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Development of Ecological Driving System Using Model Predictive Control

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Abstract: Ecological driving aiming at optimizing energy consumption is highly desirable for sustainable intelligent transportation systems. This paper presents a unique development of ecological vehicle driving system in model predictive approach. The vehicle's fuel consumption model and the model based anticipation of future road-traffic situations are used in this rigorous reasoning approach of deriving the control input. A combination of Continuation and Generalized Minimum Residual Methods is used to optimize the sequence of vehicle control actions required in the prediction horizon aiming long run fuel economy while maintaining a safe driving. Performance of the proposed system is evaluated through simulations in AIMSUN NG microscopic transport simulator. The driving behavior with fuel saving aspects is graphically illustrated, compared and analyzed to signify the achievement of the developed system.

Keywords: Ecological driving, model predictive control.

1. INTRODUCTION

Maneuvering a vehicle in a changing road-traffic environment is a very complex task. Human driver can cope with such changing situations utilizing his complex and experience-based reasoning and attain his own typical behavior in cruising or following a car. A car following or cruising behavior describes processes by which drivers follow each other in the traffic stream, and various models have been proposed to approximate driving behavior since its research began about sixty years back [1]. The driving behavior, in which the vital issues are the speed and range clearance patterns, varies widely among the drivers, and a single behavior model neither fully represents all the driving situations nor matches every driver [2, 3]. Ecological driving means controlling a vehicle in any traffic streams and road situations in such a way so that the fuel consumption in long run is minimum. Obviously, the ecological driving behavior is much more complex since it is necessary to forecast the road-traffic situation ahead.

Besides many physical factors, driving styles have a great influence on vehicle emissions and energy consumption [4]. Proper driving styles may improve the travel economy or driving efficiency considerably. A recent experiment through ecological-driving contest conducted on urban roadway shows a reduction of fuel consumption by 25%, which yields an improvement in fuel economy (km/l) by 35% [5]. Generally, fuel economy is maximized when acceleration and braking are minimized. Therefore, a fuel-efficient or ecological strategy is to anticipate what is happening ahead, and drive in such a way so that it minimizes acceleration and braking, cruises at the optimal speed and maximizes coasting time at stops. Since the changing nature of the road-traffic affects the driving behavior, a simplified model that does not anticipate situations ahead cannot represent ecological driving behavior completely. Various speculative formulations of desired driving behavior for ecological driving are well known. The existing ecological driving tips or assistance are a bit superficial and based on rough vehicle engine characteristics [6]. Some recent efforts uses optimal control approach in which only the model of the engine, in terms of speed, gear ratio and load, are considered [7]. They do not have any rigorous reasoning by analyzing the instant road-traffic situation and its trends in future.

Model predictive control is a potential control technique for non-linear systems that suits vehicle driving. This paper presents a novel and unique approach of developing an ecological driving system using model predictive control that measures how the current situations may affect the fuel consumption in long run and determines the optimal control input based on maximization of traveling distance per unit fuel consumption. This rigorous approach of deriving optimal control input would make the proposed system more efficient, reliable and trustworthy. The system senses the status of the subjective host and its surrounding vehicles, and the traffic signal ahead through information technology. It anticipates the possible behavior of the surrounding vehicles in near future using some sort of simplified model. Based on this information and fuel consumption model of the vehicle, it generates an immediate control action that may lead to a long-range economy travel. It is expected that new sensing and communication technology be incorporated for the development of road-traffic infrastructure in coming decades. Through this advancement in intelligent transportation systems, the proposed ecological-driving can be realized.

The model of the vehicle control system, used in this paper, expresses the dynamic relationship of the host vehicle, preceding vehicle and traffic signal system at any instant. The optimization of control inputs in the prediction horizon is conducted using Continuation method combined with generalized minimum residual method known as C/GMRES method [8, 9]. From the viewpoint

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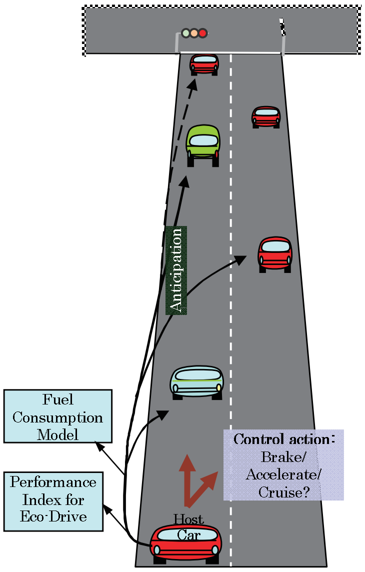

Fig. 1 Concept of ecological vehicle driving through anticipation of road traffic system ahead.

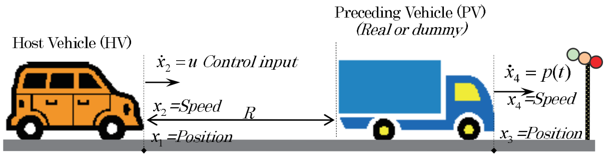

Fig. 2 Model of vehicle control system incorporating a preceding vehicle and traffic signal.

of real-time control, C/GMRES method has the favorable feature that the computational time is almost constant for updating the control input, while the computational time varies in an iterative optimization method in general [9]. Performance of the proposed model predictive ecological driving is evaluated by various observations in AIMSUN NG, a microscopic transport simulator with an integrated traffic environment, using its extension developed through application program interface (API) [10, 11]. Fuel saving behavioral aspects, in driving a Ford Fiesta car, attained at the starting, stopping and cruising are graphically illustrated and analyzed. Average fuel saving and travel economy achievements are compared with the vehicle controlled by Gipps model based method installed in AIMSUN NG [12, 13]. The simulations results are analyzed to focus the significance of the developed system.

2. ECOLOGICAL DRIVING

Ecological driving is a way of driving intended to enable energy conservation, cut air and noise pollution, reduce emissions of carbon dioxide, and contribute to the effort to reduce global warming. Energy consumption and emission in a vehicle depend on various physical factors relating road-traffic-vehicle conditions, including engine size and efficiency, road conditions, load on the vehicle, and many others. Besides these physical factors, driving styles have also a great influence on energy consumption for the same physical conditions. Practicing a few straight forward driving tips based on engine characteristics helps a driver in reducing energy consumption. Aggressive driving with speeding, rapid acceleration and braking waste energy substantially. Avoiding unnecessary acceleration and practicing smooth braking, and cruising at optimal economy speed are not very easy to be attained while driving on crowded urban roadways directed by traffic signals, due to various inevitable traffic phenomenon.

The existing ecological driving assisting approaches provide very general qualitative advice without analyzing the traffic situation. For example, it may be suggested not to accelerate aggressively when a driver goes for abrupt acceleration at higher than some threshold value. It does not provide any information about the required level or values of acceleration so that the driver can adjust his action at optimal level without any vague. The trend of traffic (whether it goes to be slowing down or continues cruising) has a strong relationship with desirable vehicle behavior. Therefore, for developing an efficient system, it is necessary to derive the control input that suits both current situation and situations that may happen in near future.

An overall idea of the model predictive ecological driving of a host vehicle is illustrated in Fig. 1, [14]. The host vehicle has to anticipate the movement of preceding vehicles and status of the traffic signal ahead. At the same time, it has to use the model of engine fuel consumption characteristics, and decide a control action that optimizes the given performance index reflecting ecological driving context. For implementing the computational reasoning system analogous to such illustrated human anticipation, it is necessary to split the prediction time horizon in some suitable way for computational simplicity. In realizing such ecological driving system, it is necessary to have vehicle fuel consumption model and formulation of the vehicle control problem, which are described in the next section.

3. MODELING AND CONTROL

3.1 Driving System Model

The most important element for developing a model predictive ecological driving system is the formulation of the vehicle control problem. A simplified model considering only the longitudinal motion of a vehicle is taken into account, in which the only immediate preceding vehicle is included besides the subjective host vehicle Fig. 2. Due to limitations in sensing technology in reality and for simplicity in computation, other preceding or surrounding vehicles are ignored in this study. In spite of the model simplicity, the simulation results described later show the proposed system can significant fuel consumption reduction. In this modeling, the vehicle-traffic nonlinear system is governed by the following state equation:

$$\dot{x} = f(x, u, p) = \begin{bmatrix} x_2 \\ u \\ x_4 \\ p \end{bmatrix} \tag{1}$$

where, $x = [x_1, x_2, x_3, x_4]^T$ denotes state vector representing location and speed of the host vehicle (x_1, x_2), and location and speed (x_3, x_4) of the preceding vehicle, respectively. The only control input u, accelerations/deceleration of the host, is bounded by an inequality constraint as $-u_{max} \leq u \leq u_{max}$, to meet physical limits of actuators (the accelerator and the brake). The time dependent parameter p represents the model of preceding vehicle in term of its acceleration/deceleration by which movement of the preceding vehicle is anticipated in the prediction horizon. In absence of any preceding vehicle within a reasonable range, a dummy vehicle is assumed to be maintaining a typical speed and range ahead the host vehicle. The traffic control signal is also taken into account utilizing this dummy preceding vehicle. In case of the red or yellow signal at the end of a section or junction point without following a preceding vehicle, the dummy vehicle is set to be idling at the signal stopping point. In this way, the signalling system is introduced in the modeling without any change in the dynamic equations or states in this formulation.

3.2 Fuel Consumption Model

The fuel consumption model assumes that a vehicle is either idling, or cruising at constant speed, or accelerating or decelerating. The consumption rates in ml per sec of an idling and decelerating vehicle is assumed to be constant and given by F_i and F_d respectively.

$$F_i = constant, \tag{2}$$

and

$$F_d = constant. \tag{3}$$

For an accelerating vehicle, the consumption rate, F_a ml per sec, is approximated by

$$F_a = (c_1 + c_2 av), \tag{4}$$

where c_1 and c_2 are constants, and a and v are the acceleration and speed of the vehicle. The fuel consumption per second of a cruising vehicle F_c is approximated by

$$F_c = \left(k_1 \left(1 + \frac{1}{2} \left(\frac{v}{v_m} \right)^3 \right) + k_2 v \right), \tag{5}$$

where k_1 and k_2 are constants, and v_m is the speed at which the vehicle fuel economy (in km/l) is maximum. The fuel consumption model presented here is originally derived from [15] and used in AIMSUN NG traffic simulator [13]. Conventional idling-stop system saves fuel by automatically shutting down the engine when the driver brings the vehicle to a halt (at red traffic lights) and automatically restarting the engine when the driver subsequently wishes to pull away. Therefore, in this paper, a vehicle is only controlled while it is moving forward, recommending idling stop for further fuel savings.

Equations (2)-(5) describe the consumption in ml per sec in respective distinct cases of driving modes at any instant. To implement the controlling algorithm it is necessary to express the fuel consumption relationship using a single continuous function. The fuel consumption per second when a vehicle is either cruising, or accelerating, or decelerating is approximated by the following function which is mainly derived from (2)-(5) by multiplying sigmoid and Gaussian functions using some suitable coefficients:

$$\begin{aligned} F_{vehicle} &= \frac{F_d}{1 + e^{\beta(u+C)}} + \frac{c_1 + c_2 u x_2}{1 + e^{-\beta(u-C)}} \\ &+ e^{-(\frac{u}{\sigma})^2} (k_1 + k_2 x_2 + k_3 (x_2)^3). \end{aligned} \tag{6}$$

This approximate and continuous fuel consumption equation is used in the performance index, and also for evaluation purposes. For calculating the fuel consumption of the vehicle, fuel consumed at idling is also taken into account in addition to equation (6).

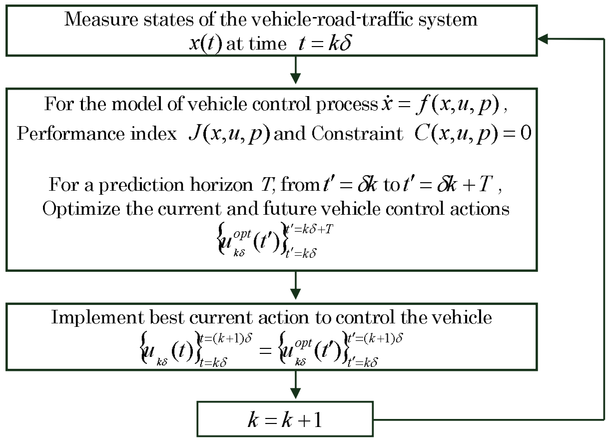

Fig. 3 Model predictive control of a vehicle.

3.3 Model Predictive Control

In this model predictive control, at any instant, the system conducts the measurement of current states. Then it derives a set of vehicle control inputs required for safe and economy travel within the prediction horizon. An iterative optimization algorithm is used for this derivation of optimal control inputs from a set of initial values obtained or guessed in a suitable way. Once a set of optimal control inputs over the horizon is available, only the first input is taken and used to control the vehicle. The other control inputs correspond to future time ahead are ignored [16, 17]. At the next sampling step, the whole process is repeated, and it is continued throughout the driving course. In this way, ecological driving that maximizes fuel economy by safely cruising or following other traffics can be realized. This model predictive control process is illustrated in Fig. 3.

The prediction horizon, T, should be logical and set by keeping analogy with anticipation of human driver. A long horizon would be meaningless since the traffic movement has a lot of variations. The performance index should consist of fuel consumption terms as well as safety related terms, and they should be properly traded off by setting some weights to reflect their contextual merits or eligibility. In line with this requirement, the performance index in this model predictive control is chosen to minimize the following function

$$J = \int_{t'}^{t'+T} L[x, u, p] dt', \tag{7}$$

where,

$$\begin{aligned} L &= w_1 \left[\frac{F_{vehicle}}{x_2} \right] + w_2 \left[(h_d x_2 - x_1 + x_3 - l_v)^2 \right] \\ &+ w_3 \left[(x_1 - V_d)^2 \right], \end{aligned} \tag{8}$$

which consists of three terms namely the fuel consumption rate, cost due to unsafe range clearance from preceding vehicle, and cost for not moving forward at a better speed, each of them is multiplied by a weight w_1, w_2, and w_3 respectively. The third term in the cost function is needed to force the vehicle to move forward for long term advantages even the acceleration cost is very high. The reference speed V_d can be equal to the best economy speed of the vehicle or the speed limit imposed on the road section. Safe headway h_d represents a desired headway to ensure a enough span to avoid any collision while following a preceding vehicle, l_v is the vehicle length. At each step in the prediction horizon, these weights represent their relative contextual merits or eligibility in the subjective situations. The weight w_2 is dynamically calculated as $w_2 = 11.0 * e^{(-0.3R)}$, that ensures a large penalty at closing range R (distance of the preceding car), and negligible weight when the preceding vehicle is far enough. Even the weight w_2 is calculated using a function of states, it is used as a constant or coefficient in the cost function to avoid further complexity in computation. The weight w_1 and w_3 are kept constant at some suitable values.

The prediction horizon T is divided into N steps of δ sec each, and the continuous optimal control problem is discretized resulting in a nonlinear algebraic equation for the discretized sequence of control inputs. Using the model (1) and performance index (7), for a prediction horizon T, from virtual time $t' = k\delta$ to $t' = k\delta + T$, the instant and future vehicle control actions $\{u_{k\delta}(t')\}_{t'=k\delta}^{t'=k\delta+T}$ are optimized. Therefore a set of optimum actions, $\{u_{k\delta}^{opt}(t')\}_{t'=k\delta}^{t'=k\delta+T}$, for the instant and future time is available at this stage, and only the optimal action corresponds to the current time is used to control the vehicle up to next sampling instant,

$$\{u_{k\delta}^{opt}(t)\}_{t=k\delta}^{t=(k+1)\delta} = \{u_{k\delta}^{opt}(t')\}_{t'=k\delta}^{t'=(k+1)\delta}. \tag{9}$$

C/GMRES method is used to generate the sequence of control inputs by optimizing numerically. From the viewpoint of real-time control, it solves the differential equation only once at each sampling time, therefore requires much less computational burden [9]. At each simulation step, the immediate action calculated by this way is fed to control the host vehicle, and the whole process is repeated through out the driving course, except at idling time. A more realistic technique for calculating initial guess of the input vector is chosen in this paper. The optimal sequence of inputs derived at the current time is used as the initial guess at the next step with a slight modification. Since the time axis is shifted in the next cycle by the simulation step, the new set of initial guess of input vectors are formed by simple interpolation of their values at the discrete points on the prediction horizon.

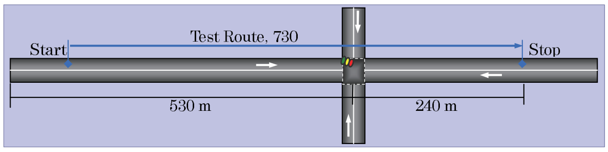

Fig. 4 An image of the test environment used in AIMSUN NG.

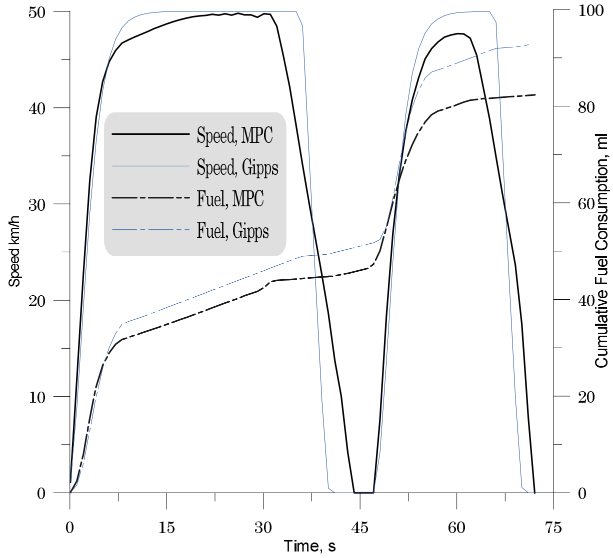

Fig. 5 A typical ecological driving pattern on a road of two sections compared with Gipps based driving.

4. SIMULATION RESULTS

The simulation of the proposed model predictive ecological driving has been conducted by choosing suitable values of the parameters as, $u_{1max} = 3.00$, $\beta = 35$, $C = 0.09$, $\sigma = 0.11$, $h_d = 1.3$. Fuel consumption parameters of Ford Fiesta car are taken for the simulation as $F_d = 0.10$, $k_1 = 0.222999$, $k_2 = 0.0033529$, $k_3 = 0.000042$, $c_1 = 0.42$, $c_2 = 0.26$, $w_1 = 4.5$ [13, 18, 19]. An extension of AIMSUN NG is created through application program interface (API) to collect traffic data and control a vehicle from the outside of AIMSUN NG for evaluating the developed system. The simulation step is set at 0.1 sec. In the simulations, the host vehicle is controlled by the proposed model predictive ecological driving algorithm, except at idling. The comparisons are made with vehicles driven by the Gipps based method with their default parameters set stochastically[11, 12]. The Gipps model, which is widely used in microscopic traffic simulation, is mainly based on the collision avoid-

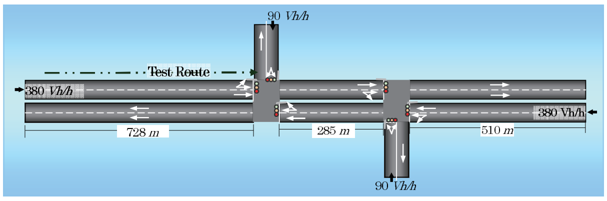

Fig. 6 An image of the test environment, traffics, and route used in AIMSUN NG.

ance principle.

Firstly, the host vehicle is tested on the road having two sections connected by traffic control signals. An image of the environment and route in AIMSUN NG on which this test was conducted is shown in Fig. 4. The driving characteristics with fuel saving aspects of the host vehicle at starting up from standstill, stopping at red signal, restarting and stopping finally without a preceding vehicle are examined.

The comparative speed and fuel consumption characteristics are shown in Fig. 5. The system generates sufficiently large acceleration at beginning that satisfies the economy driving requirement in long run. Within 10 sec, the host vehicle reaches close to the peak economy speed and continues cursing ahead at the best operating point. But just before the peak, the lower rate in acceleration helps reducing fuel consumption. Just after 20 sec of starting the traffic signal ahead turned into red, where it must stop. It started to decelerate when the stopping scenario appeared in its prediction horizon. The smooth and slower deceleration ensure utilization of kinetic energy and cutting off fuel into the engine. By this way, it could also reduce the idling time and fuel wastage at the red signal. It restarted in the same way, and reached at the stopping destination.

The comparative fuel savings for the same are compared with Gipps based vehicle, which is also set to operate at the same and best fuel economy speed. It is found that, after a travel of about 730 m with one complete stop in red signal and for the same maximum speed, the vehicle operated by the proposed model predictive ecological strategy required only 82.45 ml of fuel, whereas Gipps based vehicle consumed 93.06 ml (12.87% extra fuel). The fuel savings by only adjusting the braking and accelerating reveals the necessity of traffic anticipation based vehicle control for ecological driving. It is obvious that the fuel consumption varies at events of acceleration and deceleration. If the number of such events are few (for steady running) then the difference in consumptions would not be large. But if such events are frequent which is usual in urban roads, the difference in fuel savings would be large, and the proposed ecological driving would be highly suited for such situations.

Finally, comparative fuel consumption rates for a complete travel on a road consisting of two sections in a pseudo-realistic traffic environment of AIMSUN NG are observed. An image of the test environment, traffic flow rates, and route are illustrated in Fig. 6.

In this test, a vehicle is forced to stop at the beginning

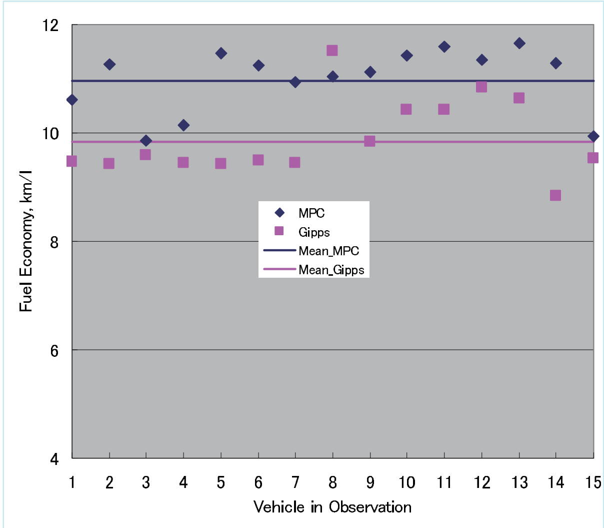

Fig. 7 Economy rates of vehicles tested in AIMSUN NG simulator using the proposed MPC and Gipps based algorithms.

of a section, and then it is set as the host vehicle. Next, the host vehicle is driven up to the end of the section and stopped at red signal using both the model predictive algorithm and Gipps-based method separately. Average results of 15 different vehicles in various distinct situations are illustrated in Fig. 7. For each of these 15 vehicles, the initial conditions were kept the same for both observations. The straight lines represent the average economy of these 15 vehicles tested on AIMSUN NG. When the cars were controlled by Gipps method, for a travel of $660.73\ m$, $66.35\ ml$ of fuel is consumed, that yields an economy rate of $9.84\ km/l$. In the case of the proposed ecological driving system, only $59.96\ ml$ of fuel is consumed for a travel of $661.33\ m$ that yields an economy rate of $10.96 km/l$. An average improvement in economy rate by 11.39%, or fuel saving of $6.39\ ml$ for a travel on a road section signifies the achievement of this contribution.

5. CONCLUSIONS

A novel approach of ecological driving using model predictive control has been presented in this paper. Based on vehicle's fuel consumption model, anticipation of the preceding vehicle behavior and status of traffic signal, the system derives appropriate vehicle control input. The vehicle controlled by the proposed method could choose appropriate course in various driving situations and maintain safety requirements that lead to attain higher economy rate. Comparative statistics reveal the significant achievement in overall fuel savings. The proposed ecological driving system using model predictive control can be very effective in reducing fuel wastage in urban roadways, and may contribute for realizing sustainable and environment friendly intelligent transportation systems.

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