DESIGN AND OPTIMIZATION OF POWERTRAIN SYSTEM FOR AUTOMATED CONTROLLING SYSTEM ON PROTOTYPE FUEL CELL ELECTRIC VEHICLE

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ABSTRACT

This paper reports analysis on an automatic intelligent controller use to drive a prototype fuel cell electric vehicle while maintaining maximum efficiency and completing a course with in a specific period of time. The objective is to reduce driving error while minimizing energy usage for the Shell Eco-marathon Asia 2014 race. The vehicle is equipped with a proton exchange membrane (PEM) fuel cell system, brush DC motor and DC/DC converter. This prototype vehicle is a single seater with streamline body shape that is designed for energy-efficiency race with the objective of driving the archive furthest distance with the least amount of fuel within the specific time given. In the design's process, the car's fuel cell efficiency test, energy demand, track behavior, motor efficiency analysis, and driving control strategy must be conducted. Experiment on automated intelligent controller was conduct to analyze the performance of powertrain system for certain time given. This powertrain system for automated intelligent controller analysis is part of energy efficiency study for electric vehicle. It forms the basis of knowledge for the energy efficiency analysis.

***Keywords*:** prototype fuel cell electric vehicle, energy-efficient race, automatic intelligent controller, fuel cell efficiency, brush DC motor, motor efficiency, track parameters and energy demand.

INTRODUCTION

Energy and pollution are becoming a bigt problem around the world. Crisis of energy consumption used by human population in daily life is increasing and when talking about energy of a vehicle transportation most of the world using fossil fuel to generate power. Energy is one of the concerns of engineers out there trying to configure on how to generate power through several of techniques and applications. As a

consequence, novel renewable and clean energy power sources must be considered. One of the prevalent alternative sources of electric power is the fuel cell (FC) (von Helmolt, 2007; Drolia, 2003). For many years now, fuel cells, and more especially Proton Exchange Membrane (PEM) fuel cells, are very promising as a replacement, for the internal combustion engine in automobiles (von Helmolt, 2007). Proton exchange membrane fuel cell (PEMFC) is one of the renewable energy devices which by electrochemically generated DC power converting chemical reaction of gasses to an electric energy as the power source of an electric vehicle. In future movement of automobiles will have to move away from conventional gasoline based internal combustion engine due to depleting fossil fuel reserves (Drolia, 2003).

Research in fuel cell development, performances and hybridization with application for vehicles has been taken seriously by many institution especially automotive makers (Corbo P, 2009; Pei P, 2004). The usages of fuel cell vehicles are not limited. Many sectors are involved including public transportation (Ouyang M, 2006; Lin CC, 2003) military (Jain M, 2009), and also recreation (Thounthong P, 2009: Wang Y, 2011). Fuel cells have no advantages over the internal combustion engine at full load. Fuel cell system efficiency drop sharply at low power output because of balance of plants components such as blower and auxiliaries systems (fuel cell controller, DC/DC converters, motors, motor controller and etc.). To overcome the problem, optimization of the powertrain of fuel cells need to be conducted to allow the fuel cell system to operate more efficiently. The objective of the Shell Eco-marathon Asia competition is energy efficiency race. Students must to customize a single seated vehicle to achieve the highest possible fuel efficiency. They must drive a vehicle the furthest with the lowest quantity of fuel (at a minimum average speed 30km/h). This paper reports the methodology that was followed by our team to design a fuel cell powertrain in order to participate in this competition in 2014. This involves the following challenges:

- The nominal power used for this prototype vehicle is below 1kW. As a fuel cell is used as a power source, the operation of a fuel cell system at maximum efficiency needs to be studied. Energy losses from auxiliary system are identified. This allows us to operate the fuel cell at maximum efficiency by employing an intelligent control system.
- The powertrains system is a primary contributor to the efficiency of vehicles. In the race, the constraint is to travel at Luneta Park track: 1.2 km per lap and need 10 laps to finish the race (12km) within 24 minutes (average speed = 30km/h). The energy demand can be calculated based on track road behaviour of Luneta Park track. The results must be used to determine the lowest energy consumption.
- The driving techniques must also determine so that to minimize acceleration. Fixed amplitude speed range and constant speed need to be study. By conduct fixed amplitude speed range experiment, the vehicle can travel freewheeling and to save energy. Hence, the energy management throughout the race is an important issue to be addressed.

METHODOLOGY

Proton Exchange Membrane (PEM) Fuel Cell Efficiency Test.

As a starting point, recall that fuel cells offer many advantages such as high efficiency and high power density but have some drawbacks also, such as a high sensitivity to load variations (J. Larminie, 2003). Considering a motor efficiency of 93%, the fuel cell stack nominal power has to be around 50W. The fuel cell stack must supply this electric power with the highest efficiency. In a first approximation, the stack efficiency is directly related to the stack voltage by the following relation:

$$\eta\ stack = \frac{v\ .\ i}{mH2\ .\ LHV\frac{m}{H2}} = \frac{F}{\eta\ .LHV\frac{m}{H2}} \qquad (1)$$

where $LHV\frac{m}{H2}$ is the Lower Heating Value of H2 in mass, U the stack voltage, I the stack current, mH2 the mass hydrogen flow rate, F the Faraday constant and n the cell number. This relation indicates that the higher the stack voltage, the higher the efficiency. However, stack efficiency falls at very low power even when it is in the region where the stack voltage is the highest. The 1kW fuel cell commercialized by Horizon Fuel Cell was chosen. The H-1000XP fuel cell stack is a cathode-cooled proton exchange membrane (PEM) fuel cell stack designed to provide stable electrical power while operating on air and dry hydrogen (www.horizonfuelcell.com). With innovative materials, the H-1000XP achieved 1000W power output with less weight and more compact size.

The nominal stack power is 1100W while only 137W are typically needed to power the car. Thus, the stack efficiency is high and little heat is generated. In the choice of the appropriate PEMFC stack, the output stack voltage is the most important parameter. Experiments on fuel efficiency were conducted to ensure the efficiency of the fuel cell for each load demand. In that experiment, load was increase 50 watt, 100 watt until 1000 watt to study where the efficiency region on fuel cell.

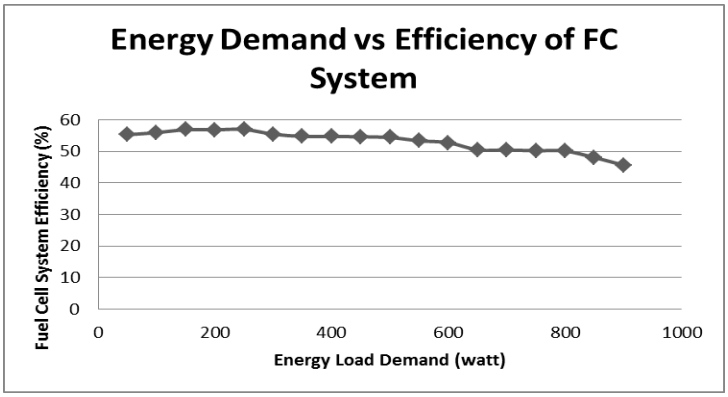


Figure 1: Efficiency PEMFC Horizon 1000XP.

Based on the experimenst conducted, the fuel cell efficiency is differennt for each load demand. The highest efficiency was when the load demand was 150 watt. Even though high efficiency are on 150 watt load demand, for other load demand such as at 100, 200, 250 and 300 watt also had a high efficiency. From this experiment, the user can know which load demand (motor) was needed to operate and maintain the fuel cell efficiency as high as possible. At load 1000 watt showed the efficiency of fuel cell are less efficiency than the others. Operating the system under this condition produce the worst efficiency. Based on result obtain from an experiment, energy load demand for vehicle to moving the car can be known to maintain the fuel cell efficiency at maximum as possible. The design of power train system need must take these results into account to maintain the fuel cell at maximum efficiency.

Vehicle Dynamics Modelling (Energy Demand).

This is an important part of designing a vehicle whereby all source of forces are considered in optimizing the energy of consumption of light weight vehicle. The gearing ratio can be determined from the value calculated using the formula derived. All forces are shown in figure below.

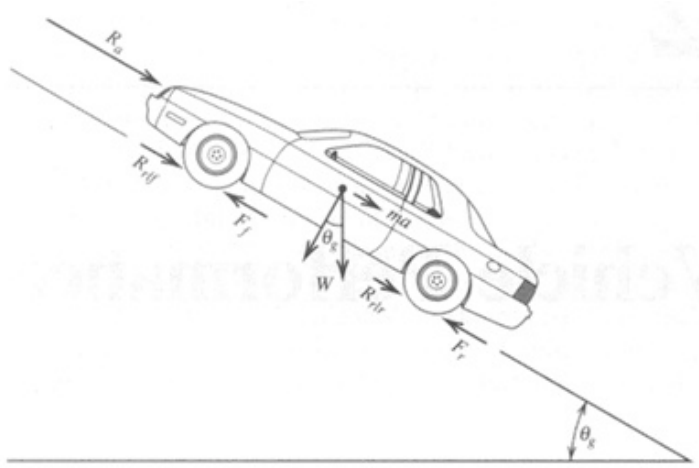


Figure 2: Force act on vehicle due to inclination track condition.

In the way of moving the vehicle, the engine has to develop sufficient power to overcome the road resistance, to move vehicle from a standstill, or to accelerate a reverse of power in addition to that absorbed by the road resistance must be available when required. Road resistance is expressed as tractive resistance. The propelling thrust at the tire to road interface needed to overcome this resistance is known as tractive effort, F_{te} (Nm) (J. Larminie, 2003).

$$F_{te} = F_{la} + F_{ad} + F_{rr} + F_{hc} + F_{\omega a} \quad (2)$$

Where is;

F_{la} = is the force required to give linear acceleration.
F_{ad} = is the force due to the friction of the vehicle body moving through the air.
F_{rr} = is the force due to friction of the vehicle tire on the road (rolling resistance).
F_{hc} = is the force due to climbing the hill.
$F_{\omega a}$ = is the force required to give angular acceleration to the rotating of motor.

The elements of all forces without accounted hill climbing force are equivalent to:

$$\frac{G}{r}\eta T = \mu_{rr} mg + 0.625AC_d v^2 + \left(m + \frac{IG^2}{\eta_G r^2}\right)\frac{dv}{dt} \quad (3)$$

Where G is a gear ratio, r for wheel radius, μ_{rr} is rolling coefficient, A is vehicle frontal area, C_d is drag coefficient, m is vehicle mass, $\frac{IG^2}{\eta_G r^2}$ is an angular acceleration mass factor normally determine by 5% from vehicle mass (J. Larminie, 2003), η for gear efficiency, $\frac{dv}{dt}$ is for acceleration, and T is equal to torque.

Track Road Behavior.

Figure 3 shows the characteristics of the Luneta Park track layout, based on the total distance and total laps needed to be complete under the 24 minutes time allowed, the average speed is 30 km/h. However, since the track consists of 90° turns for every corner, the cars need to slow down for each turn. Several factors should be considered to find the optimum speed for the vehicle, such as: if the car must slow down due to an accident in front, in front vehicle is slow down since had failure on their system and etc. This is very important to make sure the vehicle runs at maximum efficiency as possible while still finishing the race within the specific time given.

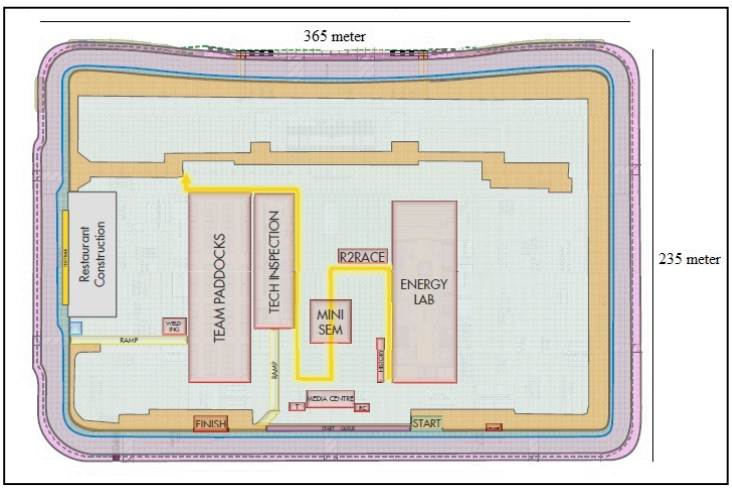


Figure 3: Track Layout Luneta Park, Manila.

Since the course is level, potential energy due to climbing the hill can be neglected. Parameters of the vehicle need to be obtained first due to find the important characteristics of the vehicle for analytical analysis. Table 1 shows the vehicle dynamic parameters. From the vehicle dynamics parameters, power needed to archive targeted speed can be obtained. Table 2 shows power needed for vehicle to achieve speed 30 km/h.

Vehicle Dynamic Parameters	Values	Vehicle Dynamic Parameters	Values
Vehicle mass + driver, m	98 kg	Drag reference area, A	0.5 m^2
Angular acceleration mass factor, $(\frac{IG^2}{\eta_G r^2})$	4.5 kg	Coefficient of drag, C_d	0.20
Rolling resistance coefficient, μ_{rr}	0.0025	Wheel radius, r	0.24 m

Table 1: Vehicle Dynamics Parameters.

Speed (km/h)	P_{grad} (W)	P_{ma} (W)	P_{aero} (W)	P_{roll} (W)	P Total (W)	P Total (Nm)
30 km/h	0	51.56	65.10	20.03	136.69	3.98

Table 2: Total power needed for speed 30 km/h.

Figure 4: SperMotive-2 on track at Luneta Park, Manila.

The total power needed for achieving speed 30 km/h is 136.69 watt but the vehicle must travel 1100 meter (around 2.2 minutes) before archiving that speed. The linear acceleration force related on acceleration from starting until reach 30 km/h within specific of distance. Acceleration from starting until reach 30 km/h can be set faster but the force will be increase and affect the efficiency of motor. Since acceleration low, the speed range where the efficiency of the system will maintain high will be calculated during selecting the electric motor.

Direct Current (DC) Motor Characteristics.

In modeling the vehicle acceleration, the motor torque must be considered. Torque is directly proportional with electrical current and the relationship between torque and current are as in equation (4), (5) and (6) where I is an armature current, V_s is a terminal voltage, R_a is an armature resistance, K_m is a torque constant, and ω is a motor speed while T_f is a torque friction (M.H.A.M. Fakharuzi, 2011) The consideration of a torque friction in torque equation will present more modeling accuracy (P. Wolm, 2008) Table 3 shows motor parameters given by the manufacturer. However, for more accurate modeling results, no load current and no load speed value must be taken from the actual test.

$$I = \frac{V_s}{R_a} - \frac{K_m}{R_a}\omega \tag{4}$$

$$T = IK_m - T_f \tag{5}$$

$$T = \left(\frac{V_s}{R_a} - \frac{K_m}{R_a}\omega\right)K_m - T_f \tag{6}$$

DC motor parameters	Values
Motor constant, K_m	0.0604 Nm/A
Supply voltage, V_s	36 V
Armature resistance, R_a	0.244 Ω
No load speed, N_0	5680 rpm
No load current, I_0	0.147A

Table 3: DC motor parameters.

The Maxon DC motor was selected since the efficiency of the motor is 94% (high enough compare with others manufacturer of dc motor). Based on data given by the manufacturer, modelling of the efficiency curve can be obtained. Table 3 shown parameters of dc motor given by manufacturer and based on these parameters, the modelling efficiency curve can been known as shown in Figure 5 below. Based on that result, the region where dc motor at maximum efficient can be determined. This result must be considered during design the automatic intelligent controller to ensure the motor runs at maximum efficiency. Based on this modelling, the reason why consider linear acceleration takes more times because if acceleration to achieve targeted speed 30 km/h takes short time (24 seconds), the linear acceleration force increase to 283.56 watt (even though still maintain at maximum efficient of fuel cell but it is beyond the region of maximum efficiency of motor).

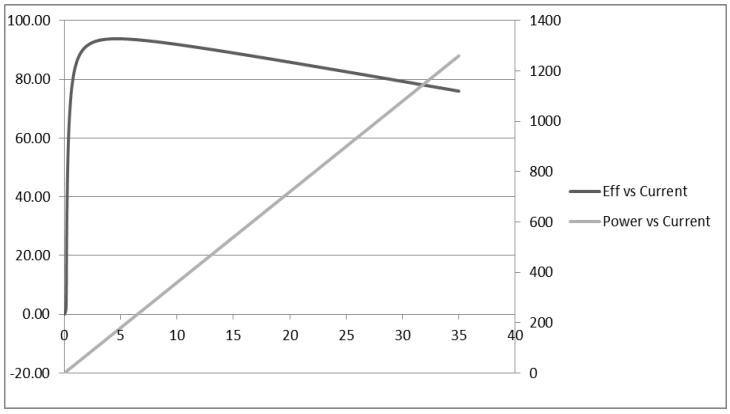


Figure 5: Modeling efficiency curve of Maxon DC motor.

Energy Efficient Driving Control Strategy.

Based on analysis and experiment that were conducted, the data will be used to configure energy efficient driving control strategy for that vehicle. In designing the controller, the powertrains configuration must be setup first to identify a suitable method of controlling (current or voltage). To respect the race rules, no battery is allowed in powertrains system (except auxiliary). Thus, two kinds of fuel cell powertrain structure can be considered (Emadi A, 2006): the direct powertrain system, see figure 6(a), and the indirect powertrain system, see Figure 6(b). Since the race does not required the vehicle to stop and go, excessive braking, and run on approximately on flat road, ultracapacitors are not required. Thus, the final powertrain is composed only of the fuel cell stack and controller, DC/DC buck converters and the DC electric motor.

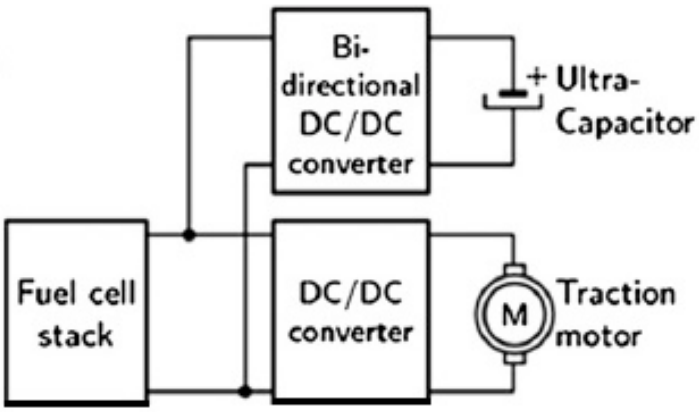


Figure 6(a): Direct powertrain fuel cell system

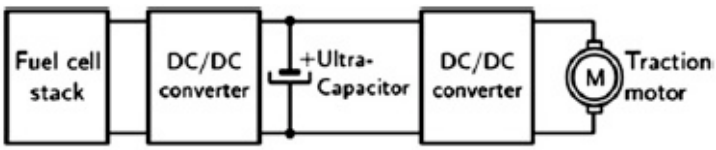


Figure 6(b): Indirect powertrain fuel cell system.

Figure 7 shows the final configurations of the powertrain system. Based on that configuration, DC/DC converter works in current-control mode where current is controlled at a target value, which is fixed with pre-calibrated potentiometer. The input from potentiometer is used to accelerate and decelerate the vehicles and also can be used in designing the automated intelligent controller. After finalising the configuration of the powertrain, focus was placed on an average car speed of 30km/h. If a speed regulation strategy is used, the speed varies between a minimum and maximum value (centered about the average value) (S.M.H.S. Omar, 2013).

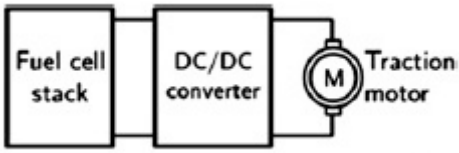


Figure 7: Configurations powertrains fuel cell system.

Acceleration or deceleration between these two velocities are achieved with a constant wheel torque. Experiment on maintaining constant speed 30 km/h and for a fixed speed amplitude around the target average value (25 to 35 km/h), the higher the wheel torque during the accelerations, the shorter the accelerations and thus a higher number of accelerations is needed to complete the race (S.M.H.S. Omar, 2013) . An experiment was conducted to verify if fixed speed amplitude or constant speed meets our previous requirements. A study involving wider speed ranges was conducted (25km/h to 35km/h) to determine the power usage from that speed range.

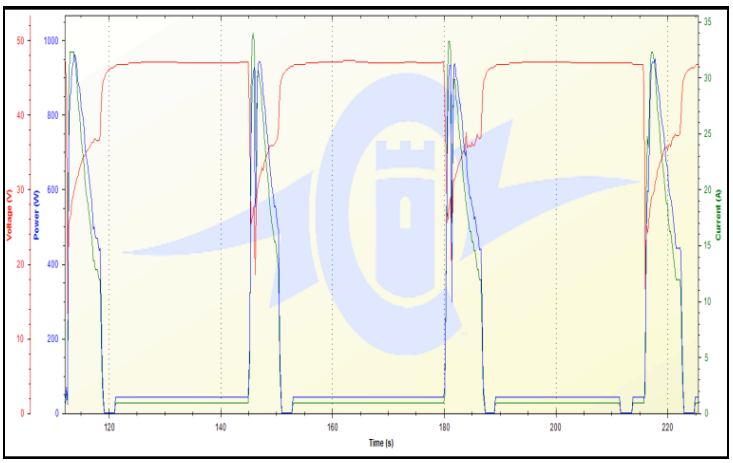


Figure 8(a): Speed range 25km/h – 35km/h

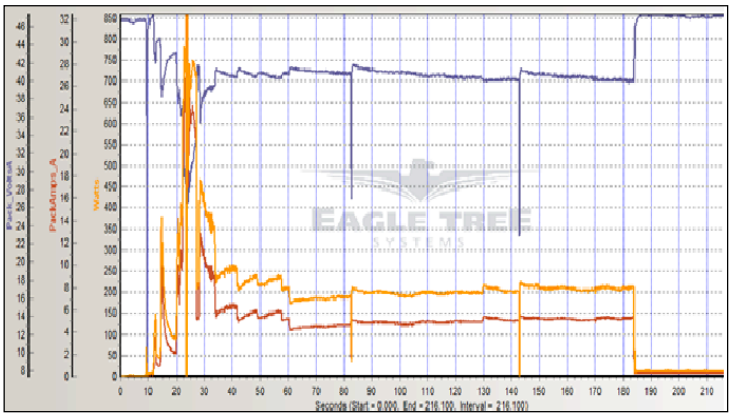
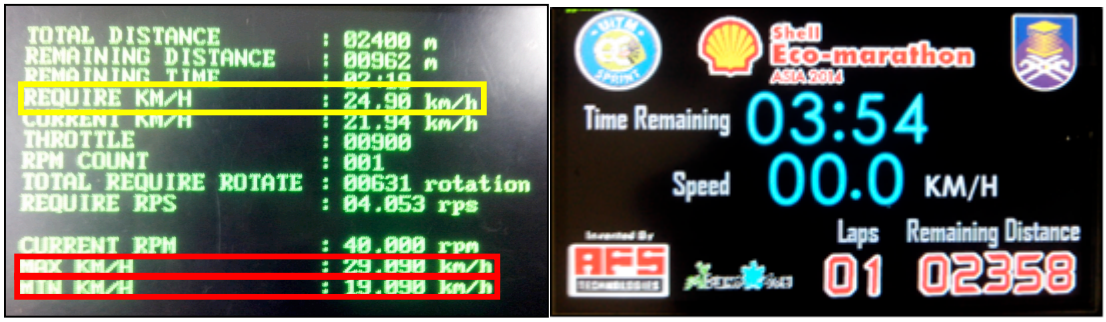


Figure 8(6): Speed constant 30km/h

Based on that experiment, although more power during acceleration was required. The power usage during idle was almost zero resulting in significant net power savings (175 watt). While for constant speed the power demanded is slightly higher (198 watt) because more power consume since there is no idle of time to maintain that speed constant. Figure 8(a) presents data for that fixed speed amplitude (25km/h to 35km/h) and Figure 8(b) present data for constant speed (30km/h).

Automated Intelligent Controller.

Usually, the driver will control the acceleration and deceleration manually by increasing and decreasing the throttle. By increasing and decreasing manually, the driver may over accelerate during driving. The general idea of the automated intelligent controller is that the driver only needs to pushes one button and then the system will run automatically until the finishing line. The system will automatically calculate the remaining distance and time required to complete the race. Based on remaining distance and time, the system will run at amplitude speed range that required archiving finishing the race with the specific time given. For example after achieving targeted speed, if required speed after that is 24.90 km/h, the amplitude speed range is between 19.90 km/h - 29.90 km/h and based on that speed range, the average still around 24.90 km/h. The same techniques were also applied during the driver braking, due to emergency, and at cornering. All system will go idle due to braking, and controller will calculate back after the driver has released the brake paddle.



(a) (b)

Figure 9: Displays for automated intelligent controller

Figure 9(a) shows the displays used in the calibration process. The red box above indicate the range amplitude of speed average based on required speed, while require speed is label at yellow box. The required speed will change time to time after the system achieves the maximum amplitude of speed range. Figure 9(b) is displays for driver to monitor the system inside the vehicle. An experiment was conduct to verify either the system finish within specific given time. The system is run with different type of obstacle to find whether the vehicle will finish within the time given. The structure of experiment is that the vehicle must to finish 2400 meter within 4.8 minutes (288 seconds).

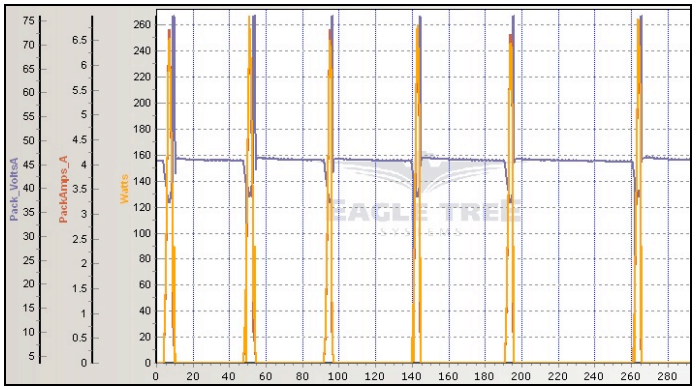


Figure 10(a): Experiment without interference

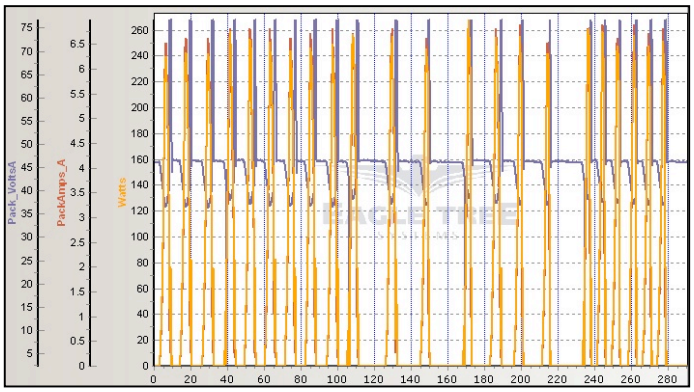


Figure 10(b): Experiment with interference

Figure 10(a) shows the system run without interference and Figure 10(b) shows the system run with interference. Without interference, the system doesn't need to accelerate. While if the system runs with interference, the system must accelerate 3 times more. This is due to the loss of momentum caused by the interference. Even though both system has different accelerations, both system finish within the time (24 minutes) or before the time. This is prove that the car will runs at maximum efficiency possible for fixed speed amplitude while still finishing within the time given.

RESULTS AND DISCUSSION

This section presents the actual results of the vehicle during Shell eco-marathon Asia 2014 that been held at Luneta Park, Manila. Based on 5 attempts given by the organizer, there are 3 valid attempts that we manage to finish. The other 2 attempts were invalid due to unrelated mechanical problems with the vehicles. Figure 11(a) (b) and (c) present an actual data of the vehicle for those 3 valid attempts.

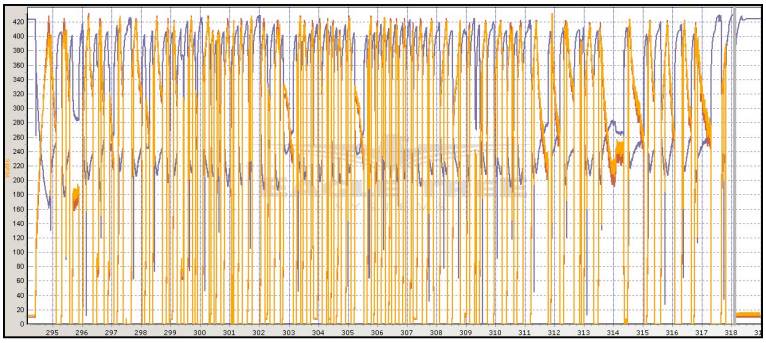


Figure 11(a): Attempts no. 1.

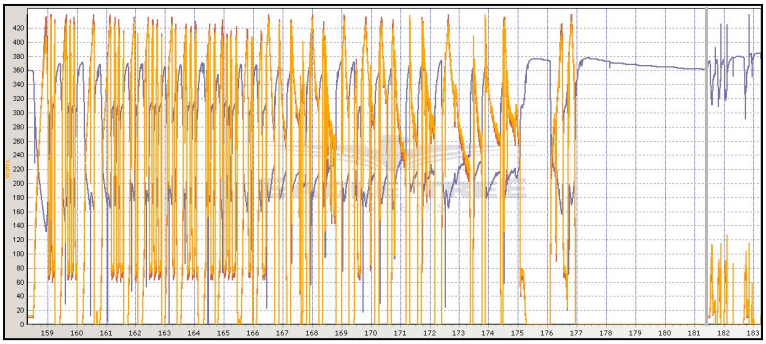


Figure 11(b): Attempts no. 2.

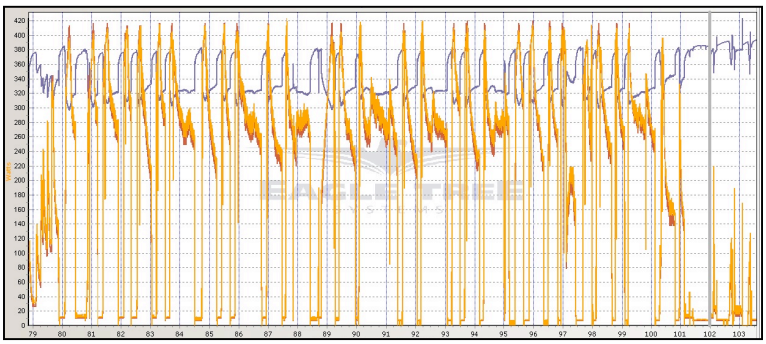


Figure 11(c): Attempt no. 3.

` On the first attempts, the average power usage was about 190 watt as shown in Figure 11(a). Figure 11(b) shows the data for second attempt, which had an average power 154 watt. Figure 11(c) present data for the third attempt and the average power for this attempt was approximately 205 watt. Many factors affected the performance of the vehicle even though the systems are designed to operate at an optimized efficiency. Based on our observation and studied, for attempts first the results is higher compare to second attempt while for the third attempt, the result are slightly higher compares with attempts first and second. On the first attempt, the vehicle runs on the afternoon when the temperature around 42°C. High temperature affects the performance of the vehicle since from heat generate, all the electronics and the fuel cell blower need to operate regularly to supply the oxygen. On the third attempt, the vehicle run in the evening where the temperature around 43°C and there was accident on the track and the car need to stop for few minutes. Since the distance needed to finish is longer while the time is shorter, the vehicle must to accelerate faster to finish the race within the time given. One the second attempt, the vehicle runs early in the morning while there are not many vehicle interference during the car moving and the temperature was very good for fuel cell working condition. Even though there is different energy used for all attempts, the vehicle finishes approximately within the time given (< 24minutes).

CONCLUSION

This paper presents a series of analysis to design, optimize and control the performance of the powertrain fuel cell electric vehicle competing in energy-efficient races. Several experiments must be conducted first before control the vehicle to run at point such as fuel cell efficiency test, vehicle dynamic modelling, track mapping analysis, DC motor characteristics and driving strategy techniques. This is to ensure an optimized sizing of the powertrain system for the vehicle and control the vehicle automatically to operate at maximum efficiency for each part of powertrain system. This technique already been applied to our vehicle and have won first place on prototype fuel cell category in Shell Eco-marathon Asia 2014 race.

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