Development of an Energy Efficient Driving Strategy for a Fuel Cell Vehicle over a Fixed Distance and Average Velocity

S.M.H.S. Omar
Faculty of Electrical Engineering
MARA University of Technology (UiTM)
Shah Alam, Malaysia
syedmharussani@yahoo.com

N.M. Arshad
Faculty of Electrical Engineering
MARA University of Technology (UiTM)
Shah Alam, Malaysia
nhash2@gmail.com

M.H.A.M. Fakharuzi
Faculty of Mechanical Engineering
MARA University of Technology (UiTM)
Shah Alam, Malaysia
fettarmes@hotmail.com

T.A. Ward
Department of Mechanical Engineering
Faculty of Engineering
University of Malaya (UM)
Kuala Lumpur, Malaysia
drtomward@hotmail.com

Abstract— This paper examines the energy efficiency of a hydrogen fuel cell vehicle operating at different power settings. The goal is to develop a driving strategy to maximize energy efficiency for a fixed distance and average velocity. The test vehicle is equipped with a proton exchange membrane (PEM) fuel cell system that provides electric power to a brushless DC motor. This vehicle was designed to compete in the Shell Eco Marathon, an international competition in which the winners are the teams that go the furthest using the least amount of energy. A computer model that simulated the motor and vehicle dynamics was used to predict the output power demanded from the fuel cell. An actual test was then conducted to verify, compare and analyze the performance of the motor for various speed ranges. The result showed how the efficiency varied for different vehicle accelerations. This data can then be used as a basis to operate the vehicle with optimal efficiency.

Keywords— prototype fuel cell electric vehicle, energy-efficient race, control/driving technique, vehicle dynamic modelling, and acceleration efficiency.

I. INTRODUCTION

Rising energy costs and increased environmental awareness have globally inspired automotive manufacturers, research institutes, and universities to conduct research on vehicles powered by alternative propulsion systems [1]. Fuel cells are devices that convert chemical energy directly into electrical energy without combustion. When fueled with pure hydrogen, fuel cell vehicles have higher efficiency than conventional vehicles, typically of the order of 30% for an urban cycle against 22% for diesel vehicles [2,3]. FCEV have been demonstrated for over five decades (since 1960s) has a promising alternative to vehicles powered by internal combustion engines (ICE) [4]. FCEV has been widely used in the transportation industry, especially for public transportation such as buses and trucks which have a 40% higher fuel economy than diesel engine [5].

Advancements in fuel cell technology have reduced the size, weight and cost of FCEV. FCEVs have been built that have a driving range of more than 400 km between refuelling and can be refuelled in less than 5 minutes [6]. The Energy Efficiency and Renewable Energy Program of U.S. Department of Energy claims that, as of 2011, fuel cells achieved 42 to 53% fuel cell electric vehicle efficiency at full power [5] and a durability of over 120,000 km with less than 10% voltage degradation [6]. This shows that FCEV are ready to compete in the automotive market. The Hyundai motor company has already announced their intention to mass produce FCEV and sell one thousand vehicles by 2015 [7]. Therefore studies on the energy efficiency of FCEV are relevant to this emerging market. This paper analyzes the performance and energy demands of a FCEV undergoing different types of FCEV acceleration schemes and driving strategies.

II. METHODOLOGY

A. Vehicle Acceleration Modeling

The power train was designed by first evaluating the mechanical power needed by the car to run on the track. Then the best acceleration needed to minimize the energy demand, while maintaining maximum efficiency was simulated. The total tractive effort \( F_a \) can be determine from the following equation [8]:

\[
F_a = m_a g + F_{air} + F_{road} + D
\]
Where $F_{rr}$ is the rolling resistance force, $F_{ad}$ is the aerodynamic drag, $F_{hc}$ is the hill climbing force, $F_{la}$ is the linear acceleration force, and $F_{wa}$ is the angular acceleration to rotating motor force. The elements of all these forces are equivalent to:

$$F_{te} = F_{rr} + F_{ad} + F_{hc} + F_{la} + F_{wa} \quad (1)$$

$$\frac{G}{r} \eta T = \mu_{rr} mg + 0.625 AC_d v^2 + (m + \frac{I_g^2}{n_G^2}) \frac{dv}{dt} \quad (2)$$

Where $G$ is a gear ratio, $r$ for wheel radius, $f_{rr}$ is rolling coefficient, $A$ is vehicle frontal area, $C_d$ is drag coefficient, $m$ is vehicle mass, $\frac{I_g^2}{n_G^2}$ is an angular acceleration mass factor normally determine by 5% from vehicle mass, $\eta$ for gear efficiency, $\frac{dv}{dt}$ is for acceleration, and $T$ is equal to torque.

Fig. 1 is an image of the FCEV vehicle at the Sepang Raceway near Kuala Lumpur, Malaysia. Mechanical features of the car can be improved for better energy usage. The topology of the Sepang Raceway consists of a slope with a 6° gradient with a distance of 2.8km/lap. The mechanical power required to drive the car depends on the topology of the track.

Table 1: Vehicle Parameters

<table>
<thead>
<tr>
<th>Vehicle dynamic parameters</th>
<th>Values</th>
<th>Vehicle dynamic parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle mass + driver, $m$</td>
<td>90kg</td>
<td>Drag reference area, $A$</td>
<td>0.5m²</td>
</tr>
<tr>
<td>Angular acceleration mass factor, $\frac{I_g^2}{n_G^2}$</td>
<td>4.5 kg</td>
<td>Coefficient of drag, $C_d$</td>
<td>0.20</td>
</tr>
<tr>
<td>Rolling resistance coefficient, $\mu_{rr}$</td>
<td>0.0025</td>
<td>Wheel radius, $r$</td>
<td>0.24m</td>
</tr>
</tbody>
</table>

Table 2: Mechanical power needed for each profile

<table>
<thead>
<tr>
<th>Profile</th>
<th>$v$ (km/h)</th>
<th>$P_{mot}$ (W)</th>
<th>$P_{max}$ (W)</th>
<th>$P_{arr}$ (W)</th>
<th>$P_{roll}$ (W)</th>
<th>$P_{total}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30.0</td>
<td>61.27</td>
<td>54.25</td>
<td>18.39</td>
<td>133.92</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>28.0</td>
<td>103.20</td>
<td>44.11</td>
<td>17.17</td>
<td>164.47</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>28.0</td>
<td>68.67</td>
<td>0.00</td>
<td>44.11</td>
<td>17.17</td>
<td>129.94</td>
</tr>
<tr>
<td>3</td>
<td>55.0</td>
<td>-397.75</td>
<td>226.44</td>
<td>334.31</td>
<td>33.71</td>
<td>196.71</td>
</tr>
<tr>
<td>4</td>
<td>21.0</td>
<td>-83.74</td>
<td>18.61</td>
<td>12.86</td>
<td>204.92</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>37.0</td>
<td>257.19</td>
<td>-83.74</td>
<td>18.61</td>
<td>12.86</td>
<td>204.92</td>
</tr>
<tr>
<td>6</td>
<td>37.0</td>
<td>-272.11</td>
<td>147.19</td>
<td>101.78</td>
<td>22.68</td>
<td>-0.46</td>
</tr>
<tr>
<td>7</td>
<td>35.0</td>
<td>147.12</td>
<td>-54.24</td>
<td>54.25</td>
<td>18.39</td>
<td>174.53</td>
</tr>
<tr>
<td>8</td>
<td>30.0</td>
<td>47.02</td>
<td>54.25</td>
<td>18.39</td>
<td>25.63</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 shows the topology of the Sepang circuit. Based on the total distance, the average speed needed to complete the race in under (24 minutes) is 30km/h. However, since the slope varies in different parts of the track; the track is divided into eight parts and the speed required to complete each section with a minimal usage of energy in under (24 minutes) is calculated. Table 2 shows the mechanical power needed for each of the eight sections of the track.

Fig. 2: Sepang circuit parameters

A flat track was also studied, requiring no sectioning of the track. As already stated the vehicle must be driven at an average velocity of 30km/h. The first phase of the race requires launching the car from rest. A mechanical model was used to assess the energy consumption and the corresponding traction power needed over a range of torques applied on the traction wheel to accelerate a car from 0 to 30 km/h.
Fig. 3 shows the results of this analysis. The energy consumption required to launch the car sharply decreases at first but later flattens as wheel torque increases. The maximum traction power needed for the launching increases linearly with the wheel torque, since it is equal to the torque multiplied by the maximum rotational speed.

In other words, it is more efficient to make a fast start than a slower start. With a fast start, the distance traveled is much shorter than a slow start. Therefore, the remaining distance to travel to finish the race is longer. However, the remaining time to finish the race is longer too. In the end, the average car speed to ensure the race is completed on time diminishes with the increase in wheel torque during the launching.

After considering the launching strategy, focus was then placed on a driving strategy based on an average car speed of 30 km/h. If a speed regulation strategy is used, the speed varies between a minimum and maximum value (centered about the average value).

Accelerations or decelerations between these two velocities are achieved with a constant wheel torque. For a fixed speed amplitude around the target average value (for example, 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. A study involving three progressively wider speed ranges was conducted (24 km/h to 36 km/h; 25 km/h to 35 km/h; and 26 km/h to 34 km/h) to determine the most efficient speed range. The performance of the vehicle was then compared to a constant baseline speed of 30 km/h.

III. RESULTS AND DISCUSSION

Road tests were conducted for the three speed ranges. SperMotive was launched on a flat road surface and accelerated until it reached the maximum speed in the range. After this the driver pulled the throttle back until the vehicle decelerated to the minimum speed in the range. This technique was repeated four times and the vehicle’s performance was measured. The experiment was conducted three times for each speed range to obtain accurate results. Since the average speed for each range is 30 km/h, the distance the car can go for each test is approximately same.

Fig. 4 presents data for the 24-36 km/h speed range. The average power for this speed range is approximately 179 Watts. Fig. 5 shows the data from the 25-35 km/h speed range, which had an average power of approximately 175 Watts. Fig. 6 shows the performance from the 26-34 km/h speed range, which had an average power of 178 Watts. These results show that maintaining a speed range of 25-35 km/h consumes less energy than the others.
less than the other cases, but the energy demand is higher. For the time that the motor will idle is longer, since the maximum speed (36 km/h) is higher compared to other ranges maximum speeds (34 km/h and 35 km/h). For the 26-34km/h speed range, the motor requires more energy because it must accelerate and decelerate within the range more frequently than the other two cases. The idle time is also reduced since the maximum speed is less than the others. The 25-35km/h speed range is the best at maintaining the system at maximum efficiency (while achieving an average total speed of 30km/h).

Fig. 6 presents data obtained while maintaining a constant speed of 30km/h. From the experiment, the power demanded by the motor in this experiment is 198 Watts. The results show that a constant and continuous power is required. More power is required to maintain a constant speed of 30 km/h, because there is no idle time. During the first experiment involving speed ranges, the motor idled for a few seconds every cycle. Although the more power during acceleration was required, the power usage during idle was almost zero resulting in significant net power savings.

Fig. 7 presents the overall energy usage from all of the experiments. Although the distances traveled and average speeds (30km/h) are the same, the total power usage is different. This proves that an optimal driving strategy can be used to make a significant difference in improving the energy efficiency of a FCEV.

IV. CONCLUSION

This paper presents a series of analysis to study and analyze the performance of SperMotive prototype fuel cell vehicle. A driving strategy is developed to minimize the total energy cost for a given distance and average velocity. This was done by determining an ideal velocity range through experimental test runs and modeling. The power consumption was calculated during acceleration (to the maximum speed) and power savings when the motor idles during deceleration (to the minimum speed). The results of this study will be used to obtain a competitive edge at the next Shell Eco Marathon competition.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support given for this work by the Universiti Teknologi MARA under the Faculty of Electrical Engineering, Faculty of Mechanical Engineering, Tabung Amanah HEP and Tabung Amanah Pembangunan Akademik HEA in the year of 2012. Thousands of thanks to all UiTM Eco-Sprint and UiTM Eco-Planet team members that have led to the construction of SperMotive car. This technique had been applied at UiTM Eco-Planet team (Bat-Motive) and got second place in the Shell Eco-marathon Asia 2012 competition.

REFERENCES