested solution. Some ofthe critical parameters that closely monitored are DC current from battery, battery voltage level, and temperature of electrical motor, individual battery and the controller. This details monitoring system are not necessary for the common user, but more for research and development of the electric vehicle. However, the user friendly GUI exhibits the future trend of the digital technology.

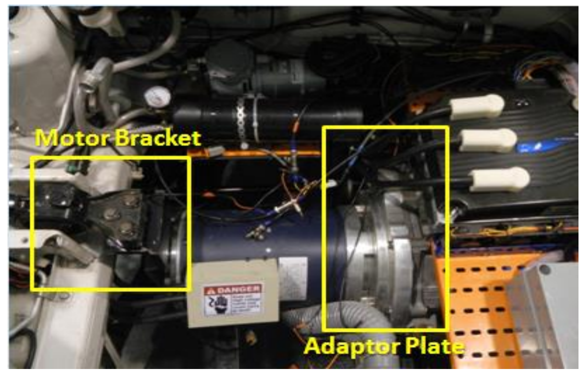


Figure 3 Adapter plate and additional support

Next, the battery unit will provide the main source of energy required to drive the vehicles. Moreover, the battery efficiency and utilization factor will affect the distance range of the EV [1,5]. Therefore, the battery is one of the most demanding technologies in EV industries. The recent research trend is now towards in minimizing the physical size while increasing the storage capacity. The Lithium Polymer Ion battery is one example of the advanced battery technology. It has different discharge characteristic compared to lead acid battery

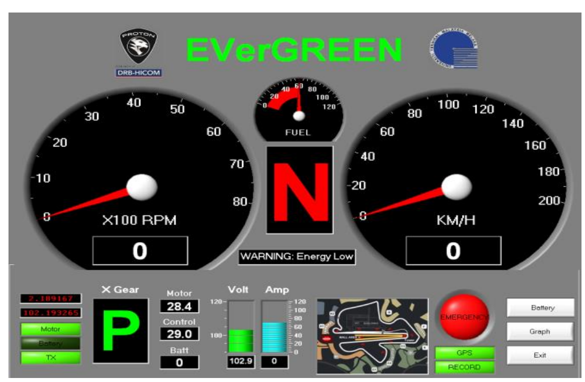


Figure 4 GUI monitoring system

■3.0 MODEL SIMULATOR

Simulation using computer modelling can be utilised to shorten the design development processof EV by testing configurations, parameters and energy management strategies before the commencement of the prototyping process. The power requirement model is a series of mathematical equation consisting the combination of several forces, referring to the law of physic. These forces represent the characteristic of the developed EV and the characteristic of the environment along the journey [4,6-7].

The vehicle model can be considered as a combination of dynamic of motor, gear, tyre and resistances of the vehicle. Resistances are divided into tire rolling resistance, wind drag resistance, and grading resistance. From (10), the equations of the system can be written as follows:

Motor:

$$J_m = J_m \frac{d\omega_m}{dt} + B_m \omega_m + T_{CF} + T_L \quad (1)$$

Gear:

$$\omega_{go} = a_g \omega_{gi} = a_g \omega_m \quad (2)$$

$$T_{gi} = T_L = J_g \frac{d\omega_m}{dt} + B_g \omega_m + \frac{a_g T_{go}}{\eta} \quad (3)$$

Tyre:

$$V_V = V_T = R_T \omega_T = R_T \omega_{go} = R_T a_g \omega_m \quad (4)$$

$$T_T = J_T \frac{d\omega_T}{dt} + R_T F_T = J_T a_g \frac{d\omega_T}{dt} + R_T F_T \quad (5)$$

$$F_T = m_V \frac{dV_T}{dt} + m_V g f_T \cos(\alpha) + m_V g \sin(\alpha) + \frac{1}{2} \rho_a A_f C_d (V_V + V_W)^2 \quad (6)$$

Equation (1)-(6) might be composed to give a dynamic vehicle as follows:

$$T_{em} = J \frac{d\omega_m}{dt} + B\omega_m + T \quad (7)$$

Solution of equation (7) for T_{em} , J, B, and T constant is:

$$\omega_m = \frac{T_{em} - T}{B} + \left(\omega_{mo} + \frac{T_{em} - T}{B}\right) e^{-\frac{B}{J}t} \quad (8)$$

Or

$$\omega_m = \omega_{mo} e^{-\frac{B}{J}t} + \frac{T_{em} - T}{B}\left(1 + e^{-\frac{B}{J}t}\right) \quad (9)$$

Where
T_{em}= Airgap torque of the motor
J_m= Inertia constant of the motor
B_m = Viscous friction of the motor
T_{FC}= Coulomb friction of the motor
T_L= Load torque at motor shaft
ω_m =Motor Speed
F_T = Force at tyre

To calculate the total power (P_T), the electrical motor efficiency (η_m) and battery utilization factor (U_f) are included in the equation below.

$$P_T = F_T V \eta_m U_f \quad (10)$$

It can be seen that motor speed depends on the initial motor speed and exponential of time. During an acceleration, engine's torque increase firstly followed by an increment of vehicle speed. Prior to steady state at the new operating point (new vehicle speed), there is additional energy required to increase the speed of the vehicle. This energy is actually stored in the mass body of the vehicle. However, in most cases the efficiency of the motor drops to its lower value during acceleration.

However, there are several constraints that should be considered and included in the development of the simulation package for EV. The first one is the power source. Power source consumption plays a critical role in driving performance. Higher power consumption will provide enough energy for the car to accelerate according to desired speed value but the batteries used has some limitation that need to be carefully monitored. Thus the usage of power source must be optimized in the development of electric vehicle system.

In motor control technology section, the current is fed into the electric motor depending on the torque needed during the drive way. In normal and clean roadway, minimum torque is adequate to move the vehicle but not in uphill situation which required more torque. Higher torque signifies high usage in power consumption and vice versa. Thus, battery management plays a critical role in the development of electric vehicle in ensuring enough energy to reach the desired destination. However, the good development of motor control shall manage to evade the drawback current when the torque pedal is released and reduce the batteries usage during the downhill drive way. Thus, the concern will be on normal roads, uphill and turning junction roadway types only.

The battery management alone does not guarantee a good driving performance. A good braking system should be considered in case of avoiding vehicle from any collision on the road. Another approach to enhance the driving performance is minimizing the loss in term of mass and friction that comes from the mechanical structure of the vehicle. Reducing the mass of electric vehicle will allow the car to move at higher speeds. Thus, the mass of the vehicle after modification may be the same as before or higher due to the weight of the batteries.

In PGMC 2012, one of the challenges is the EV should to be able to move as far as possible with the given power source. Critical design aspect is on the optimization of the power distribution along the way to reach the maximum distances for a given two (2) hours of time. However, there is a constraint on the power source which is only up to 144 V and the different road condition type that will affect the usage of the energy. Since the developed car is a manual transmission type, it is impossible to change the gears ratio automatically, which as a result will give limitation in designing the speed control algorithm. Thus, in order to optimize the usage of power source, the controller design will focus on giving the required speed to the driver based on road condition or current vehicle position, battery consumption and current temperature inside the car but instead of automatic control, the driver will manually change the transmission gear based on the recommendation given by microcontroller shown on display boards. The system is illustrated in Figure 5.

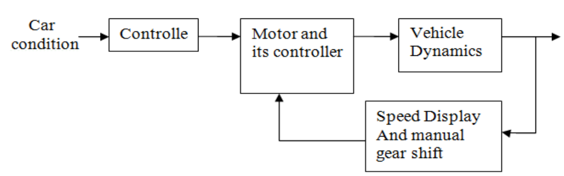


Figure 5 Speed controller based on current car condition

The following two strategies are embedded in the simulation package as to achieve the farthest distance.

i. Maintain energy consumption well above energy required to overcome vehicle resistance plus a small amount for vehicle acceleration. By doing this, it is expected that the efficiency of the motor will not drop far from its normal operating point.

ii. The torque due to the vehicle resistance is still low when the motor is at a lower speed. During vehicle acceleration at some operating region, and if it is controlled properly, it could achieve the most efficient operating point even though there is an additional torque is required for acceleration. During this period, time optimization can be performed.

Figure 6 shows a desktop of the developed computer program for motor optimization.

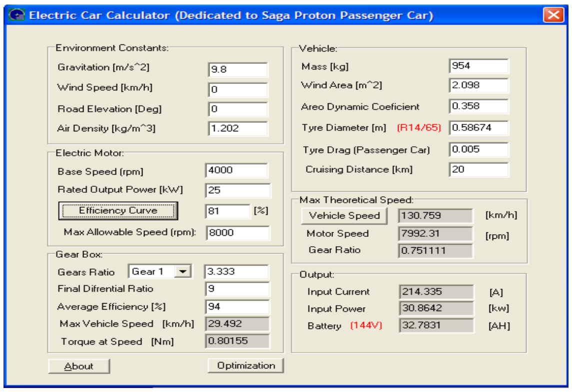


Figure 6 Desktop of the developed computer program

■4.0 EXPERIMENT

The data for all the parameters and the journey profile are gathered before the actual road test is performed. The accuracy of data will significantly affect the predicted result. The EV characteristic is collected during the construction works and the environment related parameters are measured during the on-site visit to the track and also from the online map application. The EV characteristics are shown in Table 1. The EV parameters in the simulation model for an optimization strategy are developed in order to predict and recommend the possible lowest energy consumption at maximum efficiency as shown in Figure 7 and 8. The system would advise the user the best optimum cruising parameters such as gear selection and recommended speed, which will be displayed on the GUI monitoring panel.

In order to improve the prediction model, the elevation or road angle for the circuit is prepared as details as possible. The road angle bigger than zero will significantly increase the climbing force requirement compared to the force required when the vehicle running on the flat surface. Thus the road angle for every meter is important. The elevation profile for the circuit is measured from the lowest point as shown in Figure 9 below. Based on the track's profile such as gradient, corner location and distance, the proposed velocity profile as in Figure 10 is suggested to the driver for actual road test. The sampling period for the power prediction calculation is set to 1 second.

Table 1 EV Parameters

Parameter	Notation	Value	Units
Mass	m	960	kg
Aerodynamic drag coefficient	C_d	0.4	
Air density	ρ	1.2	kg/m^2
Front area	A	2.3	m^2
Rolling resistance coefficient	δ	0.01	
Gravity	g	9.8	m/s^2
Velocity	V	Refer velocity profile	m/s
Elevation	θ	Refer elevation profile	m
Motor efficiency	E_m	85	%
Battery utilization factor	U_f	80	%

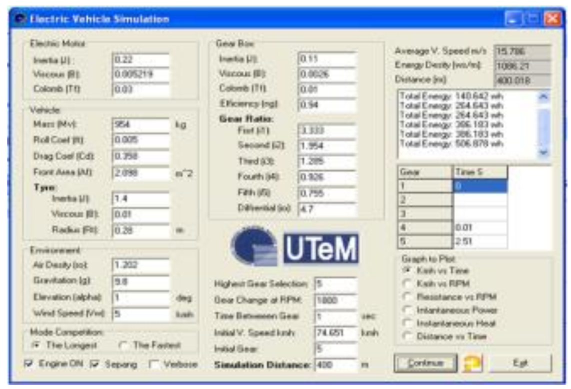


Figure 7 Developed vehicle dynamic simulation model

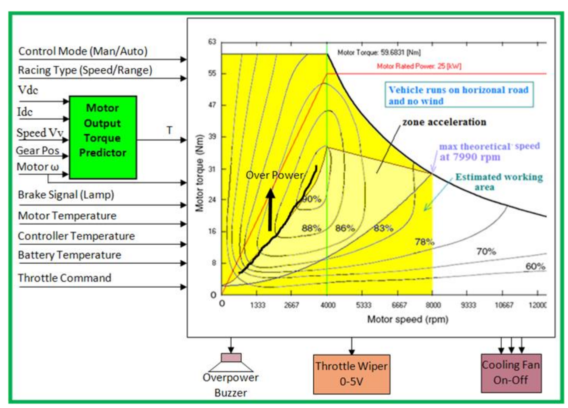


Figure 8 Optimization strategy model

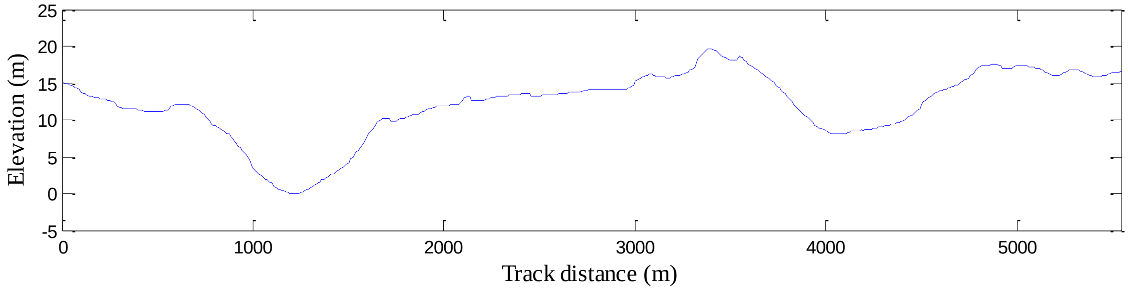


Figure 9 Elevation profile for the track

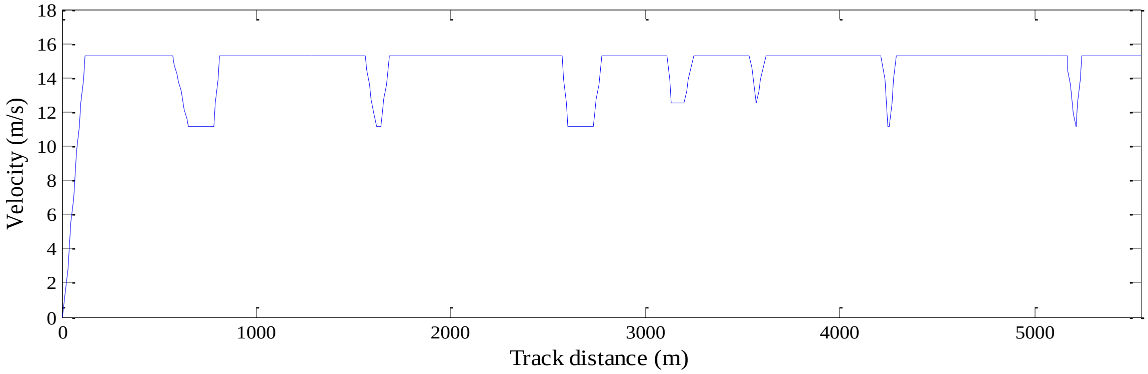


Figure 10 Suggested velocity profile

■5.0 RESULTS AND DISCUSSION

In order to validate the prediction model, the real road test during the PGMC challenge was conducted and the velocity profile for 1 lap was recorded as shown in Figure 11 below. During the road test the EV was running until the controller cut off the battery supply as the voltage level had reached its limit for protection. The farthest distance results for both simulation and actual tests are provided in the Table 2. Figure 12 shows the comparison between the predicted and actual speed during the quarter mile acceleration challenge, which showed a good agreement.

Table 2 Farthest Distance Result

	Total lap	Speed bandwidth (m/s)	Total power (kWh)
Predicted	10.2	11.11 – 15.28	5.37
Actual	10.9	6.39 - 15.28	5.91

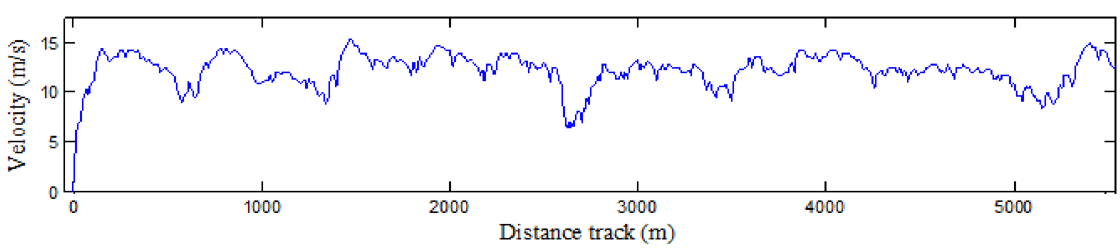


Figure 11 Velocity profile for actual road test for developed EV

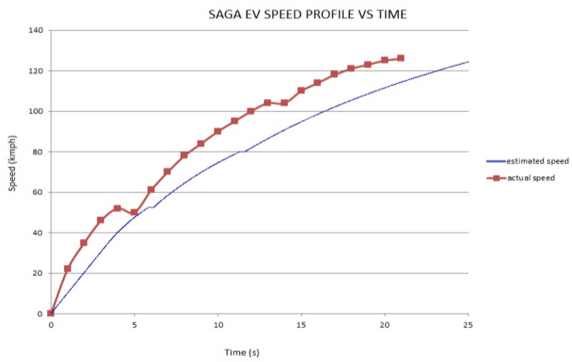


Figure 12 Velocity profile for quarter mile acceleration challenge

■6.0 CONCLUSION

This work presents the simulation model and comparison of experimental results of a sedan EV based on the converted ICE vehicle into a fully EV. Finally, the simulation results are compared with the real road tests results for analysis purposes. The developed EV prediction model for power consumption shows the accuracy is a bit larger than ten percent. One of the factors that may cause the error is the pedal state in not monitored during the road test. On the contrary, the ICE engine is continuously running even during the pedal is not pressed, whereas the electric motor is fully stopped and disconnected from the supply voltage thus reduces the power consumption. The simulation of a dynamic real EV system with the consideration of the road profile and the vehicle dynamic parameters are not a simple task especially as the expectation of the system and the car driver are different. However, the results are quite satisfactory and able to have a close agreement with reality based on this model. This type of simulation is useful and important in estimating the correct strategies in maximizing the intended performance of the vehicle. For further improvement, the battery characteristic should be incorporated into the model simulated in enhancing the model effectiveness and hence would provide better energy management for the vehicle.

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