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Ecological driver assistance system using model-based anticipation of vehicle–road–traffic information

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Abstract: This study presents a novel concept of an ecological driver assistance system (EDAS) that may play an important role in intelligent transportation systems (ITS) in the near future. The proposed EDAS is designed to measure relevant information of instant vehicle–road–traffic utilising advanced sensing and communication technologies. Using models of vehicle dynamics and traffic flow, it anticipates future situations of the vehicle–road–traffic network, estimates fuel consumption and generates the optimal control input necessary for ecological driving. Once the optimal control input becomes available, it could be used to assist the driver through a suitable human interface. The vehicle control method is developed using model predictive control algorithm with a suitable performance index to ensure safe and fuel-efficient driving. The performance of the EDAS, in terms of speed behaviour and fuel consumption, is evaluated on the microscopic transport simulator AIMSUN NG. Comparative results are graphically illustrated and analysed to signify the prospect of the proposed EDAS in building environmentally friendly ITS.

1 Introduction

The demand for environmentally friendly transportation systems has increased greatly to reduce both the dependency on oil and the impact on the environment such as air pollution and global warming. Researchers, in recent years, have set their main focus on developing vehicles that consume the least amount of fuel to meet such demand. It is expected that intelligent transportation systems (ITS), through advancement in new sensing, communication and information technologies, may provide solutions to such demand to save the ecological balance of the earth. Progress in innovative hybrid cars, electric cars and advanced traffic management system are some of the milestones in achieving comprehensive, environmentally friendly transportation systems. Beside various physical factors, driving style has a great influence on vehicle emissions and energy consumption [1]. Driving style has the capacity to improve the driving efficiency of a vehicle significantly. A recent experiment that used an ecological-driving contest method conducted on urban roadways showed that reduction in fuel consumption can be as high as 25% [2]. Generally, fuel economy is maximised when accelerating and braking events are minimised [3, 4]. Therefore a fuel-efficient or ecological strategy would be to anticipate what is happening ahead, drive with acceleration and braking as little as possible, cruise at the optimal velocity and maximise coasting time at stops. Since stochastic and time-varying road-traffic information affects driving behaviour, a simplified system that does not anticipate situations ahead would be unable to achieve effective ecological driving behaviour.

Recently, assistance for ecological driving in various forms has emerged. Speculative features of ecological driving are available in the form of driving tips [3, 4]. Some recently manufactured cars have an ecological indicator that shows green 'ECO' mark to a driver when it consumes little or no fuel. A driver would find his driving as ecological only when he maintains a steady velocity at a reasonable velocity or brakes the car. Nissan launched an off-board eco-driving support service for some users in which, after driving record is sent to a telemetric data centre for off-line analysis, advice is sent to the driver for improving his driving style in the next time. Based on the past performance they have proposed an on-board assist system to motivate the driver for ecological driving by showing his comparative driving efficiency, his position in fuel composition ranking etc. [5]. A recent work in determining ecological strategy uses an optimal control approach in which only the model of the engine in terms of velocity, gear ratio and load is considered [6]. A more realistic approach to assisting a driver uses information of traffic signal, congestion, road gradient and distance between cars, and the advice is given in a very general form, such as 'keep driving' or 'reduce pressure on pedal', depending on motivation of the driver [7]. However, existing approaches of ecological driving assistance are very superficial, they do not provide concrete information such as the level of velocity or acceleration required for long-term fuel-efficient driving by analysing current vehicle–road–traffic situation and its trend.

This paper explores a novel concept of an ecological driver assistance system (EDAS) that can be set on-board to guide a driver emphasising long-term fuel-efficient driving. It measures states of the host vehicle and surrounding vehicles, and of traffic signals utilising advanced sensing technologies. After receiving relevant information, it anticipates future states of vehicles using their dynamic models. Based on the anticipated future states and the fuel consumption model of the engine, it calculates the optimum vehicle control input required for ecological driving [8]. Once the optimal control input becomes available, a suitable human interface in the EDAS conveys it to the driver. For computing ecological vehicle control actions, in this paper, a model predictive control approach is formulated. The model used in this study expresses the dynamic relationship among the host vehicle, any preceding vehicle and the traffic signal systems at any instant. A suitable performance index is chosen to ensure a safe and fuel-efficient driving. The optimisation of control input is accomplished using the continuation and generalised minimum residual (C/GMRES) method [9, 10]. For simplicity in this paper, however, the human interface component is omitted and the control input generated by the system is directly fed to the host vehicle, focusing mainly on the vehicle control aspects.

The aim of this study is to present the concept of an EDAS, develop its control algorithm and evaluate it through simulation in a traffic simulator. The performance of the EDAS in terms of velocity characteristics and comparative fuel consumption will be observed. Obtained results will be analysed to evaluate the computational soundness of the algorithm and the ability of the EDAS to drive a car ecologically.

The rest of the paper is organised as follows. The fundamental concept of an EDAS in a broad view is introduced in Section 2. The vehicle control section of the EDAS including problem formulation, fuel consumption model and algorithm using non-linear model predictive control is presented in Section 3. Section 4 describes simulation results, followed by discussion in Section 5. Finally, conclusions and future work are included in Section 6.

2 Ecological driver assistance system

This section presents the fundamental concept of the proposed EDAS in a broad view. Ecological driving is a way of driving intended to enable energy conservation, reduce emissions of carbon dioxide and contribute to the effort to reduce global warming, while maintaining safe driving. Energy consumption and emission in a vehicle depend on various physical factors such as engine condition, road condition, weather etc. Driving style also has a great influence on energy consumption for the same physical factors. Aggressive driving, with speeding, rapid acceleration and braking, wastes energy considerably. Avoiding unnecessary acceleration and braking, and cruising at the optimally economical velocity are not very easy while driving on crowded urban roadways directed by traffic signals. Therefore an assistance system could be very effective to support a driver to be more ecological in the context of instant traffic situation. With this motivation, here, we propose an EDAS that generates optimal control input and assists a driver by anticipating the states of the host vehicle, flow of the surrounding traffic and status of traffic signals. The overall concept of the proposed EDAS for a host vehicle is illustrated in Fig. 1. The EDAS comprises three functional components, namely, measurement of vehicle–road–traffic information, generation of the vehicle control decision and assistance of a driver through a human interface.

The EDAS measures the status of surrounding vehicles and traffic signals using advanced sensing technologies. Various sensory mechanisms can be used for this purpose. The GPS-based navigation system may be used to obtain the position of the vehicle, and road alignment, slopes etc. On-board cameras or laser sensors can be used to determine the velocity, distance, position of the preceding and surrounding vehicles. In the future, it is expected that data could be collected directly through inter-vehicle and vehicle–infrastructure communication systems. Using inter-vehicle communication, the host vehicle can receive information instantly when the driver of the preceding vehicle starts depressing the accelerator or brake pedal. Through communication with road infrastructure, status of traffic signals and their exact timing (e.g. how many seconds are remaining in red or green signal) can be obtained. In these ways, various data necessary for decision making can be perceived using advanced ITS technologies to realise such an EDAS.

Once the relevant information is collected, the vehicle control decision can be made. The control action to be

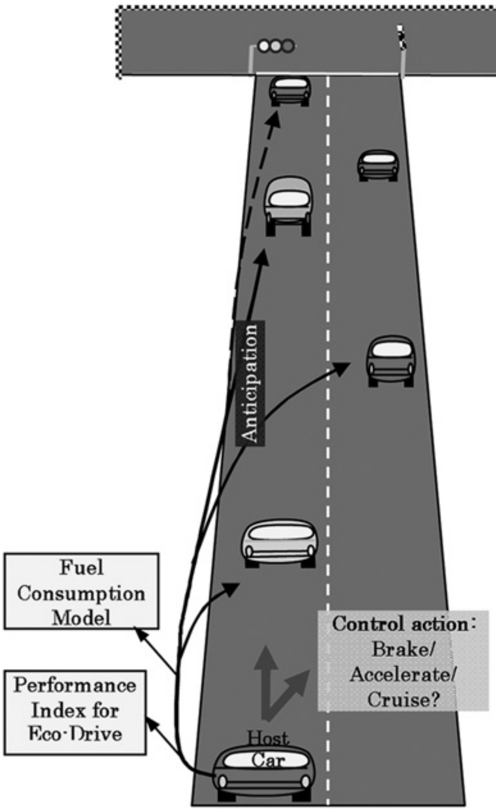

Figure 1 *Concept of EDAS through anticipation of traffic*

decided can be the level of acceleration or deceleration, steering movement, lane changes etc. The EDAS is proposed to use a set of dynamic models of vehicles to analyse their trends and anticipate future situations of the host vehicle and surrounding traffic. It uses a consumption model for estimating consumed fuel in the host vehicle. With a suitable performance index, it generates an ecological action that is suitable for long-term fuel-efficient driving while maintaining a safe distance from other vehicles. In these ways, the vehicle control input is generated by rigourous reasoning through some optimisation method.

Once optimal input is computed, using some sort of human interface, the control input can be transmitted to the driver in a friendly manner as a recommendation for ecological driving. A human interface can be a visual signal, auditory sound or mechanical vibration, or any suitable medium. Designing of such an interface, however, is outside the scope of the current study. The following section describes the details of the decision-making component of the EDAS including modelling, performance index, prediction and optimisation algorithm for a simplified vehicle control problem.

3 Vehicle control method for the EDAS

This section describes details of the decision-making component of the EDAS considered in this study. The vehicle control problem must address time-varying traffic, which is non-linear in nature and is a series of discontinuous events. In addition, it is essential to anticipate future situation of the traffic using its model. Based on these aspects, non-linear model predictive control with a fast optimisation algorithm is chosen as the decision-making method for the EDAS.

3.1 Model of vehicle dynamics

A simplified method for controlling a vehicle ecologically has been formulated. Only the longitudinal motion in a plane and a straight road are considered. The immediately preceding vehicle and status of traffic signal ahead are taken into account in the modelling (Fig. 2). It is assumed that the influence of surrounding vehicles can be approximated by the status of the immediately preceding vehicle. In this modelling, the vehicle–traffic non-linear system is assumed to be governed by the following state equation

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

where $\boldsymbol{x}(t) = [x_1(t), x_2(t), x_3(t), x_4(t)]^{\mathrm{T}}$ denotes state vector representing locations and speeds of the host vehicle ($x_1(t)$ and $x_2(t)$) and the preceding vehicle ($x_3(t)$ and $x_4(t)$), respectively. The control input $u(t)$, accelerations/deceleration of the host in longitudinal motion, is bounded by an inequality constraint in a simplified form of $-u_{\max} \le u(t) \le u_{\max}$. Although magnitudes of physical limits of actuators (the accelerator and the brake) are not the same, here symmetric limits are chosen for computational simplicity. It is assumed that such limits do not interfere in ecological decision making, since it usually avoids extreme magnitude of acceleration and deceleration. The time-varying parameter $p(t)$ represents the model of the acceleration/deceleration of the preceding vehicle. The preceding vehicle is assumed to be continuing its motion at the same current rate of acceleration over the prediction horizon. In the absence of a real preceding vehicle, a dummy vehicle is assumed to be maintaining an ideal velocity and range ahead of the host vehicle. The traffic control signal is also taken into account by utilising this dummy preceding vehicle. In case of a red or yellow signal at a junction point, this dummy vehicle is set to be idling at the stopping point. In this way, the traffic signalling system is also included in the model indirectly. In this simplified system, it is necessary to measure the velocity, location and acceleration of both the

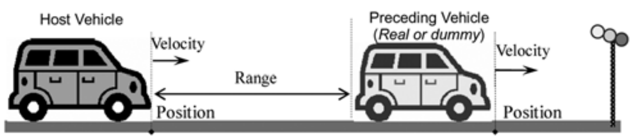

Figure 2 *Vehicle control problem including a host vehicle, a preceding vehicle and traffic signal*

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host and the preceding vehicles. Therefore existing sensing technologies such as sensor, camera etc. can be used to build an on-board system to collect such data.

3.2 Fuel consumption model

Basically, fuel consumed in a vehicle depends on various factors related to the engine speed, torque, gear ratio, temperature, calorific value of the fuel, efficiency and many others. Exact derivation of the fuel consumption equation would be very complex, which is not the main objective here. Instead, an approximate and differentiable function is enough to develop an algorithm for the proposed EDAS. The fuel consumption model is used in the objective function of the algorithm and for performance evaluation in terms of fuel efficiency. In this consumption model, it is assumed that a vehicle is either idling, cruising at constant velocity, accelerating or decelerating. The consumption rates (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

$$F_a = (c_1 + c_2 a v) \tag{2}$$

where c_1 and c_2 are constants, a and v are acceleration and velocity of the vehicle, respectively. The consumption of a cruising vehicle is approximated by

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

where k_1 and k_2 are constants, and v_m is the cruising velocity at which the vehicle fuel economy, in km/l, is maximum. The fuel consumption model presented here is originally derived from [11] and used in AIMSUN NG [12]. The above fuel consumption equations are combined to constitute an approximate continuous and differentiable equation by multiplying suitable sigmoid and Gaussian functions. Using the notation of velocity and acceleration used in (1), the fuel consumption per second is approximated as

$$\begin{aligned}\text{Fuel} = {} & \frac{Fd}{1 + e^{\beta(u(t)+C)}} + e^{(-(u(t)/\sigma)^2)} \\ & \times (k_1 + k_2 x_2(t) + k_3 (x_2(t))^3) + \frac{c_1 + c_2 u x_2(t)}{1 + e^{-\beta(u(t)-C)}}\end{aligned} \tag{4}$$

Here in (4), for simplicity, cruising fuel consumption rate (3) is inserted after defining $k_3 = k_1/(2v_m^2)$. Parameters of the sigmoid and Gaussian functions are chosen in such a way that the function values change rapidly in respect to very small change in acceleration or deceleration.

3.3 Implementation of model predictive control

The inequality constraint relating to the control input is redefined in the form of equality constraint using a dummy input u_d and expressed as

$$C(\boldsymbol{x}(t), u(t), p(t)) = (u^2(t) + u_d^2(t) - u_{1\,\max}^2)/2 = 0 \tag{5}$$

In the model predictive control process, the following optimal control problem is solved at each time t with the current state $x(t)$ used as initial state, and a prediction horizon from current time t to T ahead

$$\text{minimise } J = \int_t^{t+T} L(\boldsymbol{x}(t'), u(t'), p(t'))d(t') \tag{6}$$

In this formulation, the cost function is considered to have following form

$$L(\boldsymbol{x}(t), u(t), p(t)) = w_1 \frac{\text{Fuel}}{x_2(t)} + w_2 R_{\text{error}}^2(t) + w_3 (x_2(t) - v_d)^2 \tag{7}$$

where $R_{\text{error}}(t) = (h_d x_2(t) - x_3(t) + x_1(t) + l_v + r_0)$ represents the deviation from desired range clearance from the preceding vehicle, in which h_d is the desired headway, l_v is the length of the vehicle and r_0 is the minimum separation required between vehicles when velocity is zero. The cost function L consists of three terms namely the fuel consumption rate, cost because of unsafe range clearance and cost for not moving forward towards the most economical or recommended velocity. The third term in the cost function is needed to force the vehicle to move forward for long-term advantages even though the acceleration cost is very high. The reference velocity v_d can be equal to either the most economical cruising velocity of the vehicle or the velocity limit imposed on the road section. Each term of them is multiplied by a varying weight w_1, w_2 and w_3, respectively. At each step in the prediction horizon, these weights represent the relative contextual merits of the three cost terms in the subjective situations. The weight w_2 is calculated as $w_2 = \gamma e^{-\alpha R}$ that ensures a large penalty at closing range R (distance of the preceding car), and a negligible weight when the preceding vehicle is far away. Although weight w_2 is calculated using the function of states, it is used as a constant in the cost function. The weights w_1 and w_3 are kept constant at some suitable values.

The Hamiltonian function is formed using (1), (5) and (7), as follows

$$H(\boldsymbol{x}, \lambda, u, \mu, p) = L(\boldsymbol{x}, u, p) + \lambda^T f(\boldsymbol{x}, u, p) + \mu^T C(\boldsymbol{x}, u, p) \tag{8}$$

where λ denotes the co-state, and μ denotes the Lagrange multiplier associated with the constraint [13, 14]. Using the given performance index (6), for a prediction horizon T discretised into N steps of size h, from virtual time $t' = nh$ to $t' = nh + T$, the instant and future vehicle control inputs $\{u_{nh}(t')\}_{t'=nh}^{t'=nh+T}$ are optimised. C/GMRES is used to

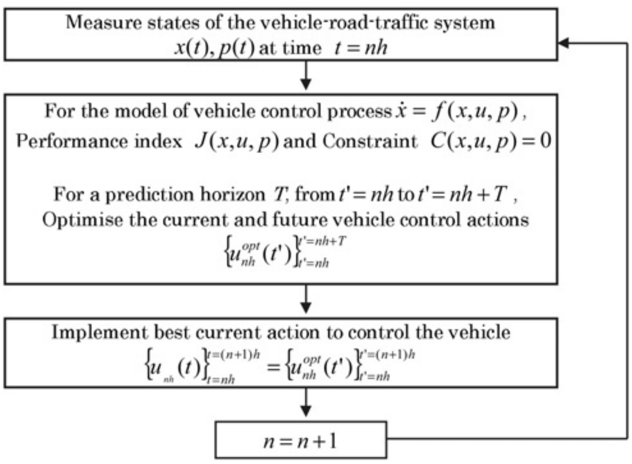

Figure 3 *Flowchart of the control algorithm described for the EDAS in this study*

generate the sequence of control inputs. Since this method does not require iterative searches, it requires less computational power and can be implemented for the proposed vehicle control problem in real time [9]. Therefore a set of optimum actions, $\{u_{nh}^{\mathrm{opt}}(t')\}_{t'=nh}^{t'=nh+T}$, for the instant and future time is available after optimisation. The optimal input corresponding to the current time is used to control the vehicle (or to assist a human driver, in case of a real driver assistance system) up to the next sampling instant

$$\{u_{nh}(t)\}_{t=nh}^{t=(n+1)h} = \{u_{nh}^{\mathrm{opt}}(t')\}_{t'=nh}^{t'=(n+1)h} \tag{9}$$

At each time step, the immediate input calculated by this way is used to control the host vehicle, and the whole process is repeated throughout the driving course, except at idling time. The whole procedure is shown in Fig. 3. Repeating the whole process and renewing the control input at each sampling time is required to overcome the influence of varying traffic and modelling error in computation. Only the initial state value corresponding to the time t is used as the actual input to the system on which the optimal control input is determined over the horizon. Therefore the whole system retains the feature of state feedback control law.

4 Simulation results

4.1 Setting for simulation

The proposed EDAS is evaluated through simulation on a Ford-Fiesta car in AIMSUN NG microscopic traffic simulator. The control input generated by the EDAS is directly applied to drive the vehicle, assuming the driver executes exact assistance in the case of a real system. Considering the changing nature of traffic, the prediction horizon is set at $T = 10$ s, which is split into $N = 10$ steps of each 1.0 s. The simulation has been conducted by choosing suitable values of the parameters as $u_{1\max} = 3.70$ m/s^2, $\beta = 120$, $C = 0.09$, $\sigma = 0.11$, $h_{\mathrm{d}} = 1.3$, $w_1 = 4.0$, $w_3 = 1.25$. The parameters in w_2 is set as $\alpha = 0.2$, and γ is set at 3.0, 9.0 or 15.0 when $\mathrm{d}R/\mathrm{d}t > 1.0$, $|\mathrm{d}R/\mathrm{d}t| < 1.0$ or $\mathrm{d}R/\mathrm{d}t < -1.0$, respectively. Fuel consumption parameters of a Ford Fiesta car are taken from [12, 15, 16], which are $F_{\mathrm{d}} = 0.10$, $k_1 = 0.222999$, $k_2 = 0.0033529$, $k_3 = 0.000042$, $c_1 = 0.42$, $c_2 = 0.26$.

For conducting the simulation, an extension of AIMSUN NG simulator is created through application program interface. It is used to collect relevant information of the host vehicle and other traffic, road and traffic control signals from the outside of the simulator, and to relay the vehicle control input at each sampling time.

The car following model implemented in AIMSUN NG is based on the Gipps model [12, 17]. For simplicity in representation here we use a notation 'EDAS vehicle' to mean a vehicle that is controlled according to the EDAS, the same applies to 'Gipps vehicle'. Therefore fuel efficiency of an EDAS vehicle is compared with fuel efficiency of Gipps model-based vehicles. In Gipps model, the velocity of a vehicle at $t + \tau$ is chosen either from the intention to achieve the desired velocity, or to keep a safe velocity if there is a slower or decelerating preceding vehicle, which is given as

$$v_n(t+\tau) = \min\{v_n^a(t+\tau),\, v_n^b(t+\tau)\} \tag{10}$$

where (see (11))

and V_n^*, a_n and d_n are the desired velocity, maximum acceleration and maximum deceleration, respectively, of the vehicle n. In AIMSUN NG, values of these parameters among vehicles are randomly sampled from a truncated Normal distribution [12].

A pseudo-realistic traffic environment is formed in AIMSUN NG, and a test route is selected for simulation. The image of the test route with traffic densities is shown in Fig. 4. The road in the route consists of two lanes, three sections with two junction points that are controlled by the traffic signals. The lane changing option is not included in

$$\begin{aligned} v_n^a(t+\tau) &= v_n(t) + 2.5 a_n \tau \left(1 - \frac{v_n(t)}{V_n^*}\right)\sqrt{0.025 + \frac{v_n(t)}{V_n^*}} \\ v_n^b(t+\tau) &= d_n\tau + \sqrt{d_n^2\tau^2 - d_n\left[2\{x_{n-1}(t) - s_{n-1} - x_n(t)\} - v_n(t)\tau - \frac{v_{n-1}^2(t)}{d'_{n-1}}\right]} \end{aligned} \tag{11}$$

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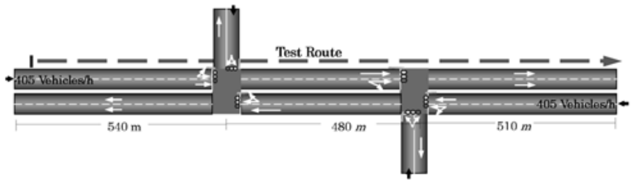

Figure 4 *Image of the test route in AIMSUN NG used in simulation*

this algorithm or tests, and it is left to the wish of the default system as per AIMSUN NG lane changing model. The traffic signals at the junctions are synchronous and set in a 90 s cycle including 50 s of Green period and 40 s of Red period, with respect to the route. The length of the road is 1530 m, on which the velocity limit is set at 50 km/h. The traffic flow rate at the entrance of the route is 405 vehicles per hour, which includes cars, taxis and trucks. They appear stochastically over the period. Therefore it is assumed that they represent the human driving in a realistic scenario. In the simulation, an arbitrary car is tracked as the host vehicle and is stopped within 30 m from the entrance. At each sampling time, states of the host vehicle and traffic are fed into the EDAS that computes the required input using the above formulated algorithm. Then the host vehicle is driven as per instruction from the EDAS until it completes the route of 1.5 km and exits. For the purpose of comparison, with the same initial situations, the same car is also run using Gipps model in a separate trial. The other surrounding vehicles run as per their default settings and interact with each other. After completion of the route, the amount of fuel consumption is measured in both cases of EDAS and Gipps model for comparison.

4.2 First observation

Although the same driving scenario never repeats in a time-varying traffic environment, initial conditions of the vehicle with the EDAS and Gipps models are set at equal values. For a meaningful comparison, a total of 63 vehicles are observed, each in separate simulations. The fuel consumed by these 63 vehicles is illustrated in Fig. 5 in the same sequence of their entrance and observation. In the cases of 49 cars out of 63, the EDAS method outperformed Gipps model in terms of fuel consumption. Complex and varying situation because of signal timings and influences of other vehicles caused Gipps model to be superior in 14 cases. The horizontal straight lines represent the mean fuel consumption of the vehicles controlled by the two models. When the vehicles were controlled by the Gipps method, for a travel of 1.5 km, an average fuel of 104.64 ml is consumed, that yields an economy rate of 14.34 km/l. In the case of the EDAS vehicle, only 95.28 ml of fuel is consumed that yields an economy rate of 15.99 km/l. On average, the EDAS vehicle was able to save 9.82% of fuel compared to Gipps model vehicle. This tremendous achievement signifies the prospect of the EDAS in realising ecological ITS.

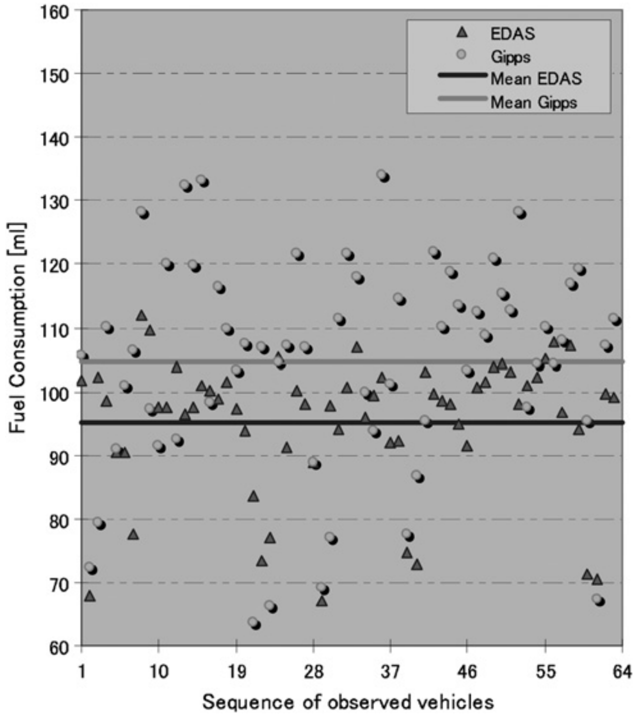

Figure 5 *Fuel consumptions of various vehicles while driving using the EDAS and Gipps model on the test route*

4.3 Second observation

To have a closer look at the driving strategy found and used in the EDAS, a typical case is considered in which the interacting environment remains the same for the observation of each method. On the same route, the traffic densities are set to very low so that no preceding or surrounding cars are available. The EDAS vehicle is compared with two typical Gipps vehicles. The vehicle in Gipps I method is forced to set the desired velocity at 50.24 km/h and a maximum desired deceleration rate at -3.75 m/s^2, which are very similar to those of the EDAS vehicle. Apparently it becomes close to an ecological vehicle in terms of parameters. Gipps II, on the other hand, has a desired velocity of 53.24 km/h, and a maximum desired deceleration at -5.00 m/s^2. Other parameters in Gipps model (11) of both cases are kept unaltered as per default values. The speeding characteristics of the vehicles controlled by these three methods in the same environment are illustrated in Fig. 6*a*.

The EDAS vehicle generates sufficiently large acceleration at the beginning that satisfies the desired ecological driving requirement in the long run. Within a short time, the EDAS vehicle reaches close to the most economical velocity and continues cruising ahead at the best operating point. But just before reaching the steady-state velocity, it lowers the rate of acceleration that helps reduce fuel consumption. When the car approaches the second intersection, the traffic signal turns to red, and the car must stop. It starts to decelerate earlier compared to the Gipps I

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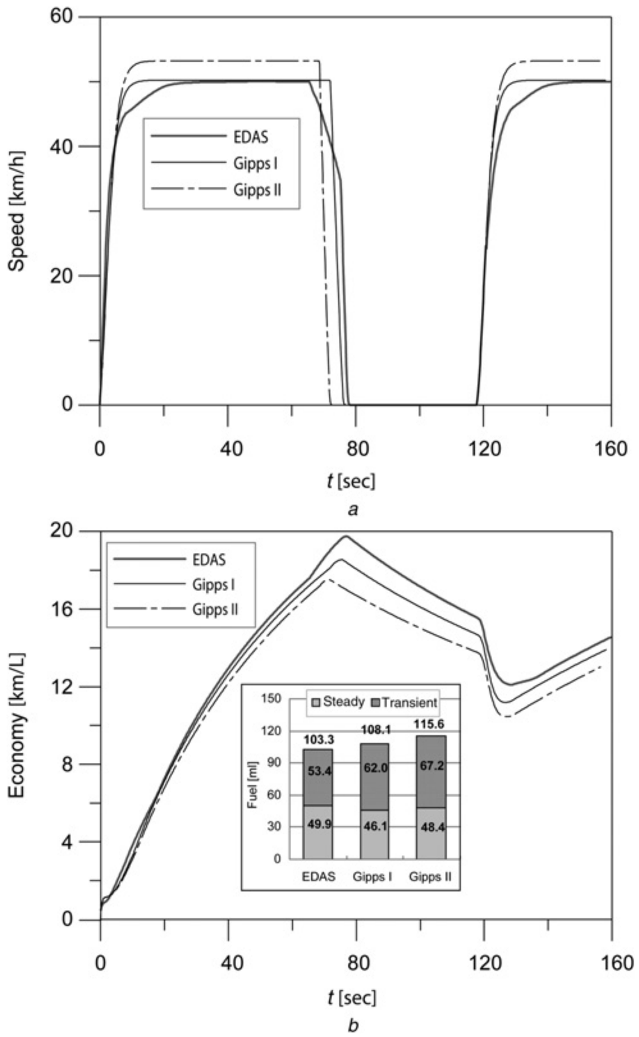

Figure 6 *Comparison of the EDAS vehicle with Gipps I and Gipps II*

a Speeding
b Instantaneous fuel efficiency, and, in the bar graph, total fuel consumption during steady and transient periods

and the Gipps II vehicles when the stopping scenario appears in its prediction horizon. This slower deceleration ensures utilisation of kinetic energy and cutting off fuel to the engine. In this way, it also reduces the idling time and fuel wastage at the red signal. When the signal turns green, the EDAS vehicle restarts in a similar fashion and finally exits the route.

Fig. 6*b* shows instantaneous fuel efficiency achieved by these three methods. At the completion of the route, total fuel consumption is 103.3, 108.1 and 115.6 ml by the car driven by EDAS, Gipps I and Gipps II methods, respectively. Although the EDAS and Gipps I cars have almost the same cruising velocity, because of adjustment of acceleration and deceleration by proper prediction, the EDAS car was able to save fuel by 4.6%. Compared to Gipps II, the EDAS car saved 11.9% of fuel. The fuel consumed in the transient period and the steady-state period is also investigated for the same observation. The transient period is defined as the time necessary for travelling 100 m after starting and 100 m before stopping. Other times are considered as steady period. The inserted bar graph in Fig. 6*b* illustrates the fuel consumptions of the cars driven by these three methods. It is revealed that, during the steady period, consumption in vehicles driven by all the methods is very similar. On the other hand, consumption during the transient periods varied significantly. During the transient periods, the Gipps I and the Gipps II vehicles, respectively, consumed 16.1 and 25.8% more fuel compared to the EDAS vehicle.

5 Discussion

The fundamental idea behind the proposed EDAS is unique since it anticipates interactions between the host vehicle and other vehicles and computes the optimal control input suitable for achieving long-term fuel-efficient and safe driving, whereas other assistance systems neither anticipate future traffic nor compute the exact optimal control input quantitatively. The EDAS vehicles were observed in various scenario such as starting, stopping, cruising and in range adjusting. It was found that the EDAS vehicle had comparatively less variation in acceleration or braking on such situations. The smooth velocity profile observed in the simulated results indicated computational soundness of the proposed EDAS algorithm. Comparative fuel savings by the EDAS vehicle is very encouraging. During steady-state driving, the EDAS vehicle consumed almost the same fuel as the other vehicles, whereas during the transient periods it reduced fuel consumption significantly. In the presence of a decelerating preceding vehicle or a red signal ahead it braked gradually through anticipation, which ensured complete utilisation of kinetic energy before stopping. In some cases, the EDAS vehicle was required to brake aggressively because of the appearance of a red signal when it was already close to a junction. If the signal timing is known a priori, such aggressive braking can be replaced by gradual and smooth braking that would further improve fuel efficiency. Therefore it is obvious that such an EDAS could play a significant role in reducing fuel consumption on urban roadways where cars are required to stop more frequently because of traffic congestion or traffic signals.

Although the EDAS was mainly developed to drive a car using the least amount of fuel, it also ensured safe driving in usual urban traffic scenarios, such as sudden braking of the preceding car, change in traffic signal, being over taken by a vehicle from other lane etc. Possibility of collision increases when the clearance between the host and the preceding car is shorter than the typical distance. In such situations, the EDAS emphasised on avoiding collision by properly braking the car. This collision avoidance was accomplished by the second term in the cost function (7). The value of weight w_2 in the cost function increased exponentially on such decreasing of range clearance, which

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ensured higher priority for maintaining safer distance by trading off the cost because of fuel consumption. In this study, it was assumed that there were no abnormal situations or traffic violations caused by the surrounding vehicles. Since the purpose of the EDAS was not for automatic driving, we assumed that the driver could handle such abnormal situations in reality, and such an extensive investigation of safety issues was not conducted in this study.

6 Conclusions

An EDAS using model-based anticipation of traffic situations has been presented in this article. The formulation of the vehicle control problem and implementation of model predictive control algorithm has been described in detail. It has been observed that the EDAS can generate appropriate vehicle control input by rigorous reasoning using the proposed algorithm in a pseudo-realistic traffic environment. An ecological driving strategy for fuel-efficient and safe driving in various situations is realised that helps minimise fuel consumption for a given travel distance. Significant savings in fuel consumption compared with other vehicles illustrates the prospect of the proposed EDAS in future ITS. Realisation of such an EDAS would play a significant role in ITS and contribute to the ecological balance of the earth.

In future, the scope of the proposed algorithm could be enhanced considering road gradient and alignment, and lane changing option. Further fine-tuning and introduction of a human interface would need to be conducted to realise such assistance systems.

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