International Review on Modelling and Simulations (I.RE.MO.S.), Vol. 3, N. 5
October 2010

A Powertrain Vehicle Model for Look-ahead Control

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Abstract – *This paper presents a powertrain model for a vehicle taking into account the impact of trajectory specifications. The model enjoys a quasi-static approach with a backward facing method. The key feature of the model is its presentation of the dynamic of the vehicle based on the road information. This ability makes the method suitable for use in look-ahead energy management and fuel economy optimal control problems. In order to maintain the operation of the combustion engine near its efficient region, a fuzzy control system with a continuous variable transmission is applied. Simulations are carried out using real road data. The results are presented and discussed.* **Copyright © 2010 Praise Worthy Prize S.r.l. - All rights reserved.**

Keywords: *Powetrain vehicle modeling, quasi-static backward facing, fuzzy logic, simulation*

Nomenclature

Roman symbols

A	Car frontal area
C_D	Drag coefficient
C_{rr}	Rolling coefficient
f_r	Final drive ratio
F_{accl}	Acceleration force
F_{grav}	Gravitational force
F_{roll}	Difference between friction forces and rolling forces
F_{tr}	Net traction force
g_r	Transmission ratio
M	Vehicle mass
P_{ch}	Extracted chemical power from tank
v	Vehicle speed

Greek symbols

α	Road slope
η	Transmission and torque converter
η_f	Final drive efficiency
η_{ice}	Internal combustion efficiency

I. Introduction

Vehicles produce emissions which pollute the air and negatively impact our environment. Improving fuel efficiency in vehicles can play an important role in alleviating their emissions and the associated environmental impacts. There exist several techniques for improving fuel efficiency in vehicles including:

i. Down weighting: Without compromising safety and performance, some steel parts of the vehicle can be replaced with light and high strength materials.
ii. Reducing rolling resistance: Using efficient tyres, rolling resistance can be reduced.
iii. Reducing aerodynamic resistance: Employing the vehicle shapes with less aerodynamic drag can reduce the wind resistance and, thus fuel consumption.
iv. Downsizing engine: Using a smaller engine, which tend to work closer to its optimal operation region, would reduce fuel consumption.
v. Choosing advanced transmission technology: Utilizing new transmission technologies improves the efficiency and, hence diminishes fuel consumption.
vi. Increasing electrification: Using advanced battery technology leads to vehicles that can run accessories without dragging power from crankshaft and, consequently the battery can be recharged in lower load conditions helping engine operate efficiently.
vii. Advanced drivetrain: Using two sources of energy in hybrid electric vehicles and storing the brake energy causes an improvement on fuel economy.

Over the past few decades, there has been significant development in vehicle engine and body technologies. Therefore, it would be challenging to achieve major gains in fuel economy through modifications of the vehicle engine and body. However, the advent of modern control strategies and the growing environmental concerns associated with vehicles provide new opportunities to enhance fuel economy of vehicles. For example, an advanced automatic transmission can offer a greater control of the engine. Additionally, the combination of road information and fuzzy control system can enable the engine to operate more efficiently over a wider variety of speeds. To improve fuel economy, a method is presented in this paper which incorporates the stated advantages in a model developed for a vehicle.

Simulation and computer modeling approach can be employed to decrease the expense of a product from design to prototyping and mass production. Improving fuel economy, performance and drivability in vehicle design has increased the number of the simulation tools either in commercial divisions or in academic communities. Several simulation tools such as simple electric vehicle simulation (SIMPLEV) [1] from the DOE's Idaho National Laboratory, MARVEL and PSAT [2] from Argonne National Laboratory, CarSim [3] from AeroVironment Inc., ADVISOR [4] from the DOE's National Renewable Energy Laboratory, Vehicle Mission Simulator [5], and others [6] have been developed to model the operation of conventional and hybrid electric vehicle powertrains. In all these software tools, the driver demand in vehicle simulation tools is determined by "drive cycle". Drive cycle specifies the vehicle speed in a predefined pattern. Road slope is defined by a constant grade in the model. Among the software tools, ADVISOR and PSAT are more popular than the others. ADVISOR is a backward facing program in which the direction of calculation of tractive effort starts from wheels and move toward engine [4, 7]. Backward model is faster in term of simulation time. PSAT, on the other hand, is a forward looking simulator which models a vehicle in the same way a real vehicle works, where the calculation direction starts from driver demand. Forward looking modeling can to be used as a hardware-in-the-loop/software-in-the-loop testing program [2]. One of the issues with the existing software tools is that their modification to incorporate different control strategies such as optimal control methods is not simple. Furthermore, in real circumstances under different loads such as wind and road slope, these programs are not very effective.

Driving behavior, driving pattern, and road topology affect the fuel consumption of a vehicle. From the standpoint of energy management and optimal flow of energy, the knowledge about disturbances relating to driving route, traffic and road geometry can help in the development of a suitable strategy. Such a strategy is known as look-ahead control or look-ahead energy management. The look-ahead control is a "predictive control scheme with additional knowledge about some of the future disturbances on the road topography ahead of the vehicle" [8]. Developing a control algorithm, using look-ahead information, allows planning how and when to speed up and slow down the vehicle.

Our study aims to introduce a powertrain simulation model considering the impact of trajectory specifications. Also, to maintain the operating point of the engine near its optimal operating region, a fuzzy controller is developed to control a continuously variable transmission (CVT). The presented model is suitable for energy management and can be implemented with a control model to decide on the control variables.

II. Quasi-static model

Vehicle is a complex dynamic system consisting of many individual components. When the interaction of the vehicle with its environment is considered, it seems that no model can describe precisely the entire behavior of its powertrain. A quasi-static model is presented in this paper to address this issue. Although, the accuracy of a quasi-static model might be generally limited, it can be sufficiently accurate for describing the flow of power in powertrain. The name of quasi-static is from the stand point of quasi-static maps which is used to describe the process of energy conversion in the engine. In electric hybrid vehicles, this term is applied for electric motor and battery as well. To illustrate the model structure in the following sections, a drivetrain and its modules are described.

II.1. Quasi static-modeling approach

In most vehicles, power is generated by an internal combustion engine (ICE), and through powertrain in a forward direction delivered to the wheels, and driver controls the vehicle speed. In the modeling of powertrain, the combination of driver and powertrain can be described in two methods: forward and backward. In the forward method, flow of power is similar to a real vehicle. The throttle position is commanded by driver. Accordingly, torque is produced in the ICE and through drivetrain flows to wheels. Based on the provided torque in wheels, vehicle achieves a certain speed. A forward model is more accurate, but has a high level of complexity. In contrast, a backward model is less accurate but also has less complexity. In this model, a specified speed profile is given to the wheels, and the operating point is calculated. Because of the dynamic behavior of the individual component, the model becomes less accurate. However, due to the fact that the fuel economy is determined by energy flow, this model is sufficient to calculate the flow of energy in powertrain and can be used in fuel economy analysis and powertrain optimal control problems. Power flow in a vehicle is demonstrated in Fig. 1.

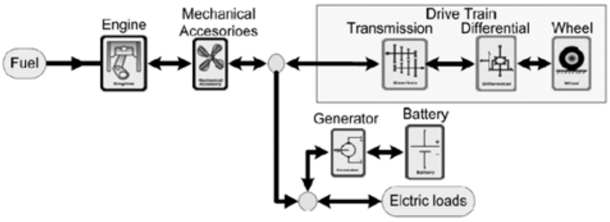


Fig. 1. Power flow diagram in a vehicle

In order to describe the relation between the speed and the required power in powertrain, each component is described by quasi-static/static in our model. The vehicle technical characteristics applied in this model are illustrated in Table 1.

II.2. Drivetrain

Drivetrain in a vehicle consists of the ICE, clutch or torque converter, transmission, final drive, wheels, and inertia. For a given vehicle and a road, the engine speed and torque for providing the required force in the wheels can be calculated from the forces acting on vehicle.

TABLE I
VEHICLE PARAMETERS FOR THE SIMULATION MODEL

Description	Symbol	Value	Unit
Vehicle mass	M	1470	kg
Continuously variable transmission	$g_r(t)$	[0.5 2.5]	-
Wheel radius	r_w	0.305	m
Rolling resistance	C_{rr}	0.01(1+V/100)[1]	-
Air drag coefficient	C_D	0.15	-
Final drive ratio	f_r	4	-
Air density	ρ	1.2	kg/m^3
Gravity	g	9.8	m/s^2
Frontal Area	A	2.2	m^2

[1] V is the vehicle speed in km/h for the speeds of up to 128 km/h [9]

The longitudinal forces in a vehicle are expressed as acceleration, rolling, gravity and drag and defined by the following equations:

$$F_{accel}(t) = M\dot{v}(t) \tag{1}$$

$$F_{roll}(t) = c_{rr}MgCos\alpha \tag{2}$$

$$F_{grv}(t) = MgSin\alpha \tag{3}$$

$$F_{drg}(t) = \frac{1}{2}c_D A(v(t) + v_w(t))^2 \tag{4}$$

Accordingly, the traction force, F_{tr} is derived from the equation of solid body motion in the following form:

$$F_{tr} = M\dot{v}(t) + c_{rr}MgCos\alpha + MgSin\alpha + \frac{1}{2}c_D A(v(t) + v_w(t))^2 \tag{5}$$

This equation is called longitudinal equation and describes the dynamic of the vehicle. F_{tr}, the traction force in the contact area of wheels and road surface, forces the vehicle forward.

Simplifying the model, considering the constant efficiencies at final drive (η_f), transmission and torque converter (η), the torque at the crankshaft can be calculated from the following equation:

$$T_m(t) = \frac{r_w}{f_r}\frac{1}{g_r(t)}\frac{1}{\eta_f\eta}F_{tr} \tag{6}$$

And the engine rotational speed is given by:

$$\omega(t) = \frac{f_r}{r_w}g_r(t)v(t) \tag{7}$$

Propulsion required power at crankshaft is given by:

$$P_m = \omega(t)\, T_m(t) \tag{8}$$

The power at crankshaft is provided by the ICE. In passenger cars, there exist two well known ICE types: spark ignition (SI) engines using petrol, and compression ignition (CI) engines using diesel. For simplicity, an energy based engine model by neglecting the dynamic behavior and temperature dependency, as explained in the following section, is considered.

II.3. Internal combustion engine

The engine converts fuel and air through an exothermic chemical reaction into heat and work. In a quasi-static model, the ICE is expressed as the relationship between its operating point and fuel consumption. The engine speed ω and the engine torque Tm [11] in crankshaft define the operating points. The mass flow rate of fuel $\dot{m}(Tm, \omega)$ [g/s] usually obtained from the empirical data which are measured on an engine test-bench. All measured data from different operating points accumulate into a look-up-table. In this way a quasi-static map is created. The fuel maps are often represented in term of brake specific fuel consumption (BSFC) which mathematically is expressed as follows:

$$BSFC(T_m, \omega) = \frac{\dot{m}(T_m,\omega)}{P_m} \times 3600 \times 10^3 \ \left[\frac{g}{kWh}\right] \tag{9}$$

P_m is the output mechanical power of engine. The engine map for the employed vehicle in this study is presented in Fig.2.

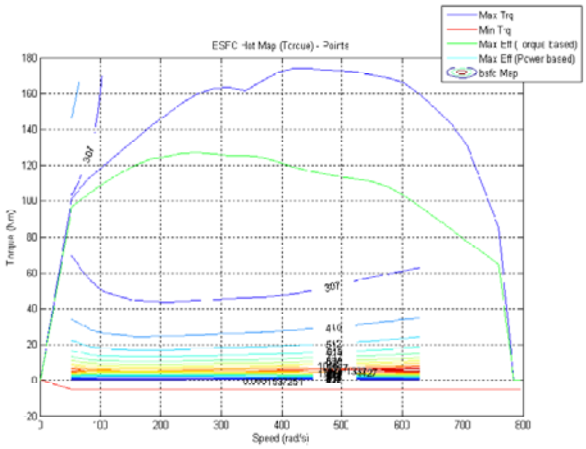


Fig. 2. The BSFC hot map based on torque

The efficiency of ICE (η_{ice}) is inversely proportional to the BSFC. This is shown in the following equation:

$$\eta_{ice} = \frac{P_m}{P_{ch}} = \frac{P_m}{\dot{m}\,(T_m,\omega)\, Q_{lhv}} = \frac{3600\times10^3}{Q_{lhv}BSFC(T_m,\omega)} \tag{10}$$

P_{ch} is the delivered mechanical power to the engine, and Q_{lhv} [J/g] is the chemical energy of fuel 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". Q_{lhv}=42.5 [kJ/g] is for petrol [10]. It means that the carried energy by each gram of fuel is 42.5 [kJ].

II.4. Transmission model

There are three types of transmission: manual, hydrodynamic, and continuously variable transmission (CVT). A manual transmission consists of a clutch and a gearbox. The gearbox provides a number of gear ratio. The gear ratio is usually less than 1 after shift 3. In other words, the maximum ratio is in the lowest gear and smallest ratio is in the highest gear. From the lowest to highest shift, ratios should be placed to provide "the tractive effort-speed characteristics as close to the ideal" [11].

In normal driving according to the vehicle speed, the selected gear ratio between the highest and the lowest gears should act such that the operating point of the engine remains near its efficient area. This approach affects the fuel economy and improves the performance of the vehicle. Usually, better combustion quality and maximum torque are reachable around the middle engine speed [9].

Hydrodynamic transmission consists of a torque converter (TC) and an automatic gearbox. The main function of the TC is to provide sufficient torque during vehicle feed and also to prevent fluid damping that causes torque fluctuation in drivetrain. Investigation of advantages and disadvantages of the hydrodynamic transmission is beyond the aim this study, and the reader is referred to reference [9].

A CVT is a transmission with infinite number of ratios between two limits which allows the combustion engine to operate near its optimal speed range. It benefits from smooth step shifting that provides better drivability in comparison with traditional automatic and manual transmissions [12, 13]. There are three types of the CVT: electrical, hydraulic and mechanical. Due to better performance, noise level, size and cost, mechanical CVTs are more attractive. Among different types of mechanical CVTs, variable pulley is more common than the variable stroke and traction drive [14].

In the following, it is demonstrated that the operation of a CVT with a fuzzy controller can give tractive effort characteristics almost near ideal. The stated components, the mathematical relations and the road database from GIS are used together to form the proposed model.

III. Proposed Model

In the proposed model, the drivetrain is represented by the backward looking method. The desired speed can be a constant speed as the input of a cruise control or a variable speed. The variable speed can be a drive cycle, an optimizer output or an adaptive cruise controller output [15]. We consider that the origin and destination of travel is known in advance and its information can be obtained from a global positioning system (GIS). In order to simplify the problem, the road points considered in a plane in two dimensions, x and y (distance and altitude). From the variation of altitude and distance, the slopes are determined for the entire path.

A moving vehicle at time t is at place $\overrightarrow{x_\iota}(t)$ and the velocity is $\overrightarrow{v_\iota}(t)$. The position vector between two consequent points can be calculated from following relation:

$$\vec{r}_i(t) = \overrightarrow{x_\iota}(t+\Delta t) - \overrightarrow{x_\iota}(t) \qquad (11)$$

where $\overrightarrow{x_\iota}$ is the position vector in the x-y coordinates. The distance between two consequent points is:

$$s_i(t) = \|\overrightarrow{x_\iota}(t+\Delta t) - \overrightarrow{x_\iota}(t)\| \qquad (12)$$

where || || represent the norm of the specified vector. The direction toward the forward point can be easily calculated from the following equation:

$$\vec{e}_i(t) = \frac{\overrightarrow{x_\iota}(t+\Delta t) - \overrightarrow{x_\iota}(t)}{\|\overrightarrow{x_\iota}(t+\Delta t) - \overrightarrow{x_\iota}(t)\|} \qquad (13)$$

The velocity, $\overrightarrow{v_\iota}(t)$ can be found as follows:

$$\vec{v}_i(t) = \frac{s_i(t)}{\Delta t}\vec{e}_i(t) \qquad (14)$$

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

$$v_x(t) = \left\|\frac{s_i(t)}{\Delta t}\vec{e}_i(t)\right\| \mathrm{Cos}\alpha(t) = \|\vec{v}_i(t)\|\mathrm{Cos}\alpha(t) \quad (15)$$

$$v_y(t) = \left\|\frac{s_i(t)}{\Delta t}\vec{e}_i(t)\right\| \mathrm{Sin}\alpha(t) = \|\vec{v}_i(t)\|\mathrm{Sin}\alpha(t) \quad (16)$$

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

$$\alpha(t) = \tan^{-1}\left(\frac{y(t+\Delta t)-y(t)}{x(t+\Delta t)-x(t)}\right) \qquad (17)$$

In our model, the demand traction force (acceleration, rolling, gravity, and drag forces) is calculated by (1-5). By using an integrator from acceleration, the actual speed is computed. This speed is fed as the process variable to a PI controller which controls the desired cruise. Dynamically, with the speed and slope angle, by employing (15-16), the velocity in x (distance) and y (altitude) directions is calculated.

By implementing two integrators and based on the mentioned theoretical background in (11-17), with $v_x(t)$ and $v_y(t)$ as the current states, x(t) and y(t) are determined. By means of these points, not only the instantaneous slope can be realized, but also the future states can be determined. This feature makes this model suitable for implementation in a look-ahead energy management system.

As in the backward facing model, the flow of energy starts from wheels and spreads toward the ICE, to facilitate the necessary calculations via the expressed relations in (6-7). The traction force and actual speed are converted to torque and rotational speed. A schematic overview of the proposed model is illustrated as a flowchart in Fig. 3.

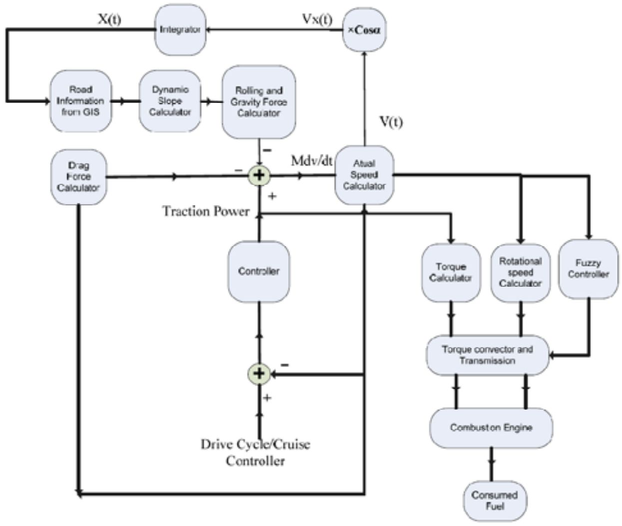


Fig. 3. Schematic overview of the model

Fuzzy controllers are used in many applications [16-19]. A fuzzy controller whose rules are extracted based on empirical knowledge of the expert, is developed to control the transmission ratio. The main objective of this controller is to maintain the ICE speed near its optimal speed range. Such a system can provide an alternative to traditional PID controller. The main 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, hence the adaptation is an additional benefit of this controller. The main idea behind the fuzzy-logic controller is to employ logic-based shifting ratio selection. A fuzzy logic controller maps inputs to outputs with a set of logic rules. Fuzzy control rules are characterized as a collection of fuzzy IF-THEN rules whose conditions and consequents 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, as shown in Fig. 4, the membership functions that define the degree of membership are Pi functions. They determine the degree of membership to the fuzzy set, from very low speed to very high speed.

The THEN-part of the rules of the controller refers to 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 Fig. 4, the membership functions that define this degree of membership are Pi functions which establish the degree of membership to the fuzzy set, from very high shift to low shift. The output of the fuzzy logic controller is the transmission ratio that determines the crankshaft rotational speed.

We implement the most frequent method of Mamdani's minimum operation. 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:

$$\mu_{C'}(w) = \vee_{i=1}^{n}[\,\mu_{A_i}(u_0) \wedge \mu_{B_i}(v_0)] \wedge \mu_{C_i}(w) \quad (18)$$

where $\mu_{\acute{c}}(w)$ is the membership function of inference.

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

$$Z_{COA} = \frac{\int_z \mu_C(z)Zdz}{\int_z \mu_C(z)dz} \qquad (19)$$

where Z is the output from the given inputs and their fuzzy relation, and $\mu_C(Z)$ is the aggregated output membership function.

By applying the gear ratio provided by the fuzzy control system to (6-8), the crankshaft torque and the rotational speed are calculated. The crankshaft speed ω and torque T_m determine the operating point. The engine is modeled by means of empirical data expressed in engine map. The map information is transferred to a look-up-table. In this way, the engine efficiency which is a function of T_m and ω can be obtained. By using (8), engine output power is calculated. Through implementing the yielded efficiency and power in (10), the rate of fuel can be obtained

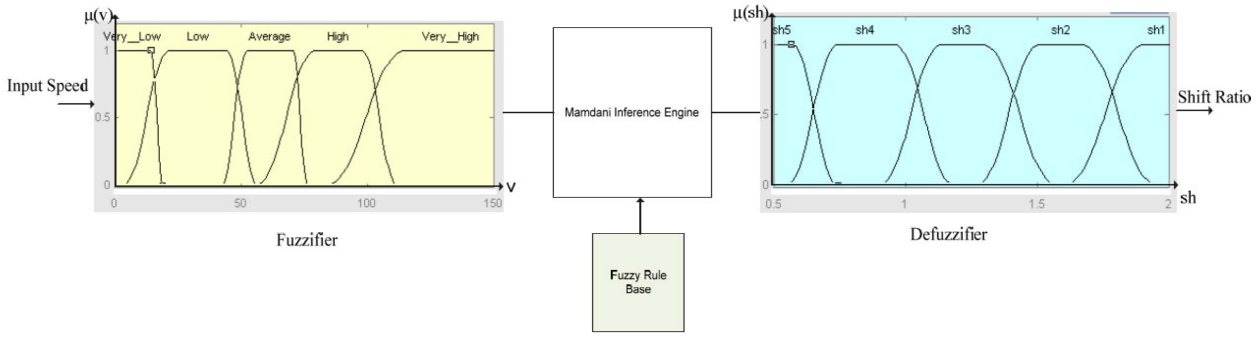


Fig. 4. Architecture of the developed fuzzy logic controller

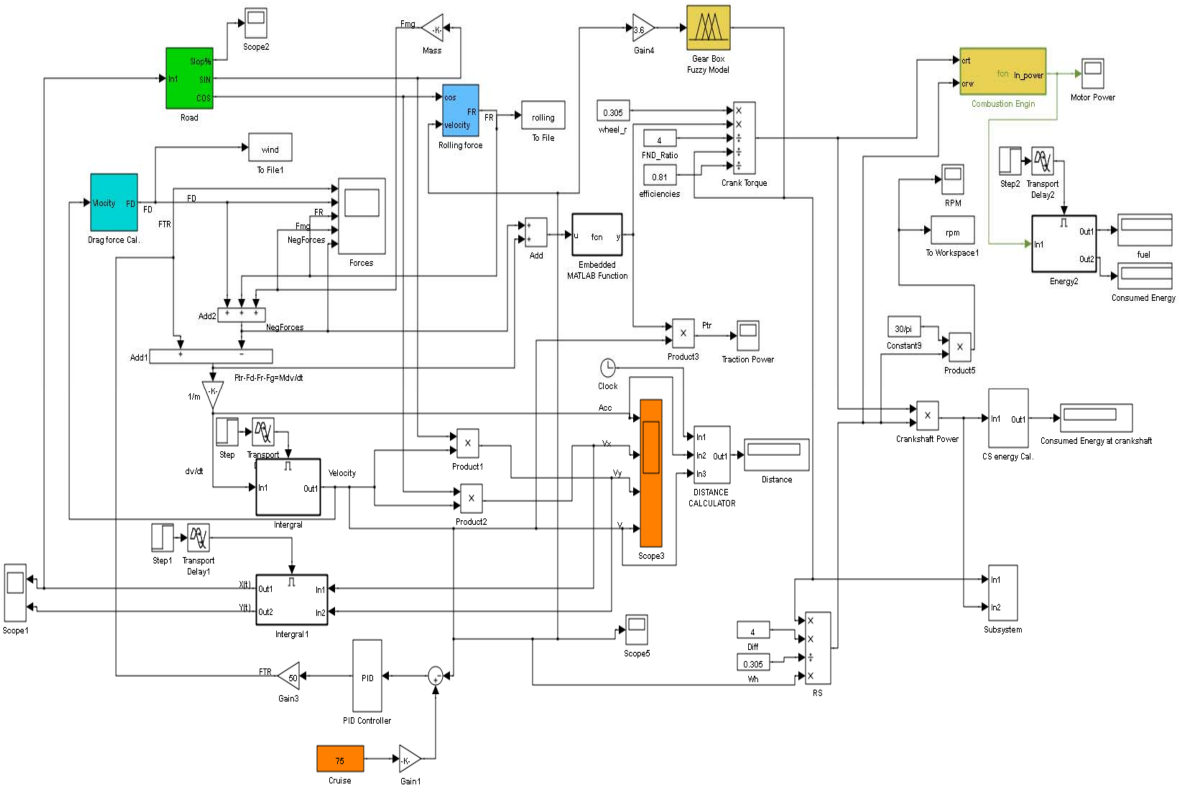


Fig. 5. Complete vehicle model

instantaneously. From the real time power and the fuel rate, the total consumed energy and fuel can be calculated. Using the presented characteristics in Table 1, the developed model is simulated as described below.

IV. SIMULATION RESULTS

A vehicle is modeled in Simulink. The developed model is presented in Fig.5. In this model, the required speed is the input of a PI controller. The difference between the desired and actual speed is the error signal in the controller input. Hence, controller should provide a command to eliminate this error. The PI controller and Gain3 block calculate the necessary power traction in wheels to reach the desired speed. From the produced traction power, and considering (5), the instant acceleration is calculated. Utilizing an integrator block, the instant speed is determined. From the obtained speed and by implementing (15-16), instant speeds in the x and y directions are calculated. Also, the instant speed is fed back to the controller. The input speed (PI set point) is assumed to be constant (100 km/h) in this simulation. The response curve of controller is illustrated in Fig. 6.

A moving vehicle can be shown by a 3D Cartesian or a 3D polar coordinates. Length, height and altitude are three elements of the Cartesian coordinate. The geographical information of the road is supplied in databases which are used in the GPS, GIS, traffic information systems and etc. Furthermore, they can be made from stochastic methods of road simulation [20]. To present the simulation results, the information of a highway, 50 km of Nowra-Bateman Bay in Australia, is implemented in the model. The Cartesian coordinates of the data is presented in Table 2 [20].

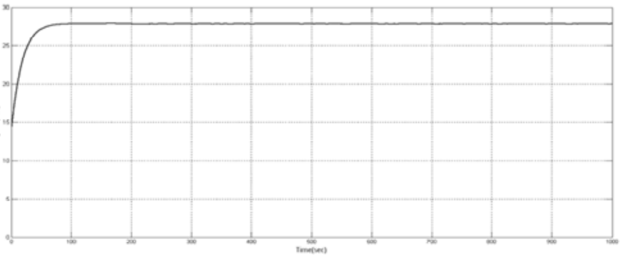
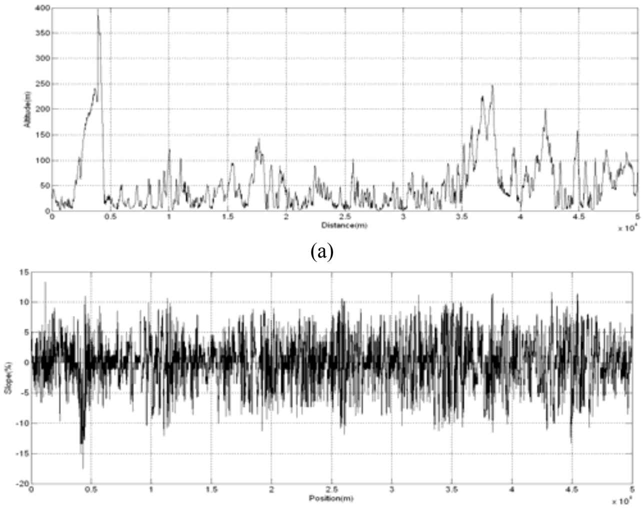


Fig. 6. Speed controller output

TABLE 2
REAL CARTESIAN COORDINATES FOR NOWRA TO BATEMAN BAY, AUSTRALIA

Road location	DIST D (km)	EAST X (km)	NORTH Y (km)	ALT Z (km)
0000001,0010,C1,0.009	0.0085	9687.603	4421.904	0.0155
0000001,0010,C1,0.019	0.0188	9687.599	4421.895	0.0158
0000001,0010,C1,0.029	0.0291	9687.596	4421.885	0.0162
0000001,0010,C1,0.039	0.0386	9687.592	4421.876	0.0164
0000001,0010,C1,0.049	0.0488	9687.588	4421.867	0.0167

Latitudinal forces affect the suspension and steering system in a vehicle. Thus for simplicity, the latitudinal effects have not been considered and the road has been presented in two dimensional coordinates, distance and height points. Accordingly, the slope is calculated based on the rate of change in altitudes on distances. The graphs of the used real road and related slope data are demonstrated in Fig. 7.



(a)

(b)

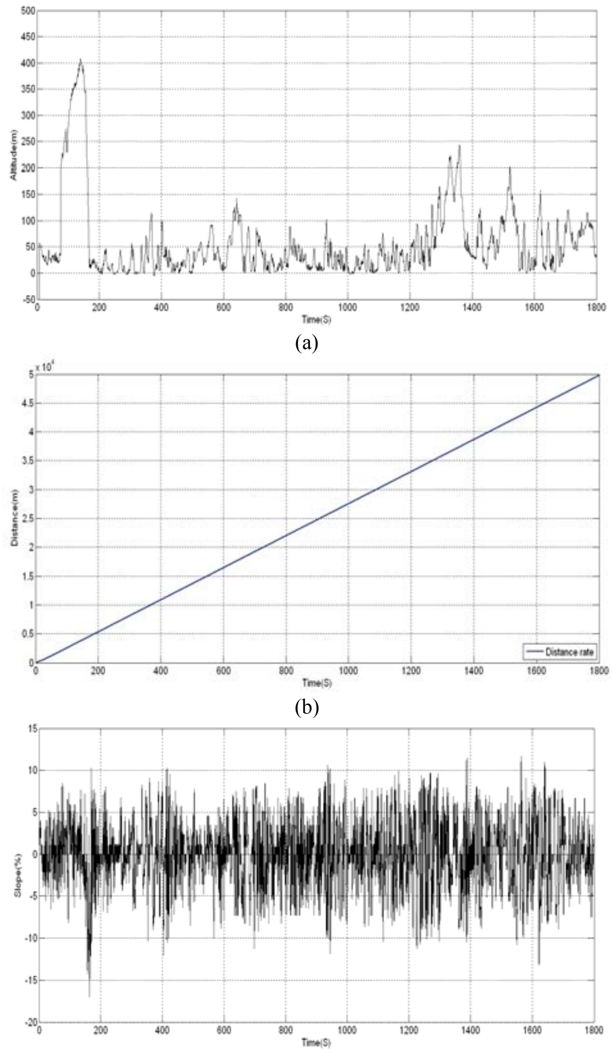
Fig. 7. (a) Altitude and (b) slope of highway

The instantaneous altitudes, y(t), and position, x(t), are calculated from the obtained $v_x(t)$ and $v_y(t)$. Using the calculated vehicle position and a look-up table including the road information (from geographical information system, GIS), the current slope is determined. The new slope is provided for obtaining the instant forces and new velocities in x and y directions. These velocities are used to determine the new states of x and y.

By means of the instantaneous speed and slope and from (2-4), the longitudinal rolling resistance force, gravity force and aerodynamic drag force are calculated. Accordingly, the torque and rotational speed are calculated via (6-7). The simulation is conducted using the information of the following highway: 50 km of Nowra-Bateman Bay in Australia. The trends of altitude, distance and slope in time domain (the entire travel time) are shown in Fig. 8. The provided trends resemble those of the static graphs presented in Fig. 7.

The use of real data in the model distinguishes this approach from the former ones which use only the drive cycle and a constant grade. To control the gear ratio for maintaining the engine operation near optimal area, the CVT is implemented with the developed fuzzy controller. To demonstrate the operation of the CVT with fuzzy controller, the plots of the tractive-effort characteristics and the engine operation points are shown in Fig. 9.

As can be seen from the figure, the tractive effort characteristics are not far from the ideal characteristics, and the engine has operated well around its optimal efficiency region.



(a)

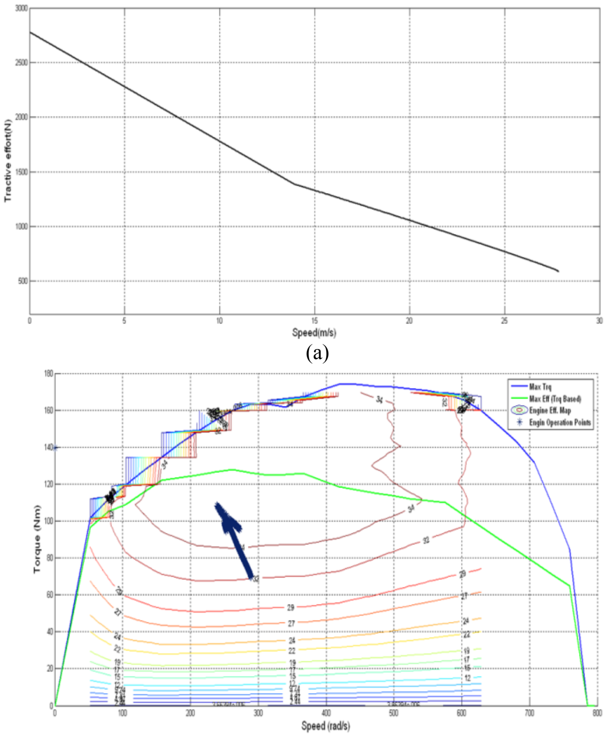
(b)

(c)

Fig. 8. Dynamic graphs of (a) altitudes (b) distances, and (c) slopes

V. Conclusions

This paper presented an approach for vehicle modeling based on the road geographical data. From the model, the dynamic position of vehicle can be obtained. The applied method uses a combination of calculated data (distance, altitude and slope) and static information from the GIS. 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, gravity and aerodynamic drag. This operation occurs in a closed loop system. The entire information of the road is accessible via the GIS, hence the future states for a look-ahead window can be extracted. This strength makes the model suitable as a foundation for look-ahead control in conventional and hybrid electric vehicles. In addition, real road data was used in our simulations. A fuzzy controller with a CVT is applied to maintain the engine speed near its optimal region. It reveals that the combination of a fuzzy controller and a CVT can provide tractive effort characteristics near the ideal state. The developed approach is not computationally intensive. Combining the implemented method and an optimization technique can provide a better performance from the standpoint of fuel economy.



(a)

(b)

Fig. 9. (a) Tractive effort characteristics and (b) engine operating points on efficiency map

Acknowledgements

The authors would like to thank AUTOCRC and Commonwealth of Australia which provide financial support for this research.

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