DEVELOPMENT OF ECOLOGICAL DRIVING ASSIST SYSTEM
MODEL PREDICTIVE APPROACH IN VEHICLE CONTROL

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ABSTRACT

This paper presents a novel concept and development of an Ecological Driving Assist System (EDAS) that may play an important role in intelligent transportation systems (ITS) in coming decades. The proposed system is planned to perceive instant vehicles-road-traffic information from ITS through its advancement with new sensing and communication technologies. It generates the optimal control input necessary for ecological driving by anticipating situations of the vehicles-road-traffic for a certain time horizon ahead, and assists a driver through a suitable human interface. Performance of the developed system is evaluated by simulations in AIMSUN NG microscopic transport simulator.

KEYWORDS
Ecological driving, model predictive control, intelligent transportation systems.

INTRODUCTION

Researchers in the field of automobile and transportation system, in this decade, have set their main focus on developing environment friendly vehicles and transportations, since the demand for fuel economy vehicles has been increased greatly to reduce both the dependency on oil and impact on environment such as air pollution and global warming. It is expected that ITS through advancement in new sensing, communication and information technologies may provide solutions of such demand in near future. Progress in innovating hybrid cars, electric cars, advanced traffic management are some of the milestones in achieving a comprehensive environment friendly system using limited resources.

Besides many physical factors, driving styles have a great influence on vehicle emissions and energy consumption [1]. Proper driving styles may improve the travel economy or driving efficiency of a vehicle significantly. A recent experiment through ecological-driving contest conducted on urban roadway shows that reduction of fuel consumption can be as high as 25%, which yields an improvement in fuel economy (km/l) by 35% [2]. Generally, fuel economy is maximized when accelerating and braking events are minimized. Therefore, a fuel-efficient or ecological strategy is to anticipate what is happening ahead, and drive in such a way so as to minimize acceleration and braking, cruising at the optimal speed and maximize coasting time at stops. Since the changing nature of the road-traffics affects the driving behavior, a simplified system that does not anticipate situations ahead is unable to 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 [3]. Some recent efforts in determining ecological strategy use optimal control approach in which only a model of the engine, in terms of speed, gear ratio and load, is considered [4]. They do not have any rigorous reasoning by analyzing the instant road-traffics situation and its trends.

This paper explores a novel concept of EDAS to guide a driver emphasizing on long-run economy. The proposed system measures the status of the host and its surrounding vehicles, and traffic control signal from the transportation system. These data can be acquired from ITS through advanced sensing, communication and information technologies. Then the system anticipates the possible behavior of surrounding vehicles and traffic signal ahead. Based on this information and fuel consumption model of the engine, it generates the immediate vehicle control input required for a long-range economy travel. Ecological driving assist system can be developed by adding a human interface to suggest a driver to execute this generated action. In this paper, a model predictive approach is used to determine a sequence of actions for optimal economy travel for the predicted horizon. The model, used in this paper, expresses the dynamic relationship of the host vehicle, preceding vehicle and traffic signal system at any instant. The optimization of actions is done using the generalized minimum residual (GMRES) method [5][6]. For simplicity in this paper, it is assumed that the driver exactly follows the control action generated by the system without any physical interface, focusing mainly on the vehicle control aspects in ecological manner.

Performance of the proposed eco-driving system 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). Average fuel saving and travel economy achievements are compared with the vehicle controlled by Gipps model based method installed in AIMSUN NG [7][8]. Fuel saving behavioral aspects, in driving a Ford Fiesta car, attained at the starting, stopping, cruising and inter vehicle range adjusting are graphically illustrated. Simulation results are analyzed to focus the contextual significance of the model predictive ecological driving assist system.

ECOLOGICAL DRIVING ASSIST SYSTEM

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. Besides, driving styles have also a great influence on energy consumption for the same physical driving conditions. Practicing a few straightforward driving tips, based on engine characteristics, helps in reducing fuel consumption. Aggressive driving, with speeding, rapid acceleration and braking, wastes energy considerably. Avoiding unnecessary acceleration and braking, and cruising at optimal economy speed are not very easy to be attained while driving on crowded urban roadways directed by traffic signals. The existing ecological driving assisting approaches provide very general qualitative advice without analyzing the current situation. For example, it may be suggested not to accelerate aggressively, when a driver goes for abrupt acceleration at higher

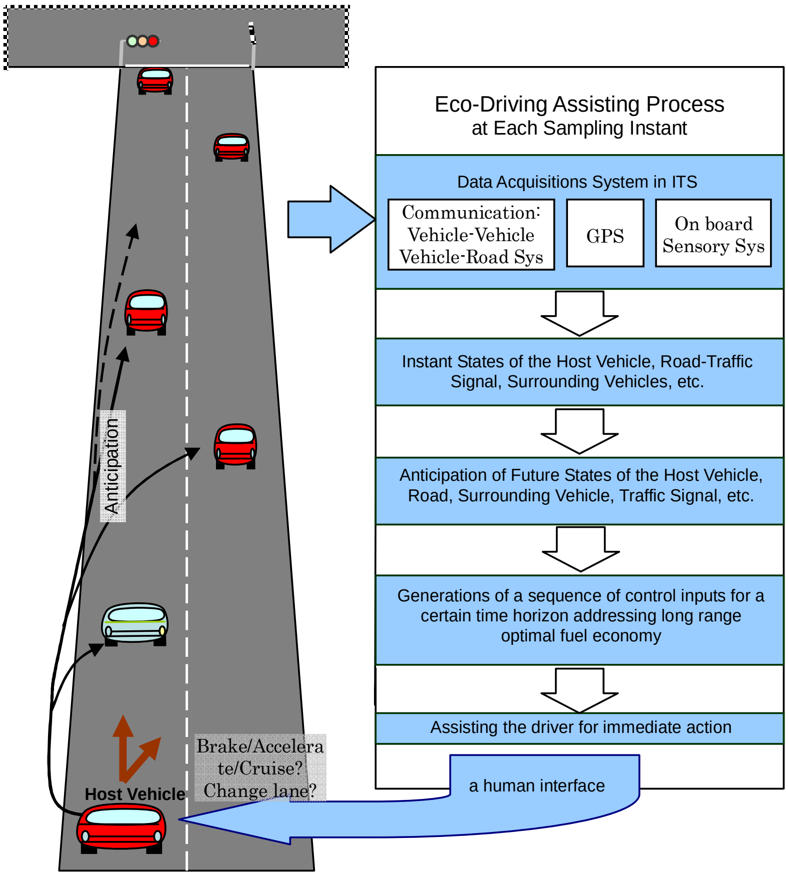


Figure 1- The Concept and procedure of the proposed model predictive ecological driving assisting system.

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. To make an assisting system widely acceptable, it is necessary to determine the exactly required control input based on rigorous reasoning considering the current road traffic situation and its trend. The trend of traffic (whether going to be slowing down or continue cruising) has a strong relationship with desirable vehicle's fuel consumption behavior. Therefore, for developing an efficient system, it is necessary to derive the vehicle control input, which suits both current situation and situations in near future, for long run optimal fuel economy.

An overall concept of the proposed EDAS for a subjective host vehicle is illustrated in **Fig. 1.** The illustration was originally proposed in [9], and here it is updated with a complete procedure including data acquisition aspects. The first step in this process is the collection of data from ITS at every sampling instant. To grasp the whole situations of the road-traffics on which the subjective host vehicle is running, various sensory mechanisms can be incorporated. GPS based navigation system may be used to obtain the instant position of the vehicle, and data of road's curvature, slopes etc. If the destination and direction of the traveling is known then it would also be possible to use GPS system to obtain this information for the predicted future position of the vehicle in advance. Onboard camera or laser sensor can be used to determine the speed, distance, position of the preceding and surrounding vehicles. Such existing system may provide precise data only of the immediate preceding vehicle.

Detection process of acceleration or deceleration through conventional technology is slow. A sensor can detect braking only when the speed of preceding vehicle dropped which happens after a few seconds of touching the brake paddle by the driver. In future these process to collect data from other vehicles or road systems through some sort of sensing technology may be replaced by the inter vehicle communication systems. Using inter-vehicle communication, a vehicle can receive information instantly when the driver of the preceding vehicle start pressing accelerator or brake. Therefore, the counter action can be decided by information processing system almost without any delay. A camera can also provide the current status of the traffic control signal ahead. But communication between road-infrastructure and a vehicle may provide information of the traffic signal ahead and their exact timing (e.g., how many seconds remaining in red or green signal). In these ways all sort of data necessary for decision making can be perceived from ITS.

After collecting data of the road-traffics system, the proposed system anticipates the future states of the surrounding vehicles using their current trends and dynamic model. Based on these current states and anticipated states in certain time horizon ahead, using some optimization method a sequence of control inputs required for ecological driving is generated. The optimization should be based on the performance index to minimize the fuel consumption per distance for the horizon. Once a set of optimal actions are generated, using some sorts of human interface, the required immediate control input is transmitted to the driver as an recommendation for ecological driving.

Model predictive control can be applied for the implementing the proposed concept of ecological driving assist system. The host vehicle has to anticipate the movement of preceding vehicles and status of the traffic signal ahead, and drive in a smooth course without any hard braking. 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.

Conventional idle-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 we propose, a vehicle is only controlled while it is running, assuming the engine is stopped at idling.

MODELING AND VEHICLE CONTROL

Driving System Model

As the first step in developing an ecological driving system proposed, in this paper, a simplified model of the road-traffic-vehicle system has been taken. Only the longitudinal motion control in a plane road is considered. In this modeling only the immediate preceding vehicle and traffic signal ahead are taken into account. Due to limitation in sensing technology at this instant and for the computational simplicity, other preceding or surrounding vehicles are ignored. The vehicle-traffic non-linear system, shown in **Fig. 2**, is governed by the following state equation:

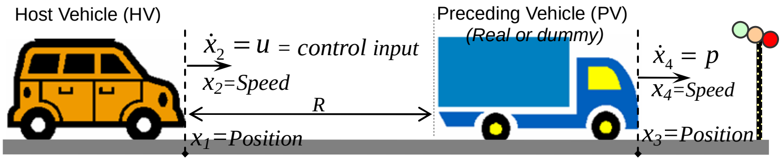


Figure 2- Model of vehicle control system incorporating a preceding vehicle and traffic signal.

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

where, $x \in \Re^4$ denote state vector consisting of locations and speeds of the host vehicle (x_1 and x_2) and preceding vehicle (x_3 and x_4) respectively, u is the only control input at time t, which is bounded by a constraint as $-u_{max} \le u \le u_{max}$,, and p is the time-dependent parameter represents the acceleration/deceleration of the preceding vehicle. The preceding vehicle is assumed to be continuing its motion at the same current acceleration/deceleration throughout the predicting horizon. In absence of a preceding vehicle, a dummy vehicle is assumed to be maintaining an ideal speed and range ahead the subjective host vehicle. The traffic control signal is also taken into account by utilizing this dummy preceding vehicle. In case of a red or yellow signal at the junction point, this dummy vehicle is set to be idling at the stopping point. In this way the traffic signaling system is also included in the model indirectly.

Fuel Consumption Model

Improvement in long run fuel economy rate is the main objective in this development. Both for evaluating the performance and developing the optimization algorithm an approximate and concise model has been considered. In this consumption model, it is assumed that a vehicle is either idling, or cruising at constant speed, or accelerating or decelerating. The consumption rates, in ml/s, of idling and decelerating vehicle is assumed to be constant and given by F_i and F_d respectively. For an accelerating vehicle, the consumption rate is approximated by $F_a = (c_1 + c_2 av)$, where c_1 and c_2 are constants, a and v are acceleration and speed of the vehicle respectively. The consumption of a cruising vehicle is approximated by $F_c = \left(k_1 \left(1 + \frac{1}{2} \left(\frac{v}{v_m} \right)^3 \right) + k_2 v \right)$, 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 [10] and used in AIMSUN NG [8]. The above fuel consumption equations for various modes are used to constitute an approximate but continuous equation valid for any modes of movement by multiplying sigmoid and Gaussian functions as-

$$F_{hv} = \frac{F_d}{1 + e^{\beta(u+C)}} + e^{-\left(\frac{u}{\sigma}\right)^2} \left(k_1 + k_2 x_2 + k_3 (x_2)^3 \right) + \frac{c_1 + c_2 u x_2}{1 + e^{-\beta(u-C)}}. \quad (2)$$

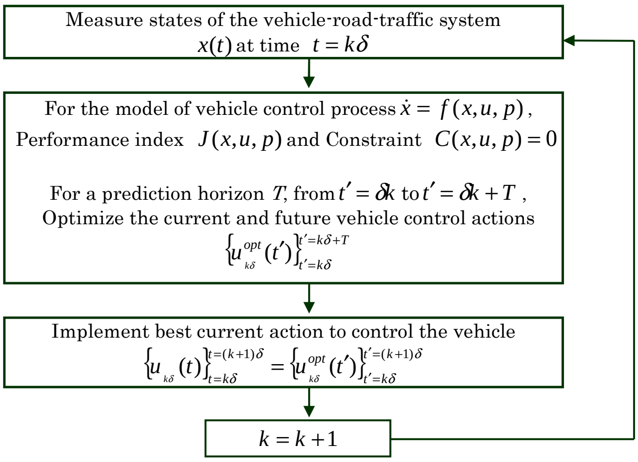


Figure 3- Model predictive control procedure for controlling the vehicle.

Model Predictive Control

Model predictive control process, illustrated in **Fig. 3**, is used for ecological driving of a vehicle [11][12]. At any instant, the sensory systems measure the current state of the vehicle-road-traffic system. The objective function for this predictive control is chosen in the form as follows:

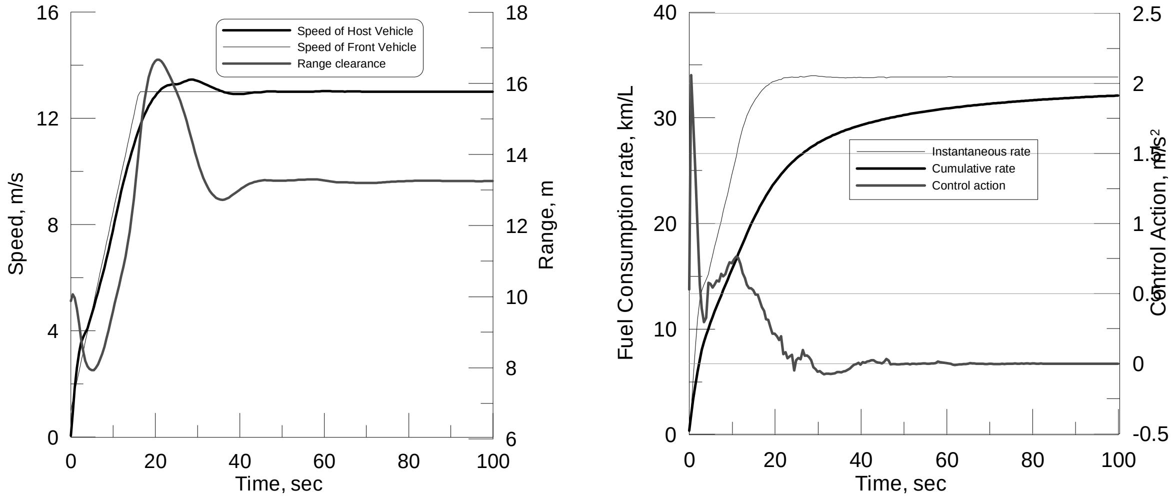
$$J = \int_{t'}^{t'+T} L[x(t'), u(t'), p(t')]dt', \tag{3}$$

where, T is the prediction horizon, and

$$L = \frac{w_1}{x_2}(F_{hv}) + w_2(h_d x_2 - x_1 + x_3 - l_v)^2 + w_3(x_1 - v_m)^2, \tag{4}$$

which consists of three terms namely the fuel consumption rate, cost due to unsafe range clearance, and cost for not moving forward at the best economy or recommended speed. 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, h_d represents a safe headway while following a preceding vehicle, and l_v is the length of the vehicle. Each term of them is multiplied by a dynamic weight w_1, w_2, and w_3 respectively. At each step in the prediction horizon, these weights represent the relative contextual merits or eligibility of three constant terms in the subjective situations. The weight w_2 is dynamically calculated as $w_2 = 11.0e^{-0.3R}$ that ensures a large penalty at closing range R (distance of the preceding car), and negligible weight when the preceding vehicle is far away. Even the weight w_2 is calculated using the function of states; it is used as a constant or coefficient in the cost function to avoid additional complexity in computation. The weight w_1 and w_3 are kept constant at some suitable values.

Using the model (1) and performance index (3), for a prediction horizon T, from time $t' = \delta k$ to $t' = \delta k + T$, the current and future vehicle control actions $\{u_{k\delta}(t')\}_{t'=k\delta}^{t'=k\delta+T}$ are optimized.



(a) *(b)*

Figure 4- Scenario in starting up (a) Speed of host and preceding vehicle and their range clearance (b) the control input, and fuel economy in instantaneous and cumulative value.

From the set of optimum current and future actions, $\{u^{opt}_{k\delta}(t')\}_{t'=k\delta}^{t'=k\delta+T}$, only the optimal action corresponds to the current time, $\{u_{k\delta}(t)\}_{t=k\delta}^{t=(k+1)\delta} = \{u^{opt}_{k\delta}(t')\}_{t'=k\delta}^{t'=(k+1)\delta}$, is used to control the vehicle for an interval of δ. The sampling instant is incremented as $k = k+1$, and the process is repeated throughout the driving course. In this paper, continuation method combined with generalized minimum residual method (C/GMRES) is used to optimize the sequence of control input by solving the above equation numerically [5]. From the viewpoint of real-time control, C/GMRES method has the favorable feature that the computational time is almost constant for updating control inputs, while the computational time varies in an iterative optimization method in general [5]. At each simulation step, the immediate action calculated by this way is fed to control the host vehicle (or to assist a human driver, in case of a real driving assisting system), and the whole process is repeated throughout the driving course. For simplicity here, it can be assumed that the driver exactly follows the recommended control inputs for ecological driving by the assisting system.

SIMULATION RESULTS

An extension of AIMSUN 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 EDAS. Fuel consumption parameters of *Ford Fiesta* car are taken for the simulation [8][12][13]. The sampling time of AIMSUN NG is set at a step of h=0.1 sec. At each sampling time host-traffic states are fed into EDAS that generates the required immediate action using the proposed method. Keeping an analogous anticipation of a human driver, the prediction horizon is set at T=10 sec. The horizon is discretized into N=10 steps of each $\delta = 1.0$ sec. The simulation of the proposed system has been conducted by choosing suitable values of the parameters as, u_{1max} = 2.75, β = 35, C = 0.09, σ = 0.11, h_d = 1.3. Fuel

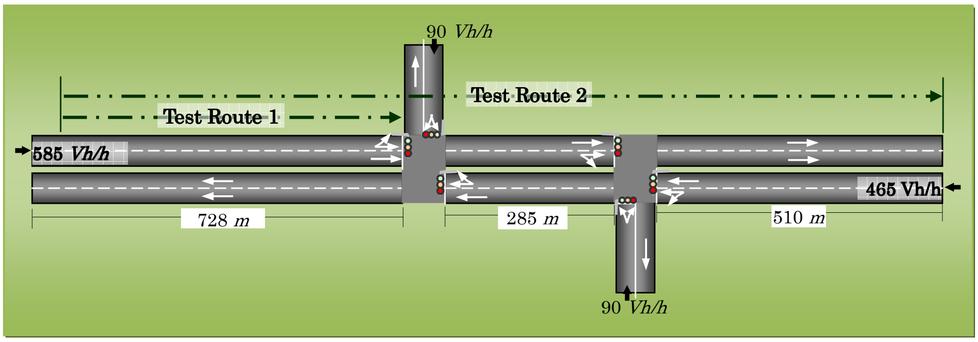


Figure 5- An image of road network, and traffic flow in AIMSUN NG, the test routes.

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, w_1 =1.0.

Firstly, driving characteristics with fuel saving aspects of the host vehicle at starting up from standstill without a preceding vehicle is verified. The system generates sufficiently large acceleration as the control input at the beginning that satisfies the economy driving requirement in long run. Within about 10 sec, the host vehicle reaches close to the peak economy speed and continues cursing ahead at the best operating point. Secondly, the behavior of the host vehicle due to a slow speeding preceding vehicle at 5.5 m ahead is illustrated in **Fig. 4**. Although the system recommended a high initial acceleration in the first case, due to a slow starting preceding vehicle, it estimated the appropriate control action to keep a safe range clearance. Avoiding braking is a key point in economy driving, which is realized this scenario. The control input is generated in such a way that the range clearance is adjusted without any braking. The fuel consumption ratio is also shown in the graph in terms of instant and cumulative values.

Finally, comparative fuel consumption rates for a complete travel on a road section in a pseudo-realistic traffic environment of AIMSUN NG are observed. The simulations in AIMSUN NG are conducted under two different scenarios. The test environment including road network and traffic signaling systems and the route/course for the tests of the host vehicle in AIMSUN NG is shown in **Fig. 5**. In the test network, the roads are of two lanes and there are two traffic signal points in between two sections. In the tests, only the longitudinal motions are considered. The lane changing option is not included in this algorithm or tests, and it is left to the wish of the default system as per AIMSUN NG lane changing model.

In these tests, a car is forced to stop at the beginning of the section, and then it is set as the host. Next, the host vehicle is driven up to the end of the section where it is stopped in the red signal. For the same initial conditions in two separate run, the host vehicle is controlled by the developed ecological method and Gipps-based method implemented in AIMSUN NG [7][8]. Ten different vehicles in distinct traffic conditions are tested on route1 shown in **Fig. 5**. Since in idling time fuel consumption is constant, it is not counted in this test. Average results of 10 different vehicles in various distinct situations are taken for analyzing the performance. It is found that when the vehicles were controlled by Gipps-based method in AIMSUN, for a travel of about 661.21 m, 67.58 ml of gasoline fuel is consumed, that yields an economy rate of 9.78 km/l. In the case of the ecological driving by the developed system, only 61.48 ml of fuel is consumed for a travel of 660.70 m that yields an economy rate of 10.75 km/l. The improvement in economy rate is achieved by 9.86%, or fuel saving of 6.09 ml. This

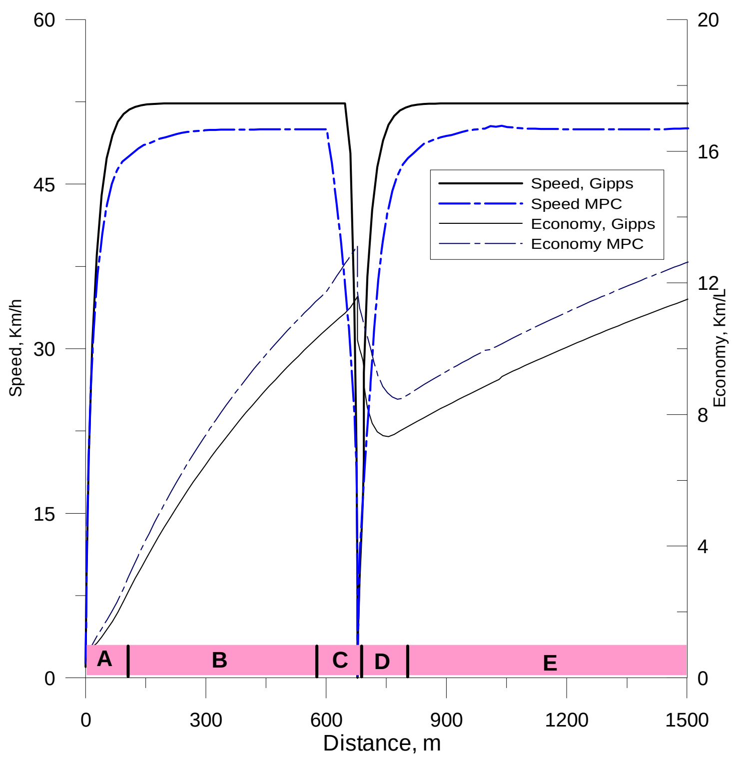


Figure 6- Scenario in the driving course on *Route*-2 in AIMSUN NG. Comparison of ecological and typical Gipps based vehicle.

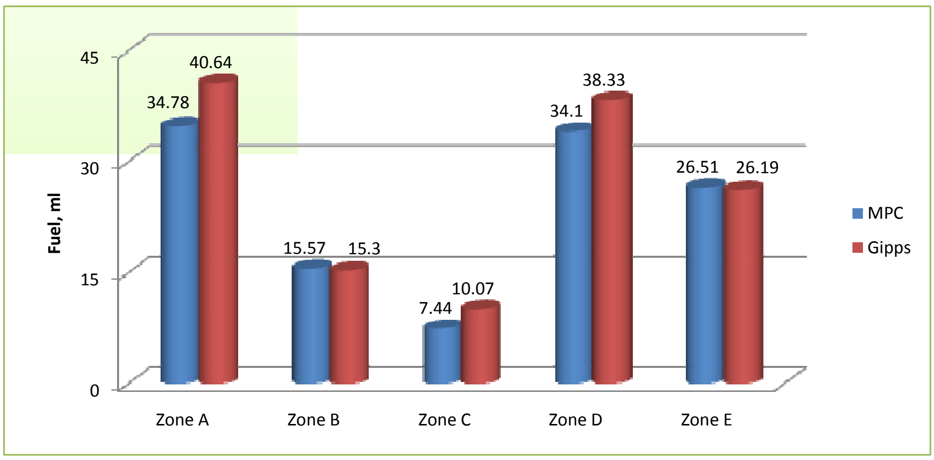


Figure 7- Fuel consumption in each zone shown in Fig.3.

comparative result signifies effectiveness of the proposed system. It is obvious that if the length a road section, in which a vehicle has to start running and then stopped, is shorter then the proposed method yields better improvements than Gipps based vehicle. Therefore the proposed ecological system would be more suitable for urban roads where a vehicle faces frequent traffic signals or traffic jam. To verify the comparative fuel consumption in speeding up for stand still, cruising and stopping modes another test has been conducted on *Route*-2 shown in **Fig. 5.**

Figure 6 shows the comparison of the proposed model predictive ecological driving with a typical Gipps based vehicle in AIMSUN NG simulator tested on *Route*-2. A vehicle at typical traffic situations is controlled to drive through the *Route*-2 by the proposed method. In the same way with and same initial conditions, the vehicle is then driven by the Gipps based default system in AIMSUN NG.

Figure 6 shows the speeding scenario in terms of traveled distance. The total travel distance of about 1500 m is divided into five zones namely, *A*, *B*, *C*, *D*, and *E*, in which the vehicle stops at the end of the first section due to red signal in both cases. At Speeding up (Zone *A*), high acceleration is generated in both cases, but near the peak speed of the proposed method shows slower acceleration. This softness in acceleration at approaching the maximum steady speed reflects the ecological behavior, since the fuel consumption increases abruptly at higher speed due to high acceleration. In the case of a red signal at the end of the first section, the vehicle controlled by the proposed model predictive control method began decelerating much earlier than the Gipps based vehicle (zone C). This attained behavior of maximizing the coasting time before a stop is very important for realizing ecological driving. The cumulative fuel economy of the proposed method is found better than the Gipps based method. At the end of traveling 1500 m the proposed model predictive vehicle achieved a fuel economy of 12.38 km/l whereas Gipps based vehicle it is 11.49 km/l.

Figure 7 shows the further break up of the scenario in the terms of distance zone in which the vehicle is accelerating, cruising or braking. It shows the exact amount of fuel consumed in each zone by the both systems. During speeding up (zone *A* and *D*) and stopping plus idling (zone *C*), the proposed model predictive ecological vehicle consumed much less amount of fuel compared to the vehicle driven by Gipps based algorithm. Whereas at cruising at steady speed (zone *B* and *E*), fuel consumption in both systems are almost the same. This reveals the necessity of such an ecological assist system in urban road-networks where accelerating and braking events are very frequent due to traffic signals or traffic congestion.

CONCLUSIONS

A novel development of Ecological Driving Assisting System using model predictive control has been presented in this paper. The model predictive control system generates appropriate control inputs and avoids unnecessary braking and acceleration in various driving situations to minimize the fuel consumption per unit distance travelled. Comparative results reveal the significant achievement in fuel economy for long run travel. Further fine tuning and enhancement of the system with incorporation of a human interface may lead to realize such assist system, that would surely play a significant role to save the ecological systems.

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