

# Look-Ahead Intelligent Energy Management of A Parallel Hybrid Electric Vehicle

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**Abstract**—Improving fuel efficiency in vehicles can reduce the energy consumption concerns associated with operating the vehicles. This paper presents a model for a parallel hybrid electric vehicle. In the model, the flow of energy starts from wheels and spreads toward engine and electric motor. A fuzzy logic based control strategy is implemented for the vehicle. The controller manages the energy flow from the engine and the electric motor, controlling transmission ratio, adjusting speed, and sustaining battery's state of charge. The controller examines the vehicle speed, demand torque, slope difference, state of charge of battery, and engine and electric motor rotation speeds. It then determines the best values for continuous variable transmission ratio, speed, and torque. A slope window method is formed that takes into account the look-ahead slope information, and determines the best vehicle speed. The developed model and control strategy are simulated using real highway data relating to Nowra-Bateman Bay in Australia, and SAE Highway Fuel Economy Driving Schedule. The simulation results are presented and discussed. It is shown that the use of the proposed fuzzy controller reduces the fuel consumption of the vehicle.

**Keywords:** Hybrid electric vehicles, backward modeling, look-ahead fuzzy control system, fuel efficiency.

## I. INTRODUCTION

The demand for petroleum continues to increase whilst oil supplies remain finite [1]. According to a report published in 2006 [2], 80 million barrels of petrol is used per day around the world. The transportation sector consumes 66% of this petrol, and the portion of the land transportation is 56% of this quantity. Consuming this amount of fuel continues to aggravate the economical and environmental concerns around the world.

When it comes to energy utilisation and climate change concerns, cars and trucks are considered one of the principal problems. They consume a large portion of the oil and emit a large amount of greenhouse gas. In response to the impacts of the vehicles on environment and energy security, improving fuel efficiency in vehicles can play a massive role. There exist many techniques to improve the fuel efficiency in vehicles. Over the past few decades, there has been significant development in automobile engine and body technology. Thus, there are little gains achievable in fuel economy through vehicle engine and body. This has resulted in the emergence of innovative technologies for automotive industry. Since pure electric vehicles do not have adequate source of energy for propulsion in relatively long distance ranges, and because their

recharging process requires several hours, hybrid electric vehicles (HEVs) can be considered as a better means of transportation. In comparison with conventional vehicles, fuel economy and reduced emissions have been achieved by HEVs [3-5]. The general concept of a HEV is the combination of an electric drive with an internal combustion engine (ICE), where both engine and motor can work in their optimal operating range.

A HEV is a complex system consisting of many components. The necessary propulsion energy is generated and converted in the component known as powertrain or propulsion system. The ways of arrangement of these components determine the configuration of the powertrain. There are a vast range of feasible configurations for a HEV. Based on the configuration of its powertrain, a HEV can be classified into series hybrid, parallel and series parallel hybrid. In this study, a parallel hybrid electric configuration is considered.

Although HEVs have made it possible to improve fuel efficiency and reduce emissions, considerable energy effectiveness can be achieved also by using driving profile, environmental effects, driving behaviour and control strategy. In this study, a control strategy that takes into account road geometry is developed.

## II. ENERGY MANAGEMENT AND CONTROL IN HYBRID ELECTRIC VEHICLES

The overall performance of a HEV depends on how its individual components are efficiently designed and how the operation of the components is coordinated with each other.

Respectively, the control in HEVs can be classified in two levels: coordinate control and component control. In a HEV, the driver demand via accelerator is translated into power as the input of the coordinate control. Accordingly, the coordinate control system manages the components to achieve certain objectives.

There are two approaches in HEVs coordinate control, heuristic methods and classical optimal methods. The major feature of the former is its success in real-time control. The deterministic rule based control and fuzzy logic control can be classified in the heuristic approaches. The applied rules are designed based on heuristic knowledge of expert and even mathematical model.

Usually the rule based coordinate controllers in HEVs benefit from “load-leveling” concept. This approach is applied by Hochgraf et al. [6]. They used engine, alternator and battery characteristics for determining an appropriate engine control strategy for a series hybrid electric vehicle. Their examination revealed that a load-leveilling strategy applied to the engine would provide better fuel economy than a power-tracking scheme. Their idea became a fundamental for some other works. Jalil et al. [7] defined a rule-based control strategy based on the engineering knowledge. Rule-based control is the foundation of the fuzzy logic which translates linguistic representation of control inputs into numerical representation with membership function in the fuzzification and defuzzification process. The knowledge of expert in controlling the process is expressed in the form of rules. Schouten et al. [8] proposed a fuzzy-logic control system in order to optimise the fuel consumption in a parallel HEV. Accordingly, the power-split strategy through fuzzy rules is formulated to manage the possible ways of power to wheels: (1) only the ICE; (2) only the EM; (3) both the ICE and the EM at the same time; (4) charge the battery, using portion of the ICE power to drive the EM as a generator and using the remainder power to drive the wheels; and (5) regenerative braking by slowing down the vehicle and letting the wheels drive the EM as a generator that provides power to the battery.

Despite the fact that, the applied controllers have enhanced the fuel efficiency the effects of in-advance information from the road has not been used in the existing works. Thereafter, we will show how real road data can be applied in a HEV model, and the impact of in-advance knowledge of road slope on fuel economy will be investigated.

### III. PARALLEL HYBRID ELECTRIC POWER TRAIN

HEVs usually consist of two sources of energy. In order to achieve the part of energy which in conventional vehicle is wasted in the form of heat, the electrical part of drive train has bidirectional energy sources and converters. In a parallel hybrid electric vehicle (PHEV), the engine supplies the mechanical power to the wheels and generator during the charge of battery. The power can be supplied by only electric motor to the wheels, or engine can be assisted by the electric motor. The engine and electric motor are coupled together by mechanical coupling. A configuration and power flow in a PHEV is illustrated in Fig. 1.

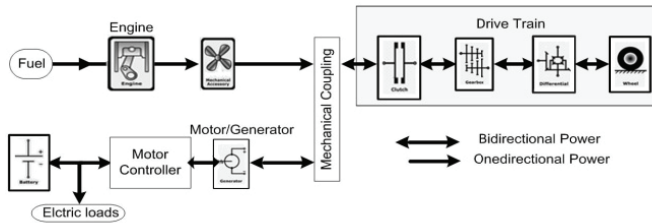


Figure 1. Parallel hybrid vehicle configuration and power flow diagram.

For a given HEV and road, the speed and torque at the output of mechanical coupling for providing the required force in the wheels can be calculated from the forces acting on vehicle.

The various longitudinal forces in a vehicle are expressed as acceleration, rolling, gravitational and drag. Accordingly, the traction force,  $F_{tr}$  is derived from the equation of solid body motion in the following form:

$$F_{tr} = M\dot{v}(t) + C_{rr}Mg\cos\alpha + Mg\sin\alpha + \frac{1}{2}C_D A\rho(v(t) + v_w(t))^2 \quad (1)$$

where the traction force parameters are listed in Table I.

TABLE I. TRACTION FORCE PARAMETERS

|                  |                       |                    |
|------------------|-----------------------|--------------------|
| M vehicle mass   | $C_{rr}$ rolling Coe. | $C_D$ drag Coe.    |
| v vehicle speed  | g gravitational acc.  | A frontal area     |
| $v_w$ wind speed | $\alpha$ road slope   | $\rho$ air density |

Equation (1) describes the dynamic of vehicle, and determines the amount of power that can be provided by the two sources of energy, battery and petrol. In the quasi-static HEV model, the engine can be modeled by the efficiency map model. The engine model is described by the following equation and Fig. 2.

$$\eta_{ice} = \frac{P_m}{P_{ch}} = \frac{P_m}{\dot{m}(T_{m,\omega}) Q_{lhv}} = \frac{3600 \times 10^3}{Q_{lhv} BSFC(T_{m,\omega})} \quad (2)$$

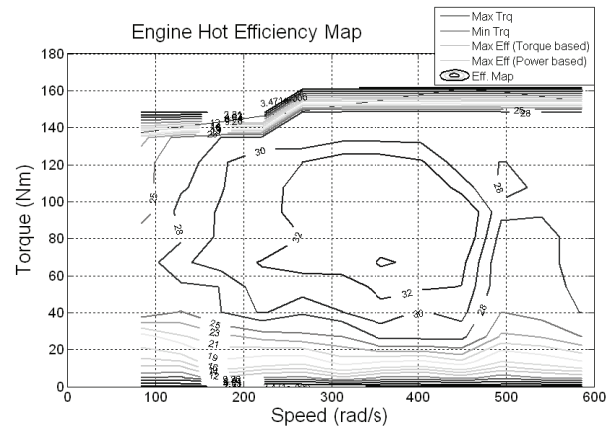


Figure 2. Engine efficiency map.

where  $\eta_{ice}$  is the engine efficiency, which is a function of internal combustion engine torque and crankshaft rotational speed,  $P_m$  is the mechanical power at the crankshaft,  $P_{ch}$  is the delivered mechanical power to the engine, and  $Q_{lhv}$  [J/g] is chemical energy of fuel which is defined as “the amount of heat released by combusting a specified quantity (initially at 25 °C or another reference state) and returning the temperature of the combustion products to 150 °C”. Typically,  $Q_{lhv}=42.5$ [kJ/g] for petrol [9].

Similar to the engine efficiency map, there exists an efficiency map for an electric machine (EM) which presents empirical data of its efficiencies as a function of torque and speed. These efficiencies can be presented as contours on a torque-speed map. The applied motor/generator efficiency map in this study is illustrated in the Fig. 3.

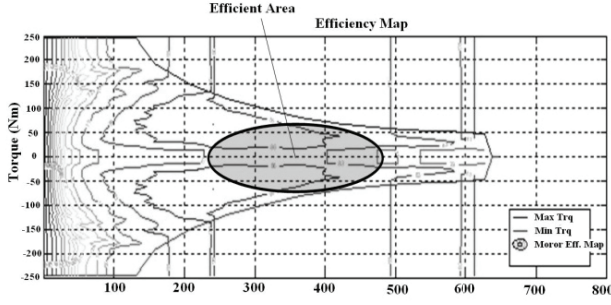


Figure 3. Efficiency map of a 33 kW (peak power) induction AC motor.

The input-output power in EM can be calculated as follows:

$$P_{in}(t) = V(t)I(t) \quad (3)$$

$$P_{out}(t) = T_{em}(t)\omega_{em}(t) \quad (4)$$

$$\eta_{em}(T_{em}(t), \omega_{em}(t)) = \frac{P_{out}(t)}{P_{in}(t)} \quad (5)$$

Where  $I$  is the EM input current in ampere,  $V$  is the input voltage in volt, and  $\eta_{em}$  is the EM efficiency. As presented in Fig. 3, according to the speed and the torque, there is an efficient area. Respectively, EM should be controlled to operate in this region. Consequently, in order to obtain the maximum efficiency when we are using the engine to charge the battery, the optimal speed range is considered in the applied fuzzy controller of this study.

Many types of battery have been modeled thus far. An overview of the battery models is available in literature [10]. Typically used batteries in HEVs are the lead acid and the Nickel metal batteries. In our modeling, we used the introduced lead acid model in [11].

#### IV. POSITIONING METHOD

In the proposed model, the drive train is represented by using the backward looking method. An overview of the different approaches in HEV modelling is available in literature [12]. A desired speed is fed to the longitudinal block. The desired speed can be a constant speed as the input of a conventional cruise control or a variable speed. The variable speed can be a drive cycle, an optimiser output or an adaptive cruise controller output [13]. We consider that the origin and destination of travel is known in advance and its information can be obtained from GIS. In order to simplify the problem, the road points are considered in a plane in two dimensions,  $x$  and  $y$  (distance and altitude) [14]. From the variation of altitude and distance, the slopes are determined for the entire path.

Assume that a moving vehicle at time  $t$  is at place  $\vec{x}_1(t)$  and its velocity is  $\vec{v}_1(t)$ . The position vector between two consequent points can be calculated from following relation:

$$\vec{r}_1(t) = \vec{x}_1(t + \Delta t) - \vec{x}_1(t) \quad (6)$$

where,  $\vec{x}_1$  is the position vector in the  $x$ - $y$  coordinates. The distance between two consequent points can be written as:

$$s_i(t) = \|\vec{x}_1(t + \Delta t) - \vec{x}_1(t)\| \quad (7)$$

where  $\|\cdot\|$  represent the norm of the specified vector.

The direction toward the forward point can be easily calculated from the following equation:

$$\vec{e}_i(t) = \frac{\vec{x}_1(t + \Delta t) - \vec{x}_1(t)}{\|\vec{x}_1(t + \Delta t) - \vec{x}_1(t)\|} \quad (8)$$

The velocity,  $\vec{v}_i(t)$  can be found as follow:

$$\vec{v}_i(t) = \frac{s_i(t)}{\Delta t} \vec{e}_i(t) \quad (9)$$

Therefore, instantaneous velocity has two orthogonal terms in vertical and horizontal directions whose scalar can be presented in the following form:

$$v_x(t) = \left\| \frac{s_i(t)}{\Delta t} \vec{e}_i(t) \right\| \cos \alpha(t) = \|\vec{v}_i(t)\| \cos \alpha(t) \quad (10)$$

$$v_y(t) = \left\| \frac{s_i(t)}{\Delta t} \vec{e}_i(t) \right\| \sin \alpha(t) = \|\vec{v}_i(t)\| \sin \alpha(t) \quad (11)$$

where  $\alpha(t)$  is the instantaneous slope angle between the direction vector,  $\vec{e}_i(t)$  and  $x$  axis, and can be calculated from following relation:

$$\alpha(t) = \tan^{-1} \left( \frac{y(t + \Delta t) - y(t)}{x(t + \Delta t) - x(t)} \right) \quad (12)$$

A moving average method is used, and the samples are averaged to estimate the future slopes. With the movement of vehicle in each meter, a new sample is entered to the look-ahead window and the oldest sample is eliminated from the sampling space (see Fig. 4).

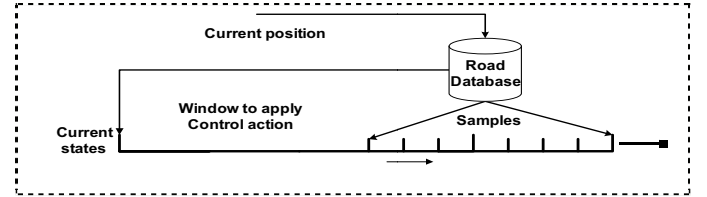


Figure 4. Look-ahead slope window.

$$\alpha(look_{ahead}) = \frac{\sum_{k=1}^n (\text{sampled date})}{n} - \frac{\text{oldest sample}}{n} + \frac{\text{new sample}}{n} \quad (13)$$

As in the backward facing model, the flow of energy starts from wheels and spreads toward ICE and EM. This facilitates the necessary calculations.

#### V. LOOK-AHEAD FUZZY LOGIC CONTROLLER

This section presents the proposed control strategy and the fuzzy controller, whose rules are based on the empirical knowledge of the expert, which is developed in this study. The main objectives of the controller are to manage the energy flow between ICE and EM, control the transmission ratio, adjust the optimal speed and sustain the battery state of charge (SOC) at an optimal level. The advantage of this system is its robustness, since it is tolerant to imprecise measurements and component variations. The fuzzy rules can be easily tuned, if required, therefore adaptation is an additional benefit of this controller. The main idea behind the fuzzy-logic controller is to employ logic-based control strategy. The look-ahead control is a strategy that relies on logical reasoning of how the vehicle should behave in certain circumstances.

In this paper, it is assumed that the environment is represented by the road slope. The longitudinal forces on a vehicle, “(1)” is associated with road slopes. Since the required propulsive energy is provided by ICE, EM or both using the road slope, making intelligent decisions can improve the fuel economy.

The operation of the modeled PHEV based on the controller commands can be electric only, engine traction, hybrid propulsion, regenerative braking and battery charging using the energy due to gravity. The controller acts such that the required torque is always met. Control in HEVs can be divided in two levels: coordinate control and components control. The coordinate controller (CC) is at the higher level and should manage the lower level controllers such as ICE controllers, EM controller, speed controller, mechanical brake controller and battery SOC controller. The inputs to CC are the demand torque, the difference between the existing slope and the future slope, SOC, the engine speed, the motor speed, and the resistive force.

From the stand point of the control problem, it is desired to find such control outputs that optimize the fuel consumption. In the proposed CC, there are inputs such as future slope, vehicle speed, demand torque, SOC, rotational speed and resistive force. From the expert knowledge, it is known that fuel saving can be made during uphill or downhill. During moderate uphill travel, vehicle loses speed and engine works in its inefficient region. During downhill travel because of the gravity, the acceleration of vehicle will increase. An expert driver will speed up before an uphill and slow down before a downhill drive. Therefore, driving can be classified into three main states: driving on level, uphill or downhill roads. This classification is not crisp (or precise) and can be best modeled using fuzzy logic. Therefore, the difference of current slope and the calculated one from the look-ahead slope estimator is considered as an input to CC. With respect to the engineering considerations of the road structure, and in order to generate the geographical fuzzy set of the road, the linguistic interpretation of slope is considered from a very high negative (-30%) to a very high positive (30%) slope. Based on the variation of this input, the controller output is the speed that manipulates the current speed with respect to the future slopes. The range of operation is from -10 to 10 km/h.

The design criteria for controlling the power split between ICE, EM and charging of battery is based on the efficiency maps. In other words, ICE and EM are confined to operate in the high efficiency area of the map. The inputs to the controller such as demand torque, shaft rotational speed and resistive force are converted to fuzzy values. These fuzzified inputs are demonstrated in Fig. 5. The fuzzy logic controller maps the inputs to the outputs with a set of logic rules. Fuzzy control rules are characterized as a collection of fuzzy IF-THEN rules whose conditions and consequences involve linguistic variables. The IF-part of the rules refers to attributes that express fuzzy set of the input variables. A particular input value, which belongs to this set to a certain degree, is demonstrated by the degree of membership. For instance, the membership functions that define the degree of membership of the speed are Pi functions. They determine the degree of memberships to the fuzzy set, from very low speed to very high speed. The defined membership functions for road slope are Gaussians which show the degree

of membership to the fuzzy set from very steep down to very steep up. Fuzzy speed is considered from zero speed to very high speed (150 km/h). Taking into consideration the linguistic representation of all of the numerical inputs, the fuzzifications which have been done are illustrated in Fig. 5.

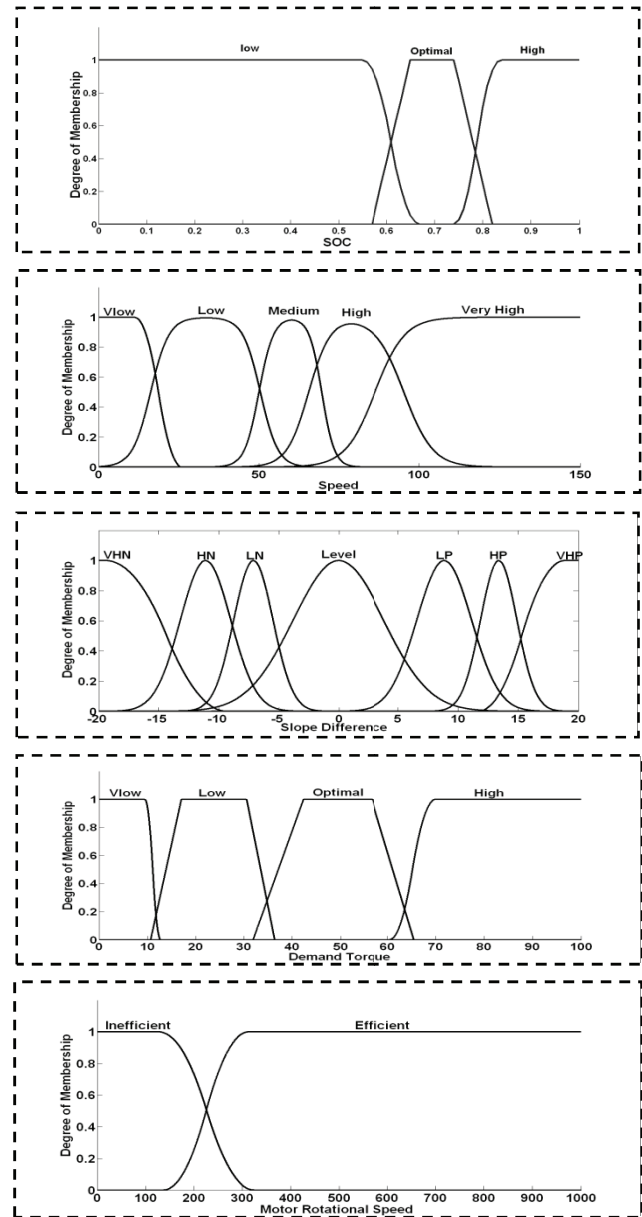


Figure 5. Input membership functions.

The THEN-part of the rules of the controller refers to the values of the output variable. To achieve the output of the controller, the degrees of membership of the IF-parts of rules are evaluated, and the THEN-parts of the rules are weighted by these degrees of membership. For example, in the membership functions that define this degree of membership for the input speed are Pi functions which establish the degree of membership to the fuzzy set, from very high shift to low shift. We implemented the most frequently used method generally known as the Mamdani's minimum operation [15]. In this

method, if the inputs are fuzzy singletons,  $A'=u_0$  and  $B'=v_0$ , then the results  $C'$  can be obtained from the following relation:

$$\mu_{C'}(w) = \bigvee_{i=1}^n [\mu_{A_i}(u_0) \wedge \mu_{B_i}(v_0)] \wedge \mu_{C_i}(w) \quad (14)$$

In order to obtain a crisp control output from an inferred fuzzy inference engine, the most common method called the centroid area is used:

$$Z_{COA} = \frac{\int_z \mu_C(z) Z dz}{\int_z \mu_C(z) dz} \quad (15)$$

where  $Z$  is the output from the given inputs and their fuzzy relation, and  $\mu_C(Z)$  is the aggregated output membership function. For instance, the crisp output of the fuzzy controller to the adaptive cruise controller increases the vehicle speed before an uphill or decreases it before a downhill. The extended or diminished speed is proportional to the fuzzified angle of slope.

For the engine considered in this model, from the ICE efficiency map, the optimal operation of engine occurs from the rotational speed of 250 rad/sec to 400 rad/sec and torque of 45 Nm to 60 Nm. Maintaining the crankshaft rotational speed in the efficient section can be achieved by the gear ratio transmission which is controlled by the controller according to the fuzzified vehicle speed. EM can be used as a load regulator to sustain ICE in the efficient torque area. Since there are two stages in the energy conversion, EM should be controlled to operate in the efficient speed range. This matter has been considered in the control strategy so far. When we are using the regenerative braking, or the energy from the gravitational force, SOC is the only parameter which is considered. During battery's charging and discharging, the efficiency of the battery can be defined as:

$$\eta_{\text{discharge}} = \frac{V}{V_o} \quad (16)$$

$$\eta_{\text{charge}} = \frac{V_o}{V} \quad (17)$$

where  $V$  is the cell operating voltage, and  $V_o$  is the thermodynamic voltage. In the discharging mode, a higher efficiency is obtained in high SOC, and in the charging mode, a higher efficiency is obtained in lower SOC. Enhancing net cycle efficiency and considering the state of health of battery, the fuzzy controller controls the battery in its middle SOC range of 0.6 - 0.8.

Beside the shift ratio and adaptive speed, the engine torque is the other output of the fuzzy controller. The membership functions of the fuzzy outputs are shown in Fig. 6.

If the vehicle speed is very low, or the demand torque is very low, SOC will be examined. If SOC is in its normal condition, the vehicle will work in electric only mode. The negative resistive force and brake will also be examined, and with the condition of SOC less than 0.8, the battery will be charged. Because of the certainty in these situations, regenerative braking and electric only mode of operation of the HEV have been controlled with crisp rules. For the other states of the fuzzy controller outputs, the engine is maintained in its optimal operation mode. Correspondingly, the fuzzy controller rules are performed. For instance, when SOC is not high and the

demand torque is low and the motor rotational speed is efficient, the engine is controlled to deliver optimal torque, EM will be controlled to work in the generator mode, and the difference between the engine torque and the demand torque will be used in the generator to produce electrical energy. The produced electrical energy will be stored in the battery.

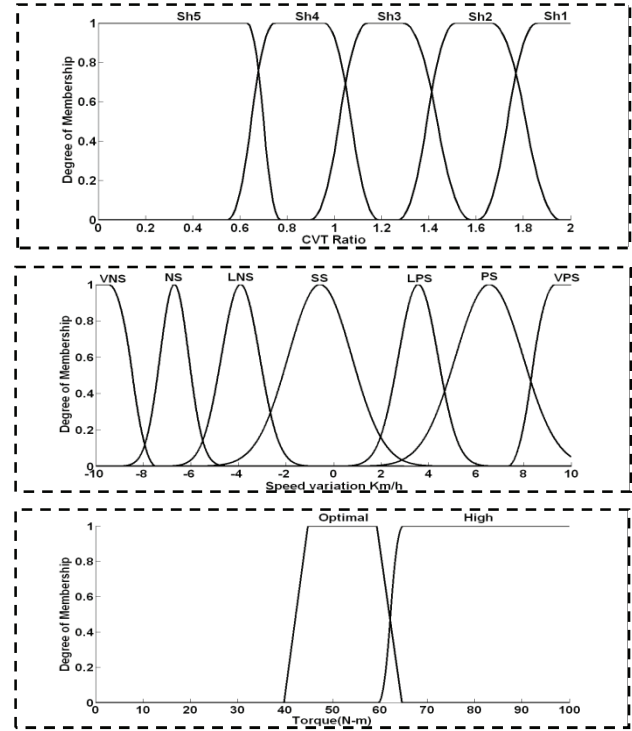


Figure 6. Output membership functions.

## VI. SIMULATION AND RESULTS

The described controller and the PHEV are modeled in SIMULINK. The recommended Highway Fuel Economy Driving Schedule (HFEDS) by SAE J1711 standard [16] and real road data are applied to evaluate the proposed model.

To present the simulation results, the information of a highway, 50km of Nowra-Bateman Bay in Australia, is implemented in the model. The Cartesian coordinate's of the data is presented in Table II.

TABLE II. REAL CARTESIAN COORDINATES FOR NOVARA TO BATMAN BAY, AUSTRALIA

| Road location    | DIST<br>D(km) | EAST<br>X(km) | NORTH<br>Y(km) | ALT<br>Z(km) |
|------------------|---------------|---------------|----------------|--------------|
| R[1,10,C1,0.009] | 0.0085        | 9687.63       | 4421.904       | 0.0155       |
| R[1,10,C1,0.019] | 0.0188        | 9687.599      | 4421.895       | 0.0158       |
| R[1,10,C1,0.029] | 0.0291        | 9687.596      | 4421.885       | 0.0162       |
| R[1,10,C1,0.039] | 0.0386        | 9687.592      | 4421.876       | 0.0164       |

Accordingly, the slope is calculated based on the rate of change in altitudes of distances. The graph of the used slope data is demonstrated in Fig. 7.

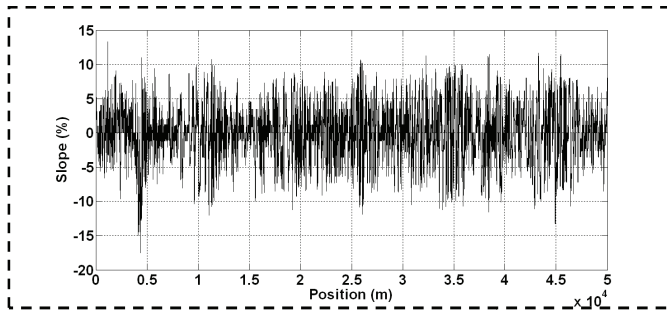


Figure 7. Slope of highway.

The use of real road data in the model distinguishes this approach from the former ones which use only the drive cycle and a constant grade. In order to evaluate the model and its fuzzy controller, simulation is run through the highway fuel economy test (HWFET). Three circumstances are considered: look-ahead information and adaptation the speed based on the future slope on the applied drive cycle, fuzzy controller with the applied drive cycle, and the default control strategy in PSAT [17]. As can be seen from the operating points of the engine on the efficiency map, which are presented in Fig. 8 for the first controller, the operation points are more controlled in the efficient area than the second and the third controllers. It means that the fuzzy controller with adaptive cruise control leads a better fuel consumption than the other controllers. Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

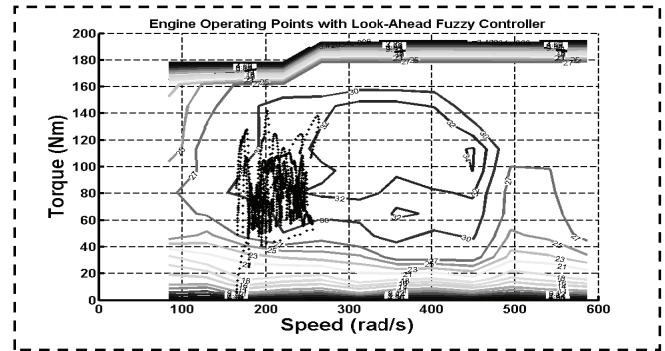
The results of the proposed controller in comparison with the other controllers, from the standpoint of fuel economy are summarised in the Table III.

## VII. CONCLUSIONS

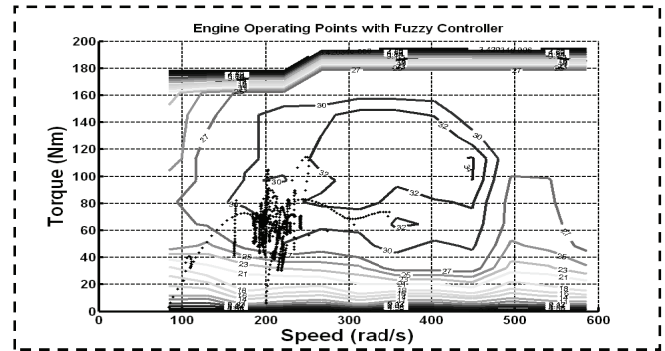
This paper presented an approach for PHEV modelling based on the real road geographical data. From the model, the dynamic position of vehicle is achievable. The applied method uses a combination of the calculated data (distance, altitude and slope) and the static information from GIS. Instantly, the calculated data is compared with the road geographical information (length and altitude). The instantaneous position and slope are extracted. The new information is applied to determine various longitudinal forces, rolling resistance, gravitational and aerodynamic drags. The future states for a look-ahead window are extracted. Accordingly, a moving average calculator is implemented to estimate the future slopes. The deference between future and instant slopes is expressed as a fuzzy value which is applied to a fuzzy controller. The control output from the fuzzy inference engine is the amount of speed change with respect to the alteration of slope ahead. The control output is added to the reference speed which is the HWFET drive cycle.

Considering the optimal operation of ICE, EM and SOC of battery, the fuzzy controller commands PHEV to achieve optimal fuel consumption. Simulations were carried out. The results show that good improvements on fuel consumption (6%)

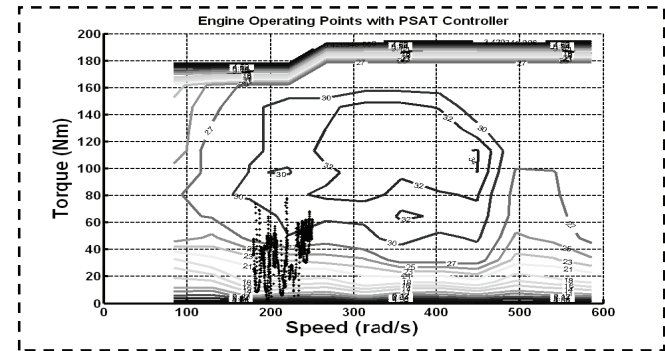
in comparison with the PSAT default controller. The comparison has been done with the fuzzy controller without look-ahead information, where fuel saving of 2.62% was recorded.



(a)



(b)



(c)

Figure 8. Engine operation points on the efficiency map. (a) Look-ahead fuzzy controller. (b) Fuzzy controller. (c) PSAT default controller.

TABLE III. FUEL CONSUMPTION FOR THREE SIMULATION MODE

| The simulated model with HWFET drive cycle               | FC<br>(lit/100km) |
|----------------------------------------------------------|-------------------|
| PHEV with look-ahead fuzzy controller and real road data | 4.83              |
| PHEV with fuzzy controller and real road data            | 4.96              |
| PHEV in PSAT with its default control strategy           | 5.14              |

## ACKNOWLEDGMENT

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