HYBRID ENGINE POWERED CITY CAR: Fuzzy Controlled Approach

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ABSTRACT. This study describes a fuzzy controlled hybrid engine powered car. The car is powered by the lithium ion battery capacity of 1000 Wh is charged by the 50 cc hybrid engine and power regenerative mode. The engine is operated with lean mixture at 3000 rpm to charge the battery. The regenerative mode that connects with the engine generates electrical power of 500-600 W for the deceleration of car from 90 km/h to 20 km/h. The regenerated electrical power has been used to power the air-conditioning system and to meet the other electrical power. The battery power only used to propel the car. The regenerative power also found charging the battery for longer operation about 40 minutes and more. The design flexibility of this vehicle starts with whole-vehicle integration based on radical light weighting, drag reduction, and accessory efficiency. The energy efficient hybrid engine cut carbon dioxide (CO\textsubscript{2}) and nitrogen oxides (N\textsubscript{2}O) emission about 70-80\% as the loads on the crankshaft such as cam-follower and its associated rotating components are replaced by electromagnetic systems, and the flywheel, alternator and starter motor are replaced by a motor generator. The vehicle was tested and found that it was able to travel 70 km/litre with the power of hybrid engine.

1. Introduction
Transportation consumes more than 20\% of the world's total primary energy and produces much of the world's air pollution. Transport service industry increasingly serves as a prerequisite in continuing and developing the productivity of other sectors in the society. If energy use trends for the worlds are projected to year 2100, transportation sector would then need to have twenty times more energy-efficient engine, which roughly equates to 169.312 km per litre. While, incomplete combustion of automobiles engine causes approximately 73.19\% of green house gas (GHG) emissions [1]. The emission of CO has significant effects on fetal health like lung cancer, binds to hemoglobin in the blood stream and infant mortality based on the study of [2, 3, 4, 5, 6]. Furthermore, the emission of CO causes the increase of Global warming which lead to major climatic changes that affect the whole world, every single country and many other organisms. Thus, optimal hybrid electric vehicle (HEV) design is becoming a hot spot in recent years as a viable way to meet requirements on both vehicle performance and environment protection [7, 8, 9, 10, 11]. The authors [12] reported that it is difficult related to packaging, fuel storage, power-train cooling, and cost. This study presents a fuel efficient and eco-friendly hybrid engine powered DC motor propelled one seated Urban vehicle. The design flexibility of this vehicle started with whole-vehicle integration, which mainly based on light weighting, drag reduction, fuel-efficient and emission. The proposed vehicle chassis frame and body are made with aluminum except the chassis side bars and the cross members which leads the vehicle weight of 1.48 kN. Drive wheel’s traction is digitally controlled by using DYNAMO, Electronic Control Module DC-DC converter is used to stabilize the voltage of DC motor for propel the car.
2. Methodology
The major target of the vehicle design is to make the vehicle fuel efficient and emission reduction with emphasizing light weighting and electric propulsion. Power train of this vehicle is consisted of hybrid engine, power controller and DC motors. The hybrid engine has been built with a 50 cc engine, a battery pack (lithium ion) of capacity 1000 Wh, a 24 volts generator, a power regenerative mode. Power regenerative mode has been built connecting 4F capacitor with a 24 V motors by accelerator control switch. The car weight is 2.36 kN including driver weight of 0.6 kN. The total dynamic analysis of the car will be taken into accounts to estimate the desired output power of the proposed engine. It has been developed with downsizing the conventional engine by removing the moving parts such as starter, flywheel, alternator, numbers of pulleys and others. An electro-supercharger has been used to develop the pressurized additional air for creating massive turbulence effect and auto oxidation and atomization and enhancing burning efficiency of air-fuel mixture about 90% in shortly [11].

2.1 Drive Line Modeling

Figure 1 shows the drive line of the developed vehicle. It consists of clutch, transmission shaft, propeller shaft, final drive, drive shafts and wheels. Using the generalized Newton’s second law motion equation has derived the fundamental equations for the driveline. Relations between inputs and outputs are in the following be described as:

\[
\begin{align*}
\dot{\omega}_w &= i_i i_f (T_e - T_{fric}) - \frac{W}{g} c_r r_w^2 \dot{\omega}_w - \frac{1}{2} c_{air} A_f \rho_a v^2 - \frac{W}{g} (c_r + g \sin \phi) r_w \\
\end{align*}
\]

where, \(W\) is the vehicle weight in kN, \(r_w\) is the wheel radius, \(J_w\) and \(J_e\) are the polar moment of inertia of the wheel and engine crankshaft, \(i_i\) and \(i_f\) are the slippage of the transmission and final drive, respectively.

The input torque of the generator (\(T_{g(i)}\)) can be considered as the torque of the clutch (\(T_c\)) when the clutch engaged and there is no internal friction. The input torque of the generator can be computed as:

\[
T_i = T_c - T_{fric} - J_e \dot{\omega}_e = T_{g(i)}
\]

![Figure 1. Vehicle driveline.](image-url)
The torque of the drive DC motor can be calculated by considering the input power of the motor in terms of the electrical power, which is generated by the generator. The torque of the motor can be computed as:

\[ T_m = \frac{\dot{\alpha}_s}{\alpha_m} \left[ T_i - T_{fric} - J_s \ddot{\alpha}_s \right] \frac{1}{\eta_e \eta_m} \]

where, \( T_m \) is the motor torque in Nm, \( \dot{\alpha}_s \) is the angular acceleration of the clutch, \( J_s \) is the gear box efficiency, \( \alpha_m \) is the motor speed, \( \eta_e \) is the efficiency of the motor. The dynamic analysis of the vehicle is conducted by considering the vehicle (Figure 2) at slope of 6.7% gradient (\( \phi = \sin^{-1} 6.7\% \)). The design parameters of the vehicle are: weight 2358 N including driver 0.59 kN, height centre-of- gravity of 0.75m, wheel base of 1.2 m, and the location of CG from front wheel 0.75m. The car is assumed to accelerate on inclined road with angle \( \phi \), the normal forces under the front and rear wheels, \( F_{zf}, F_{zr} \) are computed by using the modified equation [14]:

\[ F_{zf} = \frac{1}{2} mg \left( \frac{a_2}{l} \cos \phi - \frac{h}{l} \sin \phi \right) - \frac{1}{2} ma \frac{h}{l} \]

\[ F_{zr} = \frac{1}{2} mg \left( \frac{a_2}{l} \cos \phi + \frac{h}{l} \sin \phi \right) + \frac{1}{2} ma \frac{h}{l} \]

where, \( l \) is the wheel base in m, \( a_2 \) is the location of CG from the rear wheel in m, \( a \) is the acceleration of the vehicle in m/s\(^2\) and \( h \) is the height of the vehicle in m.

Based on the characteristics of acceleration, the normal forces of the vehicle under the front and rear
wheels can be classified as \( \frac{1}{2} mg \left( \frac{a_z \cos \phi \pm \frac{h}{l} \sin \phi}{l} \right) \) is the static part and \( \pm \frac{1}{2} mg \left( \frac{h a}{l g} \right) \) is the dynamic part. The dynamic parts, \( \pm \frac{1}{2} mg \left( \frac{h a}{l g} \right) \), depend on acceleration \( a \) and height \( h \) of mass center CG, while the static parts, \( \frac{1}{2} mg \left( \frac{a_z \cos \phi \pm \frac{h}{l} \sin \phi}{l} \right) \) are influenced by the slope angle \( \phi \) and height \( h \) of mass center. Traction force of the car can be computed as, \( F_t = F_{t1} + F_{t2} = \mu \left( F_{z1} + F_{z2} \right) \).

2.2 Hybrid Engine Model Development

An intelligent electromagnetic system has developed to control the fuel injection of the hybrid engine as shown in Figure 1. A high efficient generator has used with the 50 cc engine to generate power for the 24V motor to propel the car. A small battery pack has used just to start the engine and initially magnetized the rotor generator. A capacitor of 4F is connected with motor to recover the deceleration energy, which is 600 W when the vehicle decelerates from 90 km/h to 20 km/h and to charge the battery. The specification of hybrid engine has shown in Table 1. In continuous operation, the decelerated recovered energy by the capacitor has been used to operate the air-conditioning system of the car.

Table 1: Specification of hybrid engine powered car

| Description                  | Unit | Values |
|------------------------------|------|--------|
| VEHICLE                      |      |        |
| Weight including driver weight| kN   | 2.36   |
| Operating speed              | kM/h | 30-75  |
| Traction torque (maximum)    | Nm   | 25     |
| HYBRID ENGINE                |      |        |
| Engine size                  | cc   | 50     |
| Intake (air and fuel)        | Ratio| 25:1   |
| Fuel intake                  | Method| Electromagnetic |
| Generator Capacity           | V    | 24     |
| Nominal voltage              | V    | 24     |
| Nominal current              | A    | 86     |
| Battery                      |      |        |
| Nominal voltage              | V    | 24     |
| Capacity                     | Ah   | 86     |
| Capacitor                    | F    | 4      |

The mass flow rate of air is related to the effective throttle area can be computed by using the equation [15]

\[
\dot{m}_{thr} = \frac{C_p A_{thr} P_0}{\sqrt{RT_0}} \left( \frac{P_m}{P_0} \right)^{\gamma/2} \left[ \frac{2\gamma}{\gamma-1} \left( 1 - \left( \frac{P_m}{P_0} \right)^{(\gamma-1)/\gamma} \right) \right]^{\gamma/2} \text{ if } \frac{P_m}{P_0} > \left[ \frac{2}{\gamma+1} \right]^{(\gamma-1)/\gamma} \tag{7}
\]
with $A_{thr} = \frac{d^2}{2a} \left(1 - a^2\right)^{\frac{1}{2}} + \frac{D^2}{2} \arcsin \left(1 - a^2\right)^{\frac{1}{2}}$

where, $a = d/D$, is the diameter ratio, $D$ is the throttle bore diameter in m, $d$ is the throttle pin diameter, $\gamma$ is the ratio of the specific heat ($= c_p/c_v$), $c_p$ and $c_v$ are the heat coefficient at constant pressure and volume, respectively).

### 2.3 Control System of Hybrid Engine

Hybrid engine generates the power required to drive the vehicle via a combination of an internal combustion engine and an electric generator [16]. The reliable management of power flows or torque distributions may require the performance analysis of the engine such as engine sizing optimization. However, to assess the engine torque generation a number of indicators could be used. They are definable in dynamics with on-board information from the sensors: engine air fuel ratio $A/F$, vehicle travelling speed $\omega$, and traction torque $T_t$.

Improving the control strategy design for the on-board information is considered as one of the most promising concepts is management of power flow of a hybrid engine. Fuzzy logic controller (FLC) is used to determine proper engine air fuel ratio. Another fuzzy controller is used to control the generator output power.

The controlling variables of the hybrid engine powered car are: $A/F$ ratio for optimum of 15:1 (minimum) and 25:1 (maximum), Vehicle speed of 0-35 km/h (optimum is 30 km/h at 0 degree slope road and 8 km/h at 6.7% gradient), vehicle traction torque: 0-25 Nm (optimum is 20 Nm based on wheel torque, which is equal to the motor shaft torque as the final drive ratio is considered as 1:1), motor output power is optimized as 400 W, which in turn gives 20 Nm shaft torque based on 30 km/h vehicle travelling speed. Engine torque: 0-35, Optimum is 6.45 Nm, optimum engine speed of 4000 rpm with 2.7 kW power to run the generator in order to produce the required current and voltage for powering the DC motors to propel the car. Battery power: 0-500 W, the optimum is 400 W based on 20 A current with 20 V. Generator current: 0-75 amp, generator produces maximum current 56 amps without cooling and 72 amps with cooling to meet the car maximum traction power.

Air-fuel ratio (AF), vehicle speed (VS) and engine traction torque (TW) are used as input parameters and vehicle torque generated from generator (TG) is used as output variable in FLC “Engine”. For fuzzification of these factors the linguistic variables low (L), medium (M)and high (H) are used for the input parameters. Subsequently, the linguistic variables low (L), low medium (LM), medium (M), high (H) and very high (VH) are used for the output. The units of the input and output variables are: AF (%), VS (km/h), TW (Nm) and TG (Nm). For the three inputs and one output, a fuzzy associated memory or decision is formed as regulation rules. The creation of fuzzy rules is mainly depended on expert assessments, empirical analysis, system application, and so on. Subsequently, the rule bases can also be shaped from the neural network model. Total of 27 rules are formed in the cases under consideration. For example, Rule 5 and 15 can be interpreted as follows:

Rule 5: If $A/F = L$ and $VS = M$ and $TW = M$, then $TG = M$, i.e. if the engine’s $A/F$ is low and vehicle speed is medium and engine traction torque is medium, then torque generated from generator is medium.

Rule 15: If $A/F = M$ and $VS = M$ and $TW = H$, then $TG = H$, i.e. if the engine’s $A/F$ is medium and vehicle speed is medium and engine traction torque is high, then torque generated from generator is high.
Fuzzifications of the air-fuel ratio (AF), vehicle speed (VS), engine traction torque (TW) and torque generated from generator (TG) are made by aid follows functions. These formulas are determined by using measurement values.

\[
AF(i_1) = \begin{cases} 
  i_1; & 5 \leq i_1 \leq 20 \\
  0; & \text{otherwise} 
\end{cases} 
\quad (9)
\]

\[
VS(i_2) = \begin{cases} 
  i_2; & 5 \leq i_2 \leq 30 \\
  0; & \text{otherwise} 
\end{cases} 
\quad (10)
\]

\[
TW(i_3) = \begin{cases} 
  i_3; & 5 \leq i_3 \leq 20 \\
  0; & \text{otherwise} 
\end{cases} 
\quad (11)
\]

\[
TG(o_1) = \begin{cases} 
  o_1; & 5 \leq o_1 \leq 25 \\
  0; & \text{otherwise} 
\end{cases} 
\quad (12)
\]

In equations (9-12), \(i_1\) is the first input variable (AF), \(i_2\) is the second input variable (VS), \(i_3\) is the third input variable (TW), and \(o_1\) is the first output variable (TG). Prototype fuzzy sets for the fuzzy variables, namely, air-fuel ratio (AF), vehicle speed (VS), engine traction torque (TW) and torque generated from generator (TG) are set up using MATLAB FUZZY Toolbox.

### 3.3 Prediction of generator current

Results obtained from the engine torque generation of generator can be used thereafter in the fuzzy inference system (FIS) "Generator", which performs the prediction of generator current thus improving the management of power flow of a hybrid engine. In particular, the FIS "Generator" is intended for investigating the already obtained generator torque to assess the possible distribution in road-wheels due to the current transmission. As can be noticed from Figure 2, FIS "Generator" has the generator torque \(T_g\), and battery power \(P_b\) as input variables for calculating the generator current. In accordance with the scheme from Fig. 2, in the second stage the vehicle seeks the value of a certain current generated from the generator (I) during engine operation. In particular, this part performs the generation of current on the basis of:

- Engine torque generated from the generator (torque generation range is 0-35, optimum is 6.45 Nm at the optimum engine speed of 4000 rpm with 2.7 kW power to run the generator in order to produce the required current and voltage for powering the DC motors until zero level of the fuel).
- Battery power (battery power range is 0-500 W, optimum is 400 W based on 20 amp current with 20 V).

Implementation of fuzzy values into the system, torque generation from the generator (TG) and battery power (PB) are used as input parameters and generator current (I) is used as output variable in FIS "Generator". For fuzzification of these factors the linguistic variables low (L), low medium (LM), medium (M), high (H) and very high (VH) are used for the input parameters. Subsequently, the linguistic variables low (L), low medium (LM), medium (M), high medium (HM), high (H) and very high (VH) are used for the output. Similar procedures have been employed for the FIS "Generator". The units of the input and output variables are: TG (Nm), PB (W) and I (amp). Total of 25 rules are formed in the cases under consideration. Fuzzifications of the torque generated from generator (TG), battery power (PB) and generator current (I) are made by aid follows functions. These formulas are determined by using measurement values.
\[ TG(i_{1}) = \begin{cases} i_{1}; & 5 \leq i_{1} \leq 25 \\ 0; & \text{otherwise} \end{cases} \] (13)

\[ PB(i_{2}) = \begin{cases} i_{2}; & 0 \leq i_{2} \leq 100 \\ 0; & \text{otherwise} \end{cases} \] (14)

\[ I(o_{1}) = \begin{cases} o_{1}; & 0 \leq o_{1} \leq 80 \\ 0; & \text{otherwise} \end{cases} \] (15)

where, i and o indicate input and output of the fuzzy variables.

4.0 Result And Discussion

The city car (Figure 3) is developed with hybrid engine model. The car is tested both in laboratory as well as on the road surface at different slope. The engine tank was filled with 100 ml fuel in each test. The engine has been set at the optimum 4000 rpm to run the rotor generator in order to produce the required current and voltage to power the DC motors. In 1st test, the engine was stalled and unable to power the car to accelerate from start. The power deficiency of the generator during starting the car was overcome by using battery power, which, was connected in series with the output of the generator. It was found that the car was started to move from its first starting very smoothly with the power of generator and the additional discharge power of the battery. But the problem was incurred once the engine was at very high speed about 120 km/h. Figures 4-5 show the developed the fuzzy control surface to show the mesh plot of the example relationship between torque generated from generator (TG) and battery power (PB) on the input side and generator current (I) on the output side. The surface shown in the Figs 4 - 5 are the spatial interpretation of fuzzy rules “IF-THEN” for the chosen input and output variables. It shows that as the generator torque and battery power increase, there is concomitant increase in generator current steadily initially and further increase rapidly as expected. The current reaches the apex when the generator torque and battery power both reach their respective maximum level. Hence, all the components contribute significantly towards current generation. Subsequently, it could be noted that the effect is highly significant at the higher level of battery power. In particular, current generation increases with the increase of battery power significantly, although the effect is less prominent at the lower level of generator torque. Thus, proper management of power flow or torque distribution is a critical issue at present in order to obtain energy efficient hybrid engine. The illustration shows that monitoring the output current and improving the control strategy design for the on-board information may lead the hybrid engine car (HEC) as efficient as possible. However, the reliable management of power flows or torque distribution may require the performance analysis of the engine such as engine sizing optimization.

Analytically, it is estimated that the DC motor need to get 360-400 watt to propel the car with speed of 35-45 km/h. Test result shows the hybrid engine able to produce the desired power for the car propelling at 4000 rpm. Figure 6(a) and 6(c) shows that the hybrid can generate the power 504 W at maximum 4000 rpm without the support of battery. Figures 6(b) and 6(d) shows that the hybrid engine was not in problem to generate the required power of the vehicle propelling at operating speed of maximum 4000 rpm. However, the engine was heaped once the speed reach to 5000 rpm and above. Hybrid engine produces 15-20 A to meet the power requirement of the DC motor to propel the car at 35-45 km/h constantly until the fuel supply stop (Figure 7). It is found that the car was propelled 14.3 km (4.6 km by 100 ml fuel, 7.6km by 700 W battery power and 2.1 km by deceleration power).
with the hybrid engine powered. Equivalently for 1 liter of fuel, the car was propelling 57.4 km. The misalignment of the engine with the alternator due to the vibration, the engine was not run at high speed. The engine was heaped which was due to the safety features in the rectification circuit cut off the current supply when the current exceed the predetermine current, in this case 70A at 7000rpm. As the safety circuit activated, it cut the current supply and the voltage drop from 14.8V to less than 3 volt.

![Figure 3. Hybrid engine powered city car](image)

Figure 3. Hybrid engine powered city car

![Figure 4. Control surfaces of the fuzzy inferring system for TG with VS and AF](image)

![Figure 5. Control surfaces of the fuzzy inferring system for TG with TW and VS](image)

Figure 4. Control surfaces of the fuzzy inferring system for TG with VS and AF

Figure 5. Control surfaces of the fuzzy inferring system for TG with TW and VS
Figure 6. Hybrid engine performance
Performance investigation of the has been investigated for the vehicle speed in the range of 30-80 km/h. The result as shows in Figure 7 shows that the vehicle was not in trouble when it was operated with speed of 30-50 km/h. While, the vehicle was in trouble when its accelerated for the speed 60-75 km/h. This is due to the control system of the hybrid engine generator and limited battery power capacity. The discharging capacity and thermal behavior of the battery has been investigate during operation of the vehicle. The result shows in Figures 8(a) and 8(b) shows that discharge current of the battery in the range 60-80 A for the vehicle speed in the range of 30 – 55 km/h. Figures 8(c) and 8(d) battery temperature raised to 39°C for the activation of cooling system and increased to 65°C without activation of cooling system. It could be mentioned that cooling system needs to activate all the way during vehicle operation to maintain the battery life as the lithium ion battery’s recommended temperature would not be more than 50°C.
5. CONCLUSION
Vehicle operation with the hybrid engine power is less efficient than its operated with the fully battery power as the efficiency of the generator is recorded as maximum 70%. The engine power can be increased by adding few extra field diodes and at the neutral point of the generator (Y type) to rectify the un-rectified power. The huge engine vibration causes lot of power transmission losses. With proper alignment of the engine and generator it could be eliminated. Using 100 ml fuel both in laboratory and road experiment tested the vehicle. It was found that the vehicle travelled 4.5 km with the power of 100 ml fuel.

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