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Developing eco-driving algorithm at the signalized intersection using traffic information

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Summary

This paper focuses on developing of the eco-drive system using state information of nearby and target vehicles and intersection information. It can determine the speed profile that optimized fuel efficiency by sharing intersection shape, SPAT data, traffic situation, and vehicle status information using WAVE communication. Therefore, the paper proposes eco-driving control system to improve fuel efficiency by using Coasting reflecting real-time traffic situation information and MPC(Model Predict Control) that apply fuel consumption and forward vehicle condition. Two control systems help improve fuel efficiency and decrease CO2 emissions result from reducing rapid acceleration and deceleration and minimizing unnecessary idling time.

Keywords: Autonomous, Control system, Simulation, City traffic, Emission

1 INTRODUCTION

Autonomous vehicles that combine various technologies such as vehicle, communications, and road infrastructure are the keywords in the field of science and technology in recent years. As environmental issues are getting attractive, Eco-driving technology also getting more attentions. By realizing autonomous driving technology with eco driving, we can reduce the consumption of fuels and air pollution either. Eco-driving techniques include reducing idling state, decreasing excessive decelerating or accelerating, maintaining a steady speed and driving in high gear state, and can reduce unnecessary fuel consumption by controlling the speed of the vehicle. Therefore, compared with a highway that maintains a constant speed, a great effect can be obtained in a city where many stop situations occur frequently and acceleration or deceleration is required to a large extent.

Asadi and Vahidi (2011) proposed a Adaptive Cruise Control(ACC) system that uses upcoming traffic signal information. The proposed system uses short range radar and traffic signal information to control arrival time at green light with minimal use of brake pedal, distance between vehicles and cruising at set speed[1]. Tien-Wen Sung (2015) presented a speed control scheme of eco driving at intersection to avoid frequent stop and go situation, smooth over the variation of vehicle speed, and improve the number of vehicles to pass through the intersection[2]. Kaijiang YU (2015) presented model predictive control system for eco driving of hybrid vehicle. The control system calculates optimal vehicle speed with traffic signal and road slope information to reduce unnecessary fuel consumption[3]. M.A.S. Kamal(2015) has considered model predictive control system for Ecological Driver Assistance System using model-based anticipation of vehicle-road-traffic information. Road information and Traffic condition are reflected indirectly in the control system by dummy vehicle velocity profile which is obtained experimentally on urban road[24-27]. Such experimented velocity profile is not efficient for reducing fuel consumption because the stopping velocity pattern is depends on the road-vehicle characteristics and traffic conditions. H.Rakha(2016) reflects traffic condition directly in the eco driving control system using traffic engineering concept. Traffic condition includes queue discharge time calculated by shock wave velocity generated by traffic signal and queue length[11]. Most of the work in the literature did not consider deceleration with coasting. But coasting should be considered in eco-driving control because the vehicle doesn't use fuel during coasting fuel cut. And eco-driving controller using traffic condition also should have robustness because traffic condition estimation includes large disturbance.

This paper focus on eco-driving system using vehicle parameters and intersection information. We focus on developing fuel optimal control using traffic conditions and coasting with fuel-cut. Since crossroads in downtown are occupied with many cars at the same time, traffic conditions are complicated. Therefore, there are many factors to consider. Accordingly, in order to calculate the fuel economy optimum speed in the eco-driving system, it is necessary to use the overall state information of the intersection as well as the state of the target vehicle and the front vehicle. For example, Acceleration or deceleration can be more accurately determined by using the information such as the shape of the entering the crossway, the total number of vehicles, SPAT(signal phasing and timing) data and the queue length, driving patterns such coasting.

Therefore, the paper proposes eco-driving control system to aim at reducing CO2 emissions and improving fuel efficiency by minimizing the time delay of vehicles and reducing unnecessary acceleration with estimating traffic conditions in real time at intersections. Traffic situation and individual vehicle information used in the above system can be obtained through V2X communication. In addition, high-precision vehicle position information can be received via UWB and GPS sensor. And vehicle sensor data such as speed and acceleration can be taken by CAN communication and DR sensor. Communication will use WAVE communication.

The eco-driving control system based on the above method was implemented using the Aimsun traffic simulation tool and python. We modeled the actual intersection (Gangnam, Seoul, Korea) and simulated considering a group of various vehicles in fixed signal. The CO2 emissions from the simulation were used as the evaluation index.

2 ECO DRIVING ALGORITHM USING TRAFFIC INFORMATION AND VEHICLE STATE

2.1 Algorithm for Estimation Traffic Situation

The traffic condition estimation algorithm estimates queue length and calculates residual signal time and queue clearance time using queue length. And applying queue clearance time and residual signal time, the estimation algorithm determine optimal velocity profile to minimize stop time of vehicle that pass through a crossway at stop line and unnecessary acceleration and deceleration. The traffic condition estimation algorithm is applied to all of the vehicle that enters a specific section. In this paper, we constitute the simulation environment like Figure 1 in order to exchange vehicle information by WAVE communication and UWB. The traffic condition estimation algorithm is as follows.

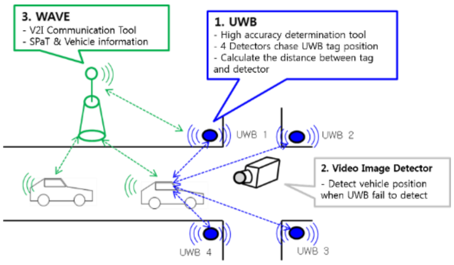

Figure 1 : Vehicle Movement(traffic condition) during traffic signal(Red=Left / Green=Right)

2.1.1 Queue Estimation

Queue length is estimated by a length, velocity, position information of the individual vehicle and traffic signal. If a vehicle enters service section of crossway, the algorithm determines the queuing vehicle by estimating the possibility of pass for individual vehicle in front of the vehicle during the current signal time. The algorithm predicts the possibility of pass of stop line using current signal time, velocity, position information if a vehicle keeps current velocity. And the condition of that is equation (1) [5] below.

$$D_{\mathrm{VtoS}} \geq (V_{veh}) \times (T_{remaining})\ \ if\ )\ P_{green}$$
$$D_{VtoS} \leq (V_{veh}) \times (T_{remaining})\ \ if\ )\ P_{red} \qquad (1)$$

Through these conditions, vehicles that can not pass through each lane are classified by queue length. Calculated using equation (2) [5] reflecting the length of the selected queuing vehicles and the minimum spacing. Because we consider multiple lane, we calculate the queue length considering the lane change of each vehicle.

$$Q_{Length} = (d_{clearance} \times N_{stop}) + \sum_{N_{stop}} L_{veh} \qquad (2)$$
$$d_{clearance} = 1.2\ \ (default)$$

2.1.2 Estimate Queue Clearance Time

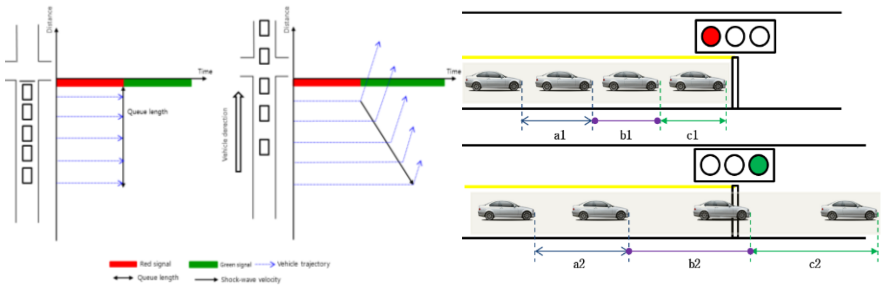

Figure 2 : Vehicle Movement(traffic condition) during traffic signal (Red=Left / Green=Right)

The algorithm estimates crossway passage time of estimated queuing vehicles during green phase, based on Shock Wave theory. In uninterrupted flow Figure 2, traffic signal data changes traffic condition and make Shock wave. Like Figure 2, when a phase is changed from red phase to green phase, queue release rate can be calculated by equation (3) [11].

$$W = \frac{q_m - 0}{k_m - k_j} \qquad (3)$$

A maximum traffic (q_m), maximum traffic density (k_m), and jam density (k_j) of the road can be calculated by Greenshield model like equation (4). Greenshield model expresses a relationship among velocity, density, traffic volume of traffic stream with assumption that velocity and traffic density are in linear relationship [11].

$$k_m = \frac{1}{2} k_j$$
$$q_m = k_m u_m = \frac{1}{4} u_f k_j \quad (4)$$

Using equation (3) and (4), we can predict stop time (T_{delay}) due to phase and waiting list. And the stop time (T_{delay}) can be expressed as equation (5) [11].

$$T_{delay(veh(k))} = \frac{Q_{Length(veh(k))}}{W} \ [s] \quad (5)$$

2.2 ECO Driving Algorithm

The Eco Driving Algorithm is applied to optimize the fuel economy considering the residual signal time and the queue clearance time. The algorithm determines the process that can optimize the fuel economy using the residual signal time, as follows.

(1) At green phase

- When the vehicle maintains vehicle speed at the current position, it can pass through the crossway during remaining green time, maintain constant speed.
- If the vehicle keeps constant speed and can’t pass for the remaining time, Deceleration profile is applied by determining the optimal time point considering the waiting list and residual time.

(2) At red phase

- Minimize rapid deceleration and idling time by applying deceleration profile depends on coasting considering the queue length and the remaining time.

(3) From red phase to green phase

- If there is no preceding vehicle, use the maximum acceleration of the vehicle to pass the intersection.
- If there is a front car, apply the optimal acceleration based on MPC algorithm that uses the distance between the cars and the fuel consumption of the front.

2.2.1 Coasting Model

Coasting can drive a vehicle with minimizing fuel consumption using the kinetic and potential energy of vehicle. With coasting, a vehicle doesn’t occur acceleration by engine because fuel-cut technology blocks fuel. And a vehicle is decelerated by a driveline efficiency and external drag force. The coasting model can be expressed by equation (6).

$$F_{coasing} = M_{veh} a_{coasting} = R_{efficiency} + R_{rolling} + R_{drag} + R_{grade} \quad (6)$$

The corresponding model can be acquired by vehicle test in a form of map data. Because the vehicle is tested at flatland, Resistance force by road inclination isn’t considered in map data. Therefore we add the value calculated by road inclination angle to Map data. Figure 3 is the Map data that we acquire with reflecting real vehicle information.

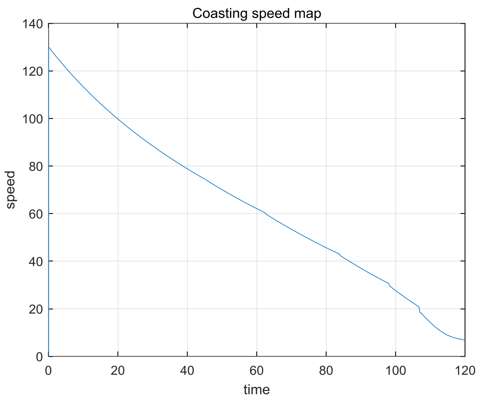

Figure 3 : Coasting Map data (target vehicle : Toyota Corolla Ascent 2004)[23]

2.2.2 Deceleration Profile Using the Coasting Model

A deceleration profile determines deceleration point of time reflecting the queue clearance time to reduce idling time and rapid deceleration when a vehicle approaches a crossway. Coasting reduces unnecessary deceleration, does not consume fuel but needs longer braking distance relatively. First, using current vehicle position, calculate the distance from the vehicle to stop line or waiting list. And then, calculate necessary braking distance and velocity at that time which need to use the coasting model. Decelerates a vehicle generally till velocity that can apply the coasting model, and then apply deceleration profile that minimize fuel consumption by coasting Acceleration.

2.2.3 Profile Using Model Predictive Control (MPC)

When the Eco-driving algorithm is applied to an individual vehicle, the delay occurs of nearby due to the applied vehicle. Such delays cause rapid acceleration or deceleration. Model Predictive Control (MPC) method was used to reduce the rapid acceleration and deceleration of the vehicle due to signal change or movement of the front vehicle. MPC is a technique of control in consideration of the future information as predictive horizon T. The optimum control input for each step is determined in consideration of the current state of the controlled vehicle and the state of the preceding vehicle. The optimal control input for each step is determined by considering the current state of the controlled vehicle and the state of the preceding vehicle. The state equation based on the dynamics of the controlled vehicle and the preceding vehicle can be defined as equation (7).

$$x = \left[x_h, v_h, x_p, v_p\right]^T \qquad u = \left[u_h \quad u_p\right]^T \tag{7}$$

x representing position and speed of host and preceding vehicle in order. u_p is time dependent variable and u_h is a control input of host vehicle.

The fuel consumption model required to generate the fuel optimal control inputs of the vehicles is constructed as shown in equation (8) [20].

$$F_{fuel} = \frac{F_d}{1+e^{\beta(u+C)}} + e^{\left(-\frac{u}{\sigma^2}\right)} \times \left(b_0 + b_1 v + b_3 v^3\right) + \frac{c_1 + c_2 u x_2(t)}{1+e^{-\beta(u-C)}} \tag{8}$$

The fuel consumption model is very complicated due to the engine dynamics, and is influenced by various variables. However, in this paper, it is not possible to consider all engine dynamics for various vehicles controlled by the algorithm, so detailed characteristics of the engine are not considered separately. Instead, the simplified fuel consumption model equation is expressed in terms of acceleration, deceleration, idling, and cruising related to fuel economy.

The control input u_h has an input range ($-u_{max} \leq u_h \leq -u_{min}$) according to the vehicle output characteristics, therefore u_h has the same inequality constraint as equation (9) [20].

$$C = u_h^2 + u_p^2 - u_{max}^2 \leq 0 \qquad (9)$$

In the model predictive control, the cost function is set as below to find u for optimizing the fuel economy. The cost function is constructed as equation (10) considering the front vehicle distance using equation (7) and the fuel consumption using equation (8) [20].

$$J = \underset{u}{minimize}\left(\sum_{t=k}^{k+T}\left[\omega_1 \frac{F_{fuel}}{v(t)} + \omega_2\left(h_d x_2(t) + \left|x_3(t) - x_1(t)\right| - l_{veh}\right)^2 + \omega_3\left(x_2(t) - v_{limit}\right)^2\right]\right) \qquad (10)$$

Discretization of the Continuous System maintains the current state for a very short time and it can be assumed that the current state affects the next state. It can be expressed as shown in equation (11).

$$u(t') = u(t) \qquad (11)$$

Through equation (11), a velocity profile can be obtained by calculating a control input u_{opt} minimizing the cost function during the predictive horizon T. In the next step, the optimal input is calculated in the same way and the optimal input for that step is also applied.

3 SIMULATION RESULT

3.1 ECO Driving Algorithm

For simulation and verification of proposed algorithm, we constituted road environment and signal system using traffic simulation software, AIMSUN. Also, we developed simulation model by linking Python and AIMSUN API in order to apply traffic situation estimation algorithm to individual vehicle. Road environment is modeled by copying the Cheongdam crossway in Gangnam, and we set a volume of traffic for simulation by measuring a volume of traffic at the Cheongdam crossway. In this paper, we realized Eco Driving Algorithm by determining applicability between coasting model and MPC model according to traffic signal information.

Apply velocity profile according to coasting by estimated traffic situation information about a control target vehicle that enters Eco Driving service section, and then, Using MPC, we realized velocity profile considering fuel consumption and forward vehicle state. In order to analyze the performance of this algorithm, we compared and analyze using Gipp's Car Following Model that express general driver.

A volume of traffic for simulation is set 200, 500 vehicles. And simulation is conducted during 600 seconds, and simulation step size is 0.1 seconds. We simulated proposed algorithm and Gipps's Car Following Model which is a basic driver model provided by AIMSUN in order to compared and analyze two algorithm at corresponding crossway.

We used Map data based on vehicle test as coasting model parameter. The parameter for Model Predict control is as follow. We determined Predictive horizon as $T = 10$, and Control horizon as $N = 10$. The maximum acceleration u is determined as $u_{max} = 2.7\,[m/s^2]$ by reflecting general vehicle acceleration that drive a crossway in urban area. The constant parameters for calculating fuel consumption model were determined as $\beta = 120$, $C = 0.09$, $\sigma = 0.11$, $h_d = 1.3$, $F_d = 0.1$, $b_0 = 0.222999$, $b_1 = 0.0033529$, $b_2 = 0.000042$, $c_1 = 0.42$, $c_2 = 0.26$, $\omega_1 = 4.0$, $\omega_1 = 4.0$, $\omega_3 = 1.25$. Here, b_0, b_1, b_2 are related to cruising, c_1, c_2 are related to acceleration. ω_2 is determined as $\omega_2 = \gamma e^{\alpha R}$, so has weight according to distance. Here, $\alpha = 0.2$, and γ is determined as 0.3 or 9.0 according to R. With above parameters, we determined acceleration profile using MPC [20].

3.2 Simulation Result

The comparison result of driving pattern between Eco driving algorithm of this paper and Gipp's Car following model, with changing simulation environment, is as follow. Through Table 1 and Table 2, we can see the difference of average velocity and fuel consumption between Eco driving algorithm according to traffic volume change and Gipp's model. The result seen through Table 1 that express average velocity of a lane, we can see that the average velocity of the case of applying Eco driving is less because it reduces idling time and rapid acceleration, deceleration. Therefore we can know that the proposed algorithm has an effect on fuel efficiency improvement not only individual vehicle but also the whole vehicles. Also, we can infer that the proposed algorithm can make vehicles get through a crossway more at the same time because the average velocity is higher. The result seen through Table 2, we can see that Eco driving algorithm reduced 8% and 15% respectively compared with Gipp's Car following model when the traffic volume cases are 200 vehicles and 500 vehicles. Therefore we can know that the proposed algorithm that minimizes idling time and reduces rapid acceleration change using Coasting and MPC control makes a large effect. Also, the simulation result is same in the case of multiple vehicles, we can confirm the validity of proposed algorithm about fuel consumption improvement.

Table 1 : Average speed of vehicles on the road (Whole Lane, Up-Stream Lane, Down-Stream Lane)

Average Velocity (km/h)	**Traffic volume : 200**		**Traffic volume : 500**	
	Control	**No control**	**Control**	**No control**
Whole lane	32.19993	33.66666	25.99956	26.70911
Down Stream Lane	27.74408	29.76748	23.67086	23.78782
Up Stream Lane	50.00477	51.23048	47.34827	52.67256

Table 2 : Total fuel consumption of vehicles on the road

Fuel Consumption (ml)	**No Control**	**Control**	**Rate (%)**
Traffic volume : 200	92556.974753	84780.625044	8.4017
Traffic volume : 500	325249.66380	266099.53024	18.186

The result of comparison and analysis about velocity and acceleration of an individual vehicle is as follow. The corresponding analysis preceded the vehicle that passes a crossway, the vehicle that couldn't pass the crossway and stop respectively.

(1) Simulation case 1 - Traffic volume 200

In Figure 4, which shows the speed of the vehicle stopped by the traffic lights, the Gipp's model is idling from 236 to 253 seconds. However, the eco-driving algorithm starts coasting from 221 seconds and shows a slow deceleration and minimizes idling time. In addition, the intersection entry speed is higher than that of Gipp's model, so the energy required for acceleration is also minimized because the eco-driving algorithm is higher.

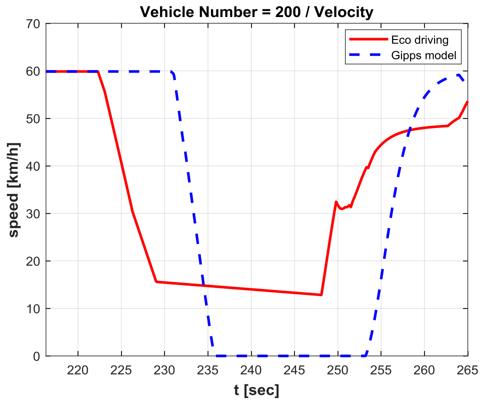

Figure 4 : Speed profile of a vehicle that stops without passing through an intersection (200 cars)

In Figure 5, which shows the acceleration of the vehicle stopped by the traffic lights, the Gipp's model showed a rapid deceleration from 231 to 236 seconds and a rapid acceleration from 253 to 263 seconds. On the other hand, the eco-driving algorithm shows a moderately slow deceleration from 222 to 228 seconds, and maintains a constant speed at the intersection pass portion and shows a gentle acceleration from 248 to 261 seconds. This shows that coasting is applied at deceleration and MPC at acceleration.

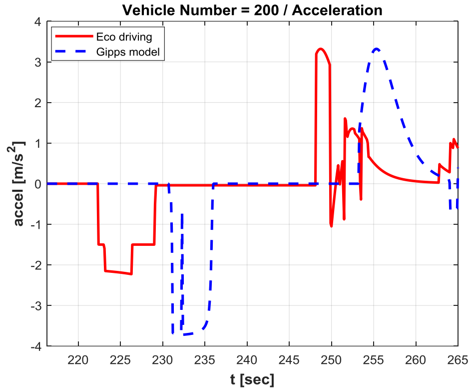

Figure 5 : Acceleration profile of a vehicle that stops without passing through an intersection (200 cars)

Figure 6 shows the speed of the vehicle passing through the intersection without stopping and Figure 7 shows the acceleration of the passing vehicle. Both the Gipp's model and the eco-driving algorithm travel at the same speed without changing speed.

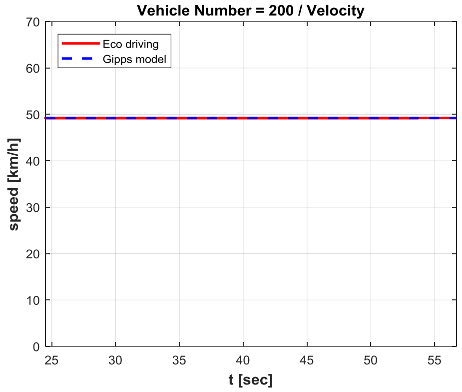

Figure 6 : Speed profile of a vehicle passing through an intersection (200 cars)

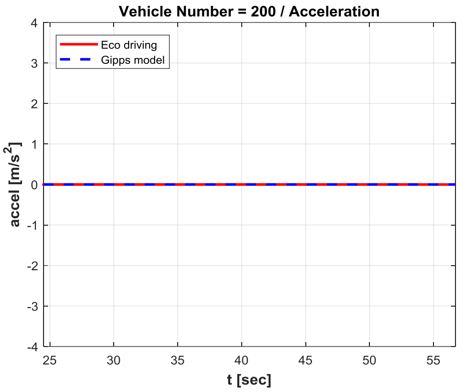

Figure 7 : Acceleration profile of a vehicle passing through an intersection (200 cars)

(2) Simulation case 2 – Traffic volume 500

Figure 8 shows the speed of the vehicle stopped by the traffic lights. Similar to the simulation case 1, it can be seen that the idling time is minimized and the deceleration is gradual.

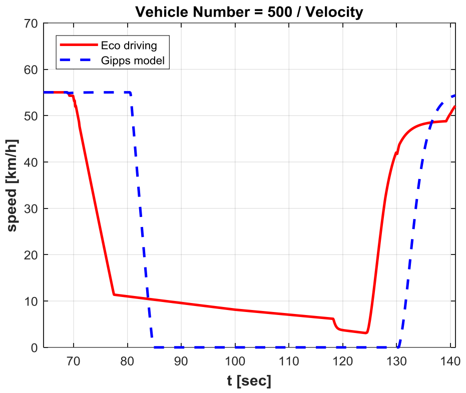

Figure 8 : Speed profile of a vehicle that stops without passing through an intersection (500 cars)

Figure 9 shows the acceleration of the vehicle stopped by the traffic lights. It is more inaccurate than in Figure 5 of simulation case 1. This result seems to be due to the occurrence of disturbance due to the existence of many vehicles.

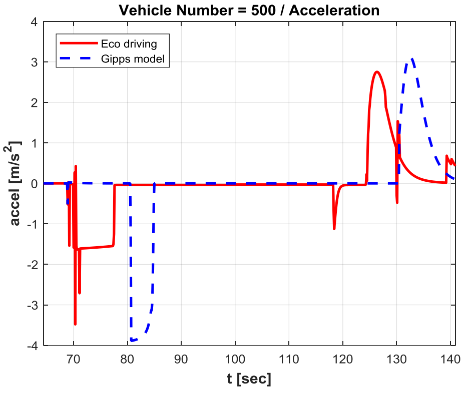

Figure 9 : Acceleration profile of a vehicle that stops without passing through an intersection (500 cars)

Figure 10 shows the speed of the vehicle passing through the intersection without stopping, and Figure 11 displays the acceleration of the passing vehicle. The two graphs are similar to the Gipp's model and the Eco driving algorithm as shown in Figure 6 and Figure 7 of Simulation Case 1. It can be seen that running at constant speed minimizes fuel consumption if the vehicle can pass through a signal intersection without changing speed.

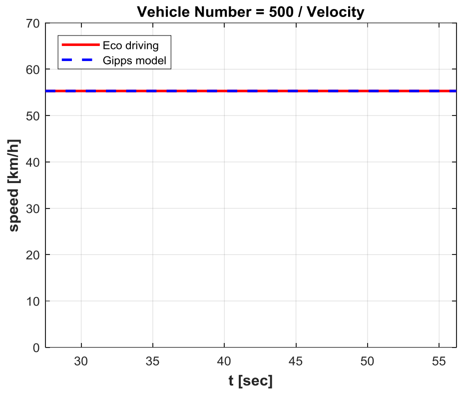

Figure 10 : Speed profile of a vehicle passing through an intersection (500 cars)

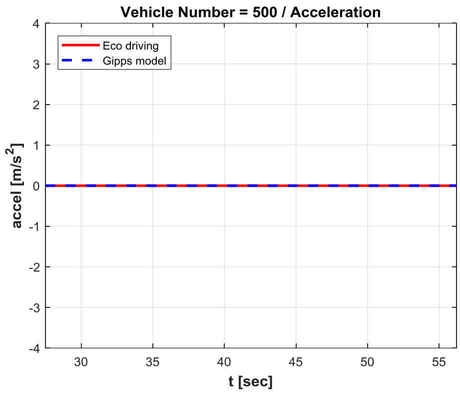

Figure 11 : Acceleration profile of a vehicle passing through an intersection (500 cars)

4 CONCLUSION

In this paper, we propose an eco-driving algorithm that minimizes fuel consumption by appropriately using the MPC algorithm and coasting. The MPC algorithm uses the surrounding vehicle information, and the coasting uses the queue length estimation and the residual signal time. and the proposed algorithm is applied to Gipp's model and Multi-lane signalized intersection, which shows that not only the fuel consumption of the individual vehicle but also improvement of the intersection's fuel consumption. Also, the average speed of traffic passing through the intersection was improved as well, confirming that the Eco driving algorithm of the individual vehicles improves the traffic flow at the intersection. It can be seen that the reduction of the fuel consumption at the intersection is the result of gentle deceleration by coasting, minimization of idling time, and gentle acceleration using MPC algorithm. However, the problem of designing the cut-in phenomenon and the leading vehicle which caused the error in the simulation and a large amount of computation according to the MPC characteristic are seen as problems to be solved in the future.

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