Energy appraisal of a gasoline-electric vehicle

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ABSTRACT

Hybrid electric vehicle technology is seen as one major solution in reducing fuel consumption and emissions of greenhouse gases of a conventional vehicle. In this paper, the energy savings potential of a 1325kg series-parallel Gasoline-Electric vehicle was evaluated using simulated high way fuel economy test (HWFET) and urban dynamometer driving schedule (UDDS) drive cycle data. Analysis showed that, the average percentage reduction in fuel compared to the most efficient conventional car is approximately 60% combining both cycles. This paper also shows that, the regenerative braking system recovers at least 1% of the energy loss associated with the internal combustion engine in every 1.789km distance of the UDDS drive cycle and 3.756km in the highway drive cycle when compared to the conventional braking system.

Keywords: Series-parallel, gasoline-electric vehicle, UDDS, HWFET, internal combustion engine, hybrid, energy, appraisal, efficient, regenerative braking.

Abbreviations: Pₒ = shaft output power, kW, T= torque, Nm, ω = angular speed, rev/min, η = efficiency, %, Fₒ =fuel input energy, kJ, e =exponential function, SOC= battery’s state of charge, %

1. INTRODUCTION

In recent years, Gas-Electric vehicle (GEV) also known as hybrid electric vehicle (HEV) has become of significant interest in vehicle design philosophy due to the pressing environmental concerns and skyrocketing price of oil (Yuliang, 2005). Hybrid electric vehicle uses two or more power sources, usually a combustion engine and an electric machine. These vehicles with onboard energy storage devices and electric drives allows braking power to be recovered and ensures that the internal combustion engine to operate only in the most efficient mode (Kwasi-Effah, 2012). Improvement of the overall energy efficiency is one of the most important subjects when developing new vehicle technologies (Babici and Alexandru, 2006). The hybrid electric vehicle (HEV) powertrain combines the advantages of conventional and electrical vehicles of long range functioning, low emissions and improved consumption. However, a combined simulation and analytical approach enables analysis of energy flows and energy losses on different energy paths within the hybrid powertrain and evaluation of their influences on energy consumption of the vehicle (Babici and Alexandru, 2006). Hybrid powertrain are originally conceived as a way to compensate for the shortfall in battery technology, and are today the realistic alternative to combustion engine vehicles (www.wikipedia.org, 2012). Research has highlighted what factors in a vehicle in motion contribute to the amount of energy available for recovery via regenerative braking. These mainly include the weight of the vehicle, driving style and how rapid the deceleration, the amount of energy to be absorbed varies. Most of the regenerated energy is from the inertia of the vehicle (Lee and Nelson, 2005). Research has found that regenerative braking is more beneficial to driving schedules with frequent starts and stops (Wyczalek and Wang, 1992). In a conventional vehicle, substantial amounts of energy are lost along the way without any form of recovery input (www.fueleconomy.gov, 2012). The degree or effectiveness of energy savings is also a factor of the hybrid system architecture (Kwasi-Effah, 2012). The most common way of classifying hybrid vehicles is by their drivetrain architecture. Thus, the configurations are series, parallel and series-parallel. However, a series-parallel powertrain brings in more degrees of freedom to vehicle engine operation with added system advantages (Wishart and Dong, 2009). As a product of advanced design philosophy and component technology, the maturing and commercialization of GEV technologies demand extensive research and developments. Thus, this paper focuses on the energy impact of a series-parallel GEV.

2. METHODOLOGY

Mat lab/Simulink was used to model the Gasoline-Electric Vehicle. The simulated model is based on the Toyota Prius series-parallel hybrid electric vehicle with the following component specification:

(a) The Electrical Subsystem is composed of four parts:
The electrical motor, the generator, the battery, and the DC/DC converter.
- The electrical motor is a 500 Vdc, 50 kW interior Permanent Magnet Synchronous Machine (PMSM).
- The generator is a 500 Vdc, 30 kW PMSM
- The battery is a 6.5 Ah, 200 Vdc, 21 kW Nickel-Metal-Hydride battery.
- The DC/DC converter (boost type) is voltage-regulated.

(b) The power split device: It uses a planetary device, which transmits the mechanical motive force from the

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engine, the motor and the generator by allocating and combining them. It has a gear ratio of 2.6 revolutions.

(c) The internal combustion engine subsystem: This is a 4 cylinder 1.5litre gasoline engine capable of producing a maximum power of 57 kW @ 6000 rpm.

(d) The Vehicle Dynamics subsystem:
* Mass of Vehicle= 1325kg
* Horizontal distance of centre of gravity to front axle=1.35m
* Horizontal distance of centre of gravity to rear axle=1.35m
* Centre of gravity height from ground=0.7m
* Frontal area=2.57m²
* Drag coefficient=0.26

The tyre dynamics represent the force applied to the ground. The parameters are as follows:
* Effective rolling radius=0.3m
* Rated vertical load=3000N
* Peak longitudinal force at rated load=3500N
* Slip factor at peak force=10%
* Relaxation length at rated load=0.2m

2.1 Drive cycle data

Figures 2.1 and 2.2 shows the simulated HWFET and UDDS drive of the car.

![Graphs showing drive cycle data](image-url)
2.2 Evaluation of Fuel Consumption

Given a torque demand from the driver, it will take a certain amount of fuel to make that torque at a given vehicle speed. The amount of fuel required to make that torque depends on the engine’s efficiency at the torque and speed. So, if the value of torque, speed, and efficiency of the engine is known at that operating point, then the fuel consumed at that point can be found via the mechanical power of the ICE (see Appendix A for simulated plot). The difference between the output power and the fuel consumed is the power loss. The instantaneous fuel energy input can be determined as follows:

\[ P_s = \omega^* \frac{(1/30)*T}{\eta} \]  

(2.1) 

\[ \eta = \frac{P_s}{F_i} \]  

Thus, from equation 2.2, fuel energy Input is given by:

\[ F_i = \frac{P_s}{\eta} \]  

(2.3)

It is known that the most fuel efficient conventional car consumes approximately 8.1 liters/100km of fuel (High way drive) and 11.1 liters/100KM of fuel for city drive (www.extension.iastate.edu, 2012).

We will assume that simulating time (i.e. 0s to 200s) will remain steady over a 100km for a complete HWFET and UDDS drive cycle.

3. RESULTS AND ANALYSIS

3.1 Analysis for HWFET Drive Cycle

From the simulated HWFET plot, Car average speed = 67.6km/hr

Distance covered = 67.6km/hr x 200/3600 hr = 3.756km

The higher heating value (HHV) of gasoline is 34.8MJ per litre (www.extension.iastate.edu).

From the simulated HWFET (Appendix A), Approximated total fuel energy input = 5,500kJ (3.756Km)

Hence fuel consumption = 5,500e^6/34.8e^6 =0.14litre per 3.756km

Assuming driving pattern remains steady over a 100km thus, the fuel consumption per 100km = 0.16 x 100/3.756 =4.26litre per 100km

Therefore, percentage reduction in fuel consumption compared to the most efficient conventional car is approximately 49%.

3.2 Evaluation of Energy Recovery:

Energy recovery during regenerative braking is a function of the weight of the vehicle and its instantaneous velocity (sandiu, 2010). Thus the degree of regeneration energy is a function of the vehicle’s instantaneous kinetic energy i.e K.E=1/2MV^2 and the efficiency of the capturing device e.g battery and ultra capacitors.

It is important to note that, during coasting, heat energy is lost due to rolling friction and no energy is captured since brakes are not applied. However, there is savings in fuel energy since the demand power will be low, thus displacing the hybrid mode. From figure 2.1, negative amplitude indicates mechanical braking. Mechanical braking was applied 3 times i.e at 130s, 150s and 162s. The energy recovered can thus be calculated from these reference points.

At 130s:

\[ \text{Vehicle Speed before braking}=110\text{km/hr} \]
\[ =30.556\text{m/s} \]

Given:

\[ \text{Vehicle Speed after braking}=75\text{km/hr} \]

Therefore percentage increase in SOC can be calculated as follows:

Battery capacity filled within 10s of applied brake = 0.0027hr x 60Amps =0.162AH

Thus, % Increase in SOC= 1 - (6.5/0.162)/6.5 =2%

Table3.1 shows a summary of the total recoverable energy in a distance of 3.756km

Table 3.1: Recoverable Energy

<table>
<thead>
<tr>
<th>Reference Point</th>
<th>Vehicle Speed (km/hr)</th>
<th>Duration of Braking (s)</th>
<th>Instantaneous Energy (kJ)</th>
<th>Recovery Energy (kJ)</th>
<th>% Increase in SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>After</td>
<td>Before</td>
<td>After</td>
<td></td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>110</td>
<td>75</td>
<td>10</td>
<td>618.556</td>
<td>287.533</td>
</tr>
<tr>
<td>150</td>
<td>90</td>
<td>50</td>
<td>10</td>
<td>414.112</td>
<td>259.712</td>
</tr>
<tr>
<td>162</td>
<td>70</td>
<td>68</td>
<td>2</td>
<td>250.533</td>
<td>236.412</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If ; 3.756km = 499.536kJ (energy recovered)

Thus, for continuous steady motion as assumed earlier 100km= 13, 145.69kJ Approximately

This recoverable energy is thus useful for the hybrid system to maintain its characteristic advantage of its fuel savings potential.

Also, from Appendix A, the average shaft power output of the ICE is 52KW. Comparing this value with efficiency map, the average efficiency is approximately 20%. Thus, the average power loss from the ICE is approximately 20KW (i.e 260KW-52KW). The Energy loss in 200s approximately is 52,000KJ.

Average loss in ICE with recovery in battery will be 52,000- Average battery recovered energy =52,000 - 171 =51,829kJ

Therefore percentage of recovered lost energy by ICE is =1/(51,829/52,000) =1%

3.3 Analysis for UDDS Drive Cycle:

From figure 2, Car average speed = 32.2km/hr

Duration of braking= 10s

Vehicle mass= 1325kg

Thus, Instantaneous Energy before braking = \( \frac{1}{2}(1325\times30.556^2) \) =618.556kJ

Instantaneous Energy after braking = \( \frac{1}{2}(1325\times20.833^2) \) =287.533kJ

Recovery Energy = 618.556-287.533=331.023kJ

Required Energy absorption rate (Power) = 331.023/10 =33.1023 kW

By comparing with the actual measurement from the plot, the total loss associated in generator, battery, motor shaft e.t.c is approximately 39%.

Also, Given:

Battery Capacity = 6.5 AH,

Generator input voltage to battery= 300V at point 130s (Appendix B)

Generator Input current to battery= 60amps at point 130s

From the simulated plot, since duration of braking is 10s (i.e 130-140s) the percentage increase in SOC can be calculated as follows:

Battery capacity filled within 10s of applied brake = 0.0027hr x 60Amps =0.162AH

Thus, % Increase in SOC= 1 - (6.5/0.162)/6.5 =2%

Table3.1 shows a summary of the total recoverable energy in a distance of 3.756km
4. DISCUSSION

From the simulated high way fuel economy test and urban dynamometer driving schedule drive cycle, within a 3.756km and 1.789km distance drive, the battery has so far been able to capture about 1% of the 80% average energy loss in the internal combustion engine. However, it is important to note that, this value will continue to vary increasingly as time elapses. Since the most efficient conventional car has a fuel consumption of about 8.1litre per 100km of the high way fuel economy test drive cycle and 11.1litre per 100km of the urban dynamometer driving schedule drive cycle, by comparing this with the fuel consumption of the gasoline electric vehicle, the percentage reduction in fuel consumption is approximately 70.50% and 49.00% of UDDS and HWFET drive cycle respectively. Thus, the average percentage reduction in fuel combining both cycles is 60%. The value of fuel savings and energy recovery of the regenerative braking system of the vehicle can be appreciated depending on the drivers driving pattern.

5. CONCLUSION

The energy recovery and fuel consumption of the gasoline-electric vehicle has been evaluated using the UDDS and HWFET drive cycle data. The average percentage reduction in fuel of the GEV was found to be 60%. The energy loss due to low efficiency of the ICE has been compensated for by incorporating a regenerative braking system. This system has shown to make up for at least 1% of the energy loss in every 1.789km and 3.756km of drive in both city and highway cycle respectively.

APPENDIX A

ICE

<table>
<thead>
<tr>
<th>Reference Point</th>
<th>Vehicle Speed (Km/hr)</th>
<th>Duration of Breaking (s)</th>
<th>Instantaneous Energy (KJ) Before</th>
<th>Recovery Energy (KJ) Before</th>
<th>SOC Increase in SOC</th>
</tr>
</thead>
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<td>50</td>
<td>7</td>
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<td>Total</td>
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</table>
APPENDIX B
Drive power

APPENDIX C
Drive power
REFERENCES