

Received May 29, 2019, accepted June 14, 2019, date of publication June 19, 2019, date of current version July 3, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2923741

# An Ecological Adaptive Cruise Control for Mixed Traffic and Its Stabilization Effect

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**ABSTRACT** With the rapid development of technologies, the ecological control strategies of connected and autonomous vehicle (CAV) technologies are gaining more and more attention. In this paper, a rule-based ecological cruise control, called the ecological smart driver model (EcoSDM), is proposed to improve the fuel efficiency of an individual vehicle and the traffic flow. By adjusting the spacing between the leading and the following vehicles, EcoSDM provides smoother deceleration and acceleration than the enhanced intelligent driver model (Enhanced-IDM) and the smart driver model (SDM). The linear stability of EcoSDM is analyzed both theoretically and numerically. The numerical results validate the results of theoretical analysis. Moreover, the simulation results show that EcoSDM outperforms the Enhanced-IDM and SDM in terms of stabilization effect on homogeneous traffic flow. In addition, the calibrated VT-Micro model is used to estimate the fuel consumption of CAVs and manually driven vehicles. The result shows that CAVs have better fuel economy than the human-driven vehicles, which is consistent with existing studies. The EcoSDM outperforms Enhanced-IDM and SDM in terms of fuel consumption. For the EcoSDM-equipped CAVs, the fuel saving benefit is greatest when a CAV is at the front of the platoon.

**INDEX TERMS** Connected and autonomous vehicle (CAV), ecological adaptive cruise control, linear stability.

## I. INTRODUCTION

In the United States, the fuel economy of personal vehicles is estimated as 24.9 miles per gallon (mpg) in 2017 and is projected to be 25.4 mpg in 2018 [1]. Driver behavior has been proved as an impact factor in the vehicle fuel economy [2]–[4]. Recent development in vehicle control strategy presents opportunities to improve fuel efficiency by improving vehicle performance [5]. Consequently, the impact and performance of autonomous vehicle have been investigated in the literature. Several studies have investigated the impact of autonomous vehicles on traffic flow [6]–[8]. Davis pointed out that autonomous vehicles can mitigate traffic jams by stabilizing traffic flow [9]. By simulating mixed traffic consisting of autonomous and manually driven vehicles, Jiang et al. found that the introduction of autonomous vehicles would enhance the free flow stability [10]. By investigating the transition probability from synchronized flow to congestion, Yuan et al. pointed out that autonomous vehicles are able to enhance the traffic stability of synchronized flow [11].

The associate editor coordinating the review of this manuscript and approving it for publication was Zhengbing He.

Moreover, the stability of control strategies have been widely studied theoretically. Talebpoor and Mahmassani [12] proposed a framework to investigate the impact of connected and autonomous vehicle on string stability by using different models with technology-appropriate assumptions. Based on linear stability analysis, Xie *et al.* [13] indicated that the stability of the heterogeneous traffic is closely related to the penetration rate and the spatial distribution of connected vehicles. Wang *et al.* [14] investigated the impact of information reliability on linear and nonlinear stability of connect vehicles. Moreover, Hu *et al.* [15] derived the stability criteria of an autonomous vehicle platoon considering actuator lag and sensor delay. They point out that both sensor delay and actuator lag deteriorate the dynamic stability of vehicle and platoon. Considering the disturbance string stability, Besselink and Johansson [16] proposed a novel delay-based spacing policy for control of vehicle platoon. Recently, Wen-Xing and Li-Dong [17] applied linear stability analysis method to investigate the stabilization effect of the proposed vehicle control strategies on traffic flow. Sun *et al.* [18] proposed a framework to investigate the stability of general nonlinear vehicle control models with multi-time delays.

Recently, Xu *et al.* [19] proposed a control strategy to guarantee the string stability of a heterogeneous vehicle platoon subject to varying road slopes, aerodynamic drag, and wireless communication delay.

Moreover, several studies investigated the energy efficiency of autonomous vehicles and proved that autonomous vehicle could improve energy-efficiency by providing optimized vehicle speed profile with smoother deceleration and acceleration rates [20]–[22]. Consequently, some autonomous vehicle control strategies are designed by targeting better fuel efficiency or less emissions [23]–[28]. Park *et al.* [29] and Ahn *et al.* [30] developed an ecological control system based on optimal control and demonstrated its potential in improving fuel efficiency. Yang *et al.* developed an eco-cooperative control for connected and autonomous vehicle (CAV) to determine the fuel-optimum vehicle trajectory through a signalized intersection [31]. Vajedi and L. Azad proposed an ecological control system for Toyota Prius Plug-in Hybrid to reduce the total energy cost [32]. Recently, considering traffic state, Huang *et al.* [33] developed a two-stage control hierarchy for CAVs to improve vehicle fuel efficiency. Moreover, Cui *et al.* [34] propose an eco-approach control method for CAV based on the data from driving simulation environment for the mixed traffic. Considering the maturity of CAV technologies, CAV and manually driven vehicles are likely to exist in the same transportation system. Therefore, the impact of ACC-equipped vehicles on fuel efficiency in a mixed traffic environment is gaining attention from researchers. Wang *et al.* proposed two MPC-based control strategies for autonomous vehicles in a mixed traffic with human-driven vehicles [35]. The simulation results showed that a 20% share of ACC-equipped vehicles may lead to 18 ~ 27% platoon-level emission reduction. Moreover, by studying the performance of a fuel-optimized control strategy, called Pulse-and-Glide, on traffic smoothness and fuel economy in a mixed traffic flow, Li *et al.* [36] pointed out that Pulse-and-Glide strategy can significantly decrease the fuel consumption of individual vehicles. However, the fuel consumption of the platoon mixed with autonomous and manually driven vehicles may increase with the under-damped pattern. Moreover, Ioannou and Stefanovic pointed out that the environment benefit may vary with the location and penetration of CAV in the string of mixed traffic [22]. In addition, in a mixed traffic stream, fuel-saving of individual vehicles does not always result in fuel-saving of the entire system. Therefore, the location of CAVs in a platoon need to be taken into account when designing autonomous vehicle control systems that are targeted at decreasing the fuel consumption of individual vehicles and the entire system.

In summary, most of the existing ecological control strategies are formulated as an optimization problem and did not take the location of CAVs in the platoon into consideration. Moreover, the stabilization effect of existing ecological control strategies are not investigated. In this paper, a rule-based ecological control strategy is developed considering the

location of a CAV in a platoon with mixed autonomous and manually driven vehicles. Moreover, the linear stability of the proposed ecological control strategy is analyzed.

The rest paper is organized as follows. Section II provides a literature review of the existing rule-based car following models for autonomous and manually driven vehicles, respectively. Moreover, the existing fuel consumption models are discussed in Section II. Section III presents the proposed adaptive cruise control strategy. Linear stability analysis is conducted in Section IV. Section V simulates single-lane vehicle dynamics with or without cut-in scenarios. The conclusion and future works are presented in Section VI.

## II. RELATED WORK

### A. HUMAN DRIVEN VEHICLE

In the past decades, numbers of car-following models have been introduced to simulate manually driven vehicle, such as Multi-anticipative Model [37], Tampere Model [38], Newell Model [39], Gipps Model [40], Full Velocity Difference Model [41] and Optimal Velocity Model [42]. Based on Gipps model, Treiber *et al.* proposed a human driver model named Intelligent Driver Model (IDM) [43], [44]. By capturing different congestion dynamics, IDM provides greater realism than most of the deterministic acceleration modeling frameworks [12]. Recently, IDM is widely used to simulate manually driven vehicle to investigate the impact of autonomous vehicle on traffic flow stability, fuel consumption and emission in a traffic system with mixed autonomous and manually driven vehicles [12], [35], [36]. In order to derive comparable results with existing studies, IDM is used in this paper to describe the car following behavior of manually driven vehicles. The IDM is formulated as follows:

$$a_{IDM}^n = a_{max} \left[ 1 - \left( \frac{v_n}{v_0} \right)^\delta - \left( \frac{s^*}{\Delta x} \right)^2 \right] \quad (1)$$

$$s^* = s_0 + \max(0, v_n T + \frac{v_n (v_n - v_{n-1})}{2\sqrt{a_{max} b}}) \quad (2)$$

where,

$a_{IDM}^n$  is the acceleration of the following vehicle based on the Intelligent Driver Model ( $m/s^2$ );

$\delta$  is the acceleration exponent;

$s_0$  is the standstill distance between stopped vehicles (m);

$a_{max}$  is the maximum acceleration ( $m/s^2$ );

$\Delta x$  is the spacing between the leading and the following vehicle (m);

$T$  is the desired time headway (s);

$v_0$  is the maximum speed (m/s);

$v_n$  is the speed of the following vehicle (m/s);

$v_{n-1}$  is the speed of the leading vehicle (m/s);

$s^*$  is the desired spacing (m); and

$b$  is the desired deceleration ( $m/s^2$ ).

### B. AUTONOMOUS VEHICLE

In recent years, car-following models have evolved to describe the behavior of vehicles with advanced cruise controls, which take advantage of the sensing and vehicle to

vehicle/vehicle to infrastructure (V2V/V2I) communication technologies. Several rule-based autonomous vehicle control models have been proposed. Davis modeled adaptive cruise control that automatically maintains the safe distance between the following vehicle and its immediate preceding vehicle [9]. Moreover, a rule-based control strategy, which is proprietary to Nissan, was described by Shladover *et al.* [45]. By using constant-acceleration heuristic (CAH) as an indicator, Kesting *et al.* proposed an enhanced Intelligent Driver Model (Enhanced-IDM) based on IDM [46]. The acceleration according to CAH is formulated as follows:

$$a_{CAH}^n = \begin{cases} \frac{v_n^2 \tilde{a}_l}{v_{n-1}^2 - 2\Delta x \tilde{a}_l} \\ \text{if } v_n (v_n - v_{n-1}) \leq -2\Delta x \tilde{a}_l \\ \tilde{a}_l - \frac{(v_n - v_{n-1})^2 \Theta (v_n - v_{n-1})}{2\Delta x} \\ \text{otherwise} \end{cases} \quad (3)$$

where,

$a_{CAH}^n$  is the constant-acceleration heuristic acceleration of the following vehicle ( $m/s^2$ );

$\Theta$  is the Heaviside step function;

$a_{n-1}$  is the acceleration of the leading vehicle; and

$\tilde{a}_l$  is the effective acceleration used to avoid artefacts that may be caused by leading vehicles with higher acceleration capabilities,  $\tilde{a}_l = \min(a_{n-1}, a_{max})$ .

As a result, the Enhanced-IDM is formulated as follows:

$$a_{Enhanced-IDM}^n = \begin{cases} a_{IDM}^n & a_{IDM}^n \geq a_{CAH}^n \\ (1-c) a_{IDM}^n + c \left[ a_{CAH}^n + b \tanh \left( \frac{a_{IDM}^n - a_{CAH}^n}{b} \right) \right] & \text{otherwise} \end{cases} \quad (4)$$

where,

$a_{Enhanced-IDM}^n$  is the acceleration of the following vehicle equipped with Enhanced-IDM ( $m/s^2$ ); and

$c$  is the coolness factor.

Recently, a rule-based ACC, named Smart Driver Model (SDM) is proposed to address the instability of IDM under homogenous traffic condition [47]. The acceleration of the following vehicle equipped with SDM is determined by the following equation:

$$a_{SDM}^n = a_{max} \left[ 1 - \left( \frac{v_n}{v_0} \right)^4 \right] - \frac{a_{max} \left[ 1 - \left( \frac{v_n}{v_0} \right)^4 \right] + \frac{v_n^2 - v_{n-1}^2}{2\Delta x}}{\exp \left( \frac{\Delta x}{s_0 + v_n \times T} - 1 \right)} \quad (5)$$

where,

$a_{SDM}^n$  is the acceleration of the following vehicle that is equipped with SDM ( $m/s^2$ );

In this study, Enhanced-IDM and SDM are applied to simulate the CAVs. The results compared the ones derived

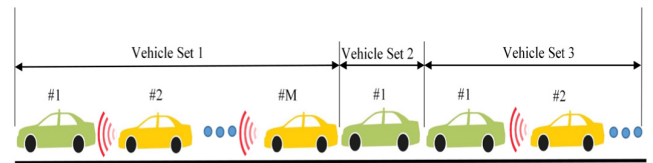


FIGURE 1. A platoon with CAVs (yellow) and human-driven vehicles (green).

by using the proposed model to evaluate the performance of the proposed model.

### C. FUEL CONSUMPTION MODELS

The fuel consumption models of gasoline vehicles have been proposed by several studies. Since vehicle speed and acceleration data can be collected by various devices, such as OBD-II loggers, on-board trackers and smartphones, instantaneous speed and acceleration are widely used as predictors to estimate vehicle fuel consumption. One pioneer work was done by Ahn *et al.* [48] and Rakha and Ahn [49] who proposed the Virginia Tech microscopic energy and emission (VT-Micro) model. This model is a regression model that takes polynomial combinations of speed and acceleration levels as the explanatory variables to estimate vehicle fuel consumption. Kamal *et al.* [25] also developed a regression-based fuel consumption model that is similar to VT-Micro, but took different polynomial terms of speed and acceleration into account. Road inclination, if collected simultaneously with speed and acceleration, was also adopted as an extra variable in fuel consumption estimation, such as by Ribeiro and Aguiar [50]. In this study, VT-Micro model is used to estimate the fuel consumption of vehicles.

### III. ECOLOGICAL SMART DRIVER MODEL

Considering the location of CAV in a platoon, a rule-based ecological control strategy, named Ecological Smart Driver Model (EcoSDM) is proposed based on SDM. With regard to CAVs, the following assumptions are made: (1) CAVs are capable of communicating with other CAVs through vehicle-to-vehicle communication with an ideal wireless connection [51]. (2) On-board sensors measure vehicle speed, gap (relative distance) and the relative speed with respect to the preceding vehicle on regular time intervals [52]. (3) There is no computational delay, sensor delay and communication delay for CAVs.

An example of platoon containing CAVs and manually driven vehicles is shown in FIGURE 1. The manually driven vehicles and CAVs are represented by green vehicles and yellow vehicles, respectively. According to the aforementioned assumptions, only CAVs can share the information and the CAV can only detect the manually driven vehicle immediately in front of it. Therefore, the number of manually driven vehicles between CAVs is unknown. As a result, manually driven vehicles separate the platoon into several vehicle sets. A manually driven vehicle is always the first vehicle in a vehicle set. That is, the location ( $N$ ) of a manually driven vehicle is assigned as 1. The locations of CAVs in the vehicle

sets are labeled as 2 to  $M$ . Note that the vehicle set definition is used to determine the location of CAV and design the EcoSDM strategy. A manually driven vehicle can still follow a CAV in the platoon, according to its car-following rules. The acceleration of the following vehicle equipped with EcoSDM is determined by the following equation:

$$a_{EcoSDM}^n = a_{max} \left[ 1 - \left( \frac{v_n}{v_0} \right)^4 \right] - \frac{a_{max} \left[ 1 - \left( \frac{v_n}{v_0} \right)^4 \right] + \frac{v_n^2 - v_{n-1}^2}{2\Delta x}}{e^{\left( \frac{\Delta x}{s_0 + v_n \times T} \right)^{-1-\beta} \times \frac{v_n}{v_0} \times \frac{(v_0 - v_n)}{v_0}}} \quad (6)$$

where,

$a_{EcoSDM}^n$  is the acceleration of the following vehicle that is equipped with EcoSDM ( $m/s^2$ ); and

$\beta$  is an adjust parameter considering the location of CAV in the vehicle set.

In order to stabilize the string of vehicles in a mixed traffic stream quickly, the CAVs located closer to the manually driven vehicles have to react more dramatically to attenuate the disturbance from manually driven vehicles in front of them. Therefore, the parameter ( $\beta$ ) of Eco-SDM is determined as follows:

$$\beta = \frac{1}{\ln(N)} + 1 \quad (7)$$

where,

$N$  is the location of a CAV in a vehicle set,  $N \geq 2$ .

According to Equation (6) and Equation (7), EcoSDM-equipped vehicle tend to accelerate with  $a_{max}$  when  $\Delta x$  is large. A CAV will brake while the speed of the CAV is greater than the leading vehicle speed and  $\Delta x$  is less than the desired spacing. When there is no speed difference between the leading and following vehicle, a CAV's acceleration increases with the ratio of  $\Delta x$  to the desired spacing. According to the characteristics of exponential function, the jerk of CAV, which represents the changing rate of CAV's acceleration, decreases with the ratio of  $\Delta x$  to the desired spacing. Moreover, CAV would adjust its speed-dependent spacing based on the location of CAV in a vehicle set. Consequently, the EcoSDM-equipped vehicle can achieve smoother acceleration and deceleration.

Several properties of EcoSDM are discussed as follows, considering special cases:

First, when CAV is cruising (i.e.  $a_{EcoSDM}^n = 0$ ,  $v_n - v_{n-1} = 0$ ), the speed-dependent spacing  $\Delta x$  between the preceding and the following vehicle is given by

$$\Delta x = \left( 1 + \beta \times \frac{v_n}{v_0} \times \frac{(v_0 - v_n)}{v_0} \right) (s_0 + v_n \times T) \quad (8)$$

In particular, when the vehicle is stopped or reached the maximum speed (i.e.  $v_n = 0$  or  $v_n = v_0$ ) the speed-dependent spacing  $\Delta x$  equals to the desired spacing, that is,  $\Delta x = s_0 + v_n \times T$ . The desired spacing is composed of

a standstill distance ( $s_0$ ) and a speed-dependent term,  $v_n T$ . When a CAV follows other CAVs,  $\beta$  decreases with the location ( $N$ ) and the speed-dependent spacing  $\Delta x$  of the CAV is closer to the desired spacing. Note that in equilibrium traffic of arbitrary density, the speed-dependent spacing  $\Delta x$  of existing models are the desired spacing; while the speed-dependent spacing  $\Delta x$  of EcoSDM would only equal to the desired spacing when  $v_n$  is equal to 0 or  $v_0$ .

Second, when the traffic density is low (i.e.  $\Delta x$  is large), CAVs will accelerate to the maximum speed. When  $\Delta x \rightarrow \infty$ ,  $\frac{v_n^2 - v_{n-1}^2}{2\Delta x}$  is close to 0 and  $e^{\left( \frac{\Delta x}{s_0 + v_n \times T} \right)^{-1-\beta} \times \frac{v_n}{v_0} \times \frac{(v_0 - v_n)}{v_0}}$  is close to infinity. As a result, the acceleration of EcoSDM is approximately equal to the maximum acceleration,  $a_{EcoSDM}^n \approx a_{max} \left[ 1 - \left( \frac{v_n}{v_0} \right)^4 \right]$ . Once the speed reaches the maximum speed, acceleration of EcoSDM is 0.

Third, when CAV is following a slower vehicle or approaching a stopped vehicle (i.e.  $v_n - v_{n-1} > 0$ ) with the limited spacing ( $\Delta x \rightarrow s_0 + v_0 \times T$ ), the acceleration equation of EcoSDM is given by

$$a_{Eco-SDM}^n \rightarrow a_{max} \left[ 1 - \left( \frac{v_n}{v_0} \right)^4 \right] - \frac{a_{max} \left[ 1 - \left( \frac{v_n}{v_0} \right)^4 \right] + \frac{v_n^2 - v_{n-1}^2}{2(s_0 + v_n \times T)}}{\exp \left( -\beta \times \frac{v_n}{v_0} \times \frac{(v_0 - v_n)}{v_0} \right)} \quad (9)$$

Especially, when a CAV with the maximum speed approaches a stopped vehicle (i.e.  $v_n = v_0$ ,  $v_{n-1} = 0$ ), the maximum kinematic deceleration is applied to avoid a collision, as follows.

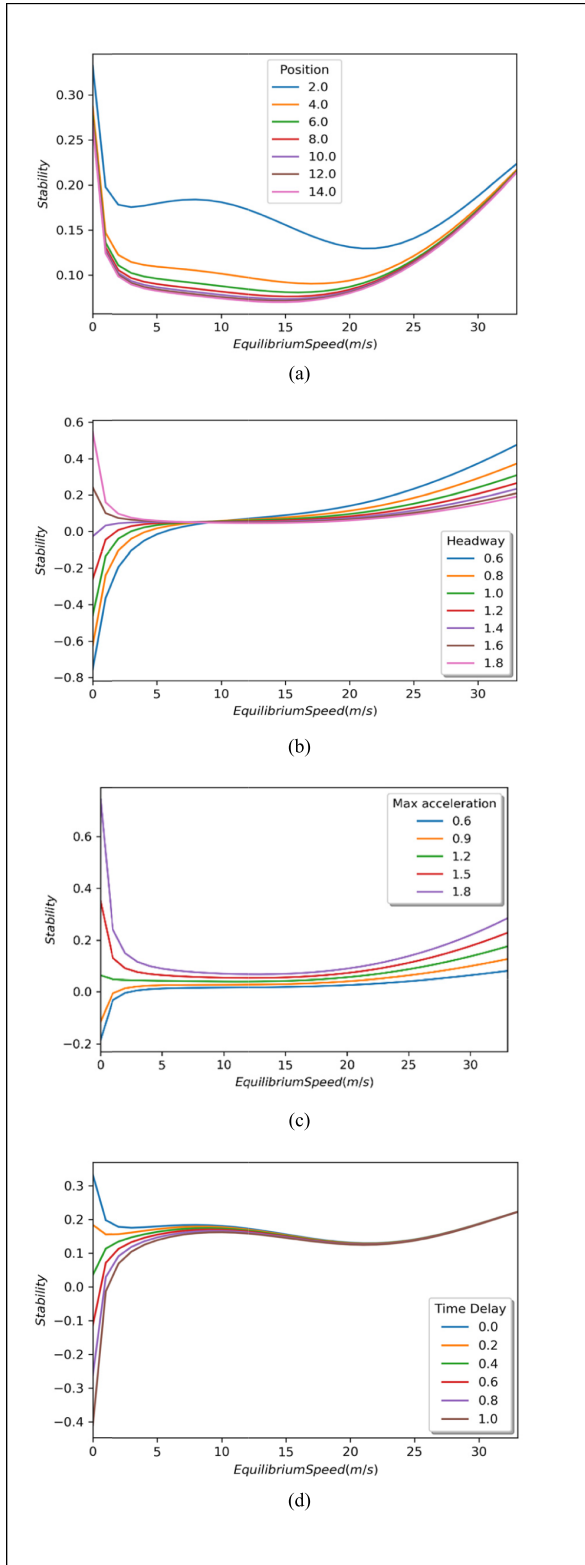
$$a_{EcoSDM}^n = -\frac{V_0^2}{2(s_0 + v_0 \times T)} \quad (10)$$

Forth, when the spacing is much smaller than the desired spacing ( $\Delta x \ll s_0 + v_0 \times T$ ) and there is no significant speed differences ( $v_n - v_{n-1} \approx 0$ ), the acceleration is determined as follows:

$$a_{EcoSDM}^n \approx a_{max} \left[ 1 - \left( \frac{v_n}{v_0} \right)^4 \right] \times \left( 1 - \frac{1}{e^{\left( \frac{\Delta x}{s_0 + v_n \times T} \right)^{-1-\beta} \times \frac{v_n}{v_0} \times \frac{(v_0 - v_n)}{v_0}}} \right) \quad (11)$$

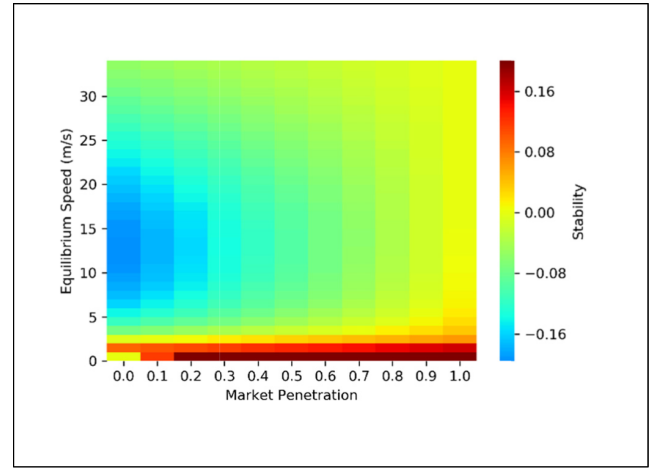
Especially, when  $\Delta x \rightarrow 0$ , Equation 11 reduces to

$$a_{EcoSDM}^n \approx a_{max} \left[ 1 - \left( \frac{v_n}{v_0} \right)^4 \right] \times \left( 1 - \frac{1}{e^{\left( -1-\beta \times \frac{v_n}{v_0} \times \frac{(v_0 - v_n)}{v_0} \right)}} \right) \quad (12)$$



**FIGURE 2. Stability of EcoSDM-equipped vehicle with different parameters. (a) Position. (b) Desired time headway. (c) Maximum acceleration. (d) Time delays.**

Since  $\beta \times \frac{v_n}{v_0} \times \frac{(v_0 - v_n)}{v_0}$  is always greater than 0,  $e^{(-1 - \beta \times \frac{v_n}{v_0} \times \frac{(v_0 - v_n)}{v_0})}$  is always less than 1. The following vehicle will adjust its deceleration according to its speed.



**FIGURE 3. Stability of heterogeneous traffic follow with different market penetration of CAVs.**

In the numerical experiment presented in Section V, a traffic stream containing both CAVs and manually driven vehicles is simulated. The CAVs are simulated using EcoSDM, Enhanced-IDM and SDM models.

#### IV. LINEAR STABILITY ANALYSIS

Since linear stability method has been widely applied to evaluate the performance of car-following models or CAV control strategies [53]–[59], we applied the linear stability method to study the string stability of the EcoSDM model. The general form of time-continuous car-following models is

$$\ddot{x}_n(t + \tau) = f(v_n(t), s_n(t), \Delta v_n(t)) \quad (13)$$

where  $\tau$  is the total time delay caused by vehicle-to-vehicle (V2V) communication, sensor, and vehicle actuator.

According to the studies conducted by [60] and [61], the stability condition is calculated as

$$Stability = \frac{1}{2}f_v^2 - f_s + f_v f_{\Delta v} + \frac{\tau}{2}f_v f_s > 0 \quad (14)$$

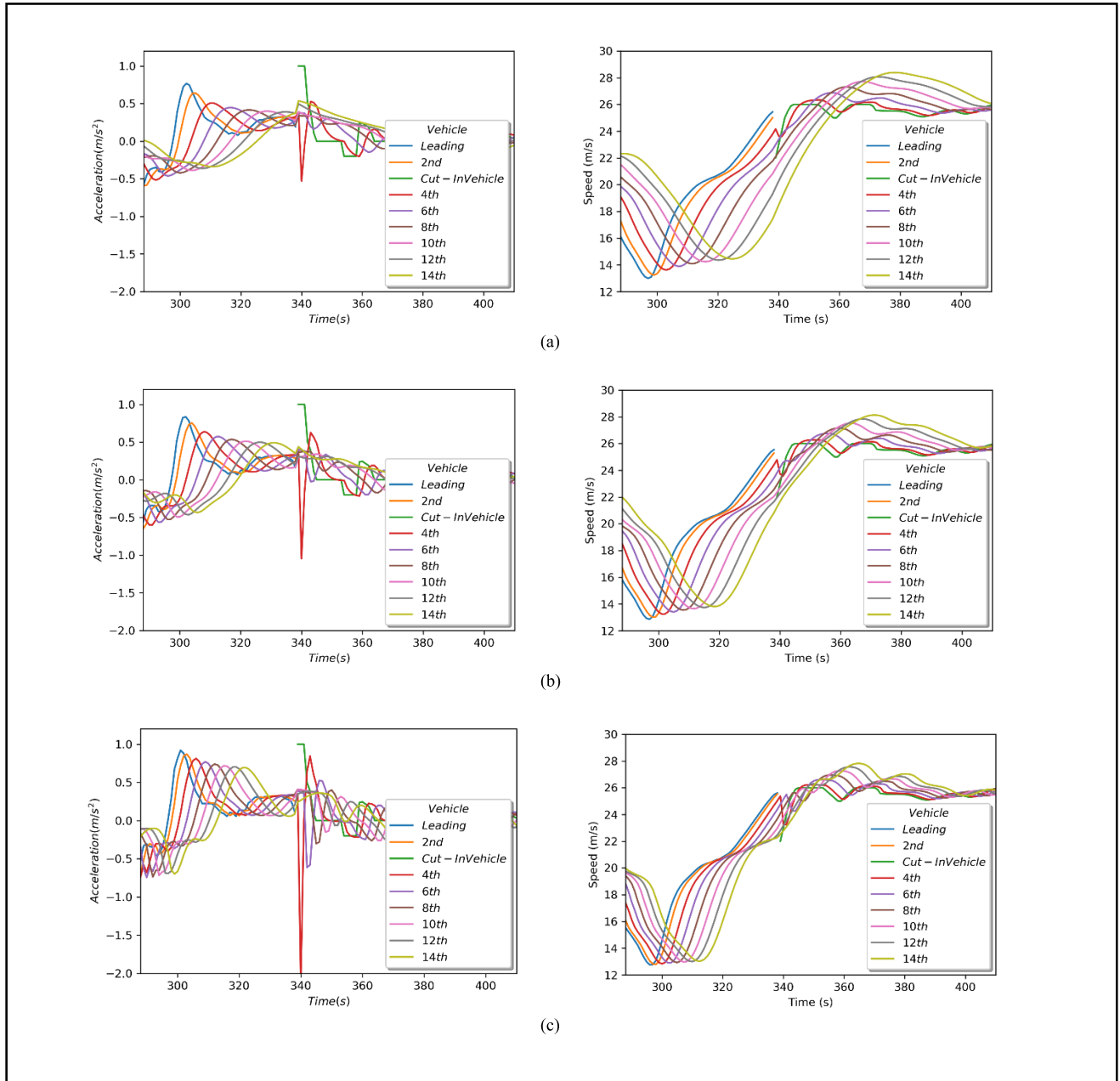
where  $f_v = \left. \frac{\partial f}{\partial v_n} \right|_{(v_e, s_e, 0)}$ ,  $f_{\Delta v} = \left. \frac{\partial f}{\partial \Delta v_n} \right|_{(v_e, s_e, 0)}$ , and  $f_s = \left. \frac{\partial f}{\partial s_n} \right|_{(v_e, s_e, 0)}$ .

Based on Equation 6, the partial derivatives at equilibrium is calculated as follows:

$$f_s = \frac{a \times \left[ 1 - \left( \frac{v_e}{v_0} \right)^4 \right]}{(s_0 + v_e \times T) \times \exp \left( -\beta \times \frac{v_0 v_e - v_e^2}{v_0^2} \right)} \quad (15)$$

$$f_{\Delta v} = -\frac{v_e}{(s_0 + v_e \times T) \times \exp \left( -\beta \times \frac{v_0 v_e - v_e^2}{v_0^2} \right)} \quad (16)$$

The stability of a platoon of EcoSDM-equipped vehicles can be evaluated based on Eq. 14 by varying the parameters, as shown in FIGURE 2. FIGURE 2.(a) shows that using



**FIGURE 4.** Acceleration and speed profiles of EcoSDM-equipped vehicles under cut-in situation considering different desired time headway. (a)  $T=1.6$ . (b)  $T=1.2$ . (c)  $T=0.8$ .

the parameters proposed by Kesting *et al.* [46], EcoSDM is always string stable. Moreover, the second EcoSDM-equipped vehicle in the vehicle set has better stability than other EcoSDM-equipped vehicles. FIGURE 2.(b) shows that

EcoSDM is string stable when equilibrium speed is larger than 10 m/s. When the desired headway is larger than 1.4 sec, the EcoSDM is string stable. FIGURE 2.(c) shows that EcoSDM is string stable when maximum acceleration is

$$f_v = - \frac{\left( \frac{T}{(s_0 + v_e \times T)} + \frac{\beta \times (v_0 - 2v_e)}{v_0^2} \right) \times a \times \left[ 1 - \left( \frac{v_e}{v_0} \right)^4 \right] + \frac{4av_e^3}{v_0^4}}{\exp\left(-\beta \times \frac{v_0 v_e - v_e^2}{v_0^2}\right)} - \frac{4av_e^3}{v_0^4} \quad (17)$$

larger than 1. FIGURE 2.(d) shows that EcoSDM is string stable when time delay is less than 1 and the equilibrium speed is larger than 3 m/s.

Moreover, according to the method proposed by Talebpour and Mahmassani [12], the stability of heterogeneous traffic flow, which contains human-driven and EcoSDM-equipped vehicles, is investigated by varying the market penetration of CAVs. The partial derivatives of IDM at equilibrium status is based on the study conducted by Li *et al.* [61]. As shown in FIGURE 3, the higher market penetration rate of CAVs improves the stability of traffic flow, which is consistent with existing study [12].

## V. NUMERICAL EXPERIMENTS

In this section, numerical experiments are conducted to evaluate the stability and fuel efficiency of EcoSDM-equipped vehicles by comparing with existing control strategies of CAVs. The acceleration model parameters of the CAVs are based on the parameters used by [46], [47], [62], where maximum acceleration is  $1.4 \text{ m/s}^2$ , desired time headway is 1.6 s, maximum speed is 30 m/s, and the standstill distance is 1.5 m.

### A. CUT-IN

Based on the cut-in scenario simulated by [47], [63], the stability of EcoSDM under cut-in condition is investigated by simulating a platoon with 14 vehicles, when a cut-in occurs between the third and fourth positions. The cut-in rules and parameters are based on the study conducted by Davis [64]. The speed profile of the leading vehicle is generated using real data from experimental tests of human-driven vehicles. The EcoSDM-equipped vehicles follow the leading vehicle. Then a vehicle cuts in between the third and fourth vehicles. For the sake of clarity in the figure, the speeds of the first three vehicles have been removed from the plots of the results for the rest of the simulation. From second 340, the cut-in vehicle, which is computer generated with small speed oscillations around 25 m/s, depicted in the graph with the green solid lane splits the string in two. As shown in FIGURE 4, the oscillations from the cut-in vehicle are reduced by the 4<sup>th</sup> to the 14<sup>th</sup> vehicles when the desired time headway is larger than 0.8. The simulation results are consistent with the theoretical analysis conducted in Section IV.

### B. OPEN BOUNDARY CONDITION

To investigate the fuel efficiency of EcoSDM-equipped vehicle, a traffic stream with 1000 vehicles is simulated in a single lane under open boundary condition. According to the research conducted by [65], [66], the traffic stream is divided into several platoons of which the size is ranging from 14 to 81 vehicles. The traffic disturbance is induced by the leading vehicle which is assumed to follow the Urban Dynamometer Driving Schedule (UDDS) [67], as shown in FIGURE 5. In the beginning, the vehicles are on a single lane with the initial spacing and time headway, which are the desired spacing and desired time headway, respectively.

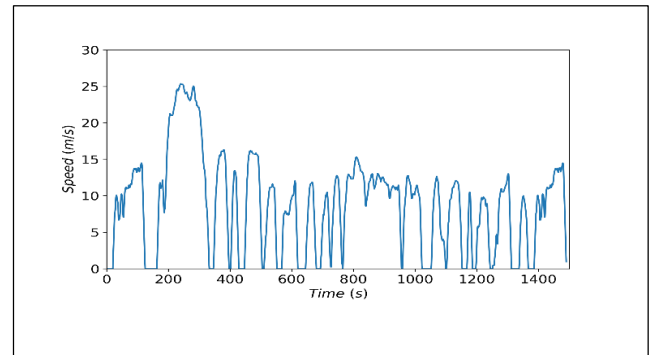


FIGURE 5. Urban Dynamometer Driving Schedule (UDDS) [67].

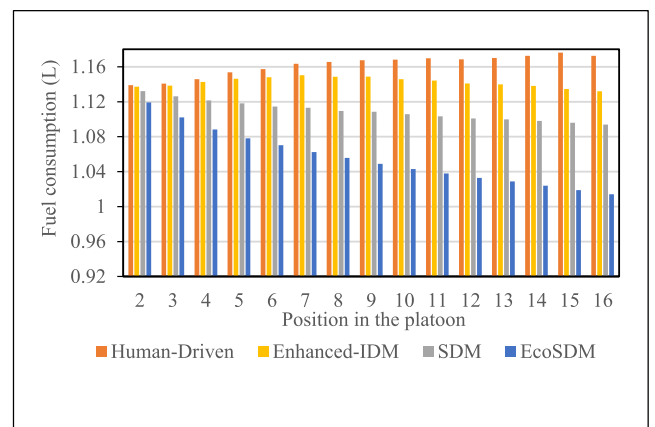


FIGURE 6. Fuel consumption of platoon with human-driven vehicles or CAVs.

Different scenarios are simulated, such as traffic stream with CAVs, Human-driven vehicles, or mix of them. In this study, IDM is applied to simulate human-driven vehicles. Moreover, Enhanced-IDM, SDM, and EcoSDM are used to simulate CAVs in the traffic stream. Moreover, since the Virginia Tech microscopic energy and emission (VT-Micro) model developed by Ahn *et al.* [48] and Rakha *et al.* [49] is widely used to estimate vehicle emission or fuel consumption. The VT-Micro model, which is calibrated by [28], is used to investigate the performance of the EcoSDM.

A typical platoon with 16 vehicles is examined to demonstrate the impact of CAVs on vehicle-level and platoon-level fuel consumption. As shown in FIGURE 6, the vehicle-level and platoon-level fuel consumption of the human-driven vehicle is compared with CAVs (i.e. Enhanced-IDM, SDM, and EcoSDM) in the traffic stream. Overall, the CAVs consume less fuel than human-driven vehicles in the homogeneous traffic stream. In addition, EcoSDM outperforms Enhanced-IDM and SDM in terms of fuel economy. EcoSDM reduces fuel consumption of the entire fleet by approximately 10%, compared to the all-manual case.

The reason for the better performance of EcoSDM is that it provides smoother deceleration and acceleration compared to SDM and Enhanced-IDM. A platoon with 100 CAVs is simulated to prove that better linear stability leads to better fuel efficiency. As shown in FIGURE 7, the acceleration variance is significantly decreasing for CAV towards the end

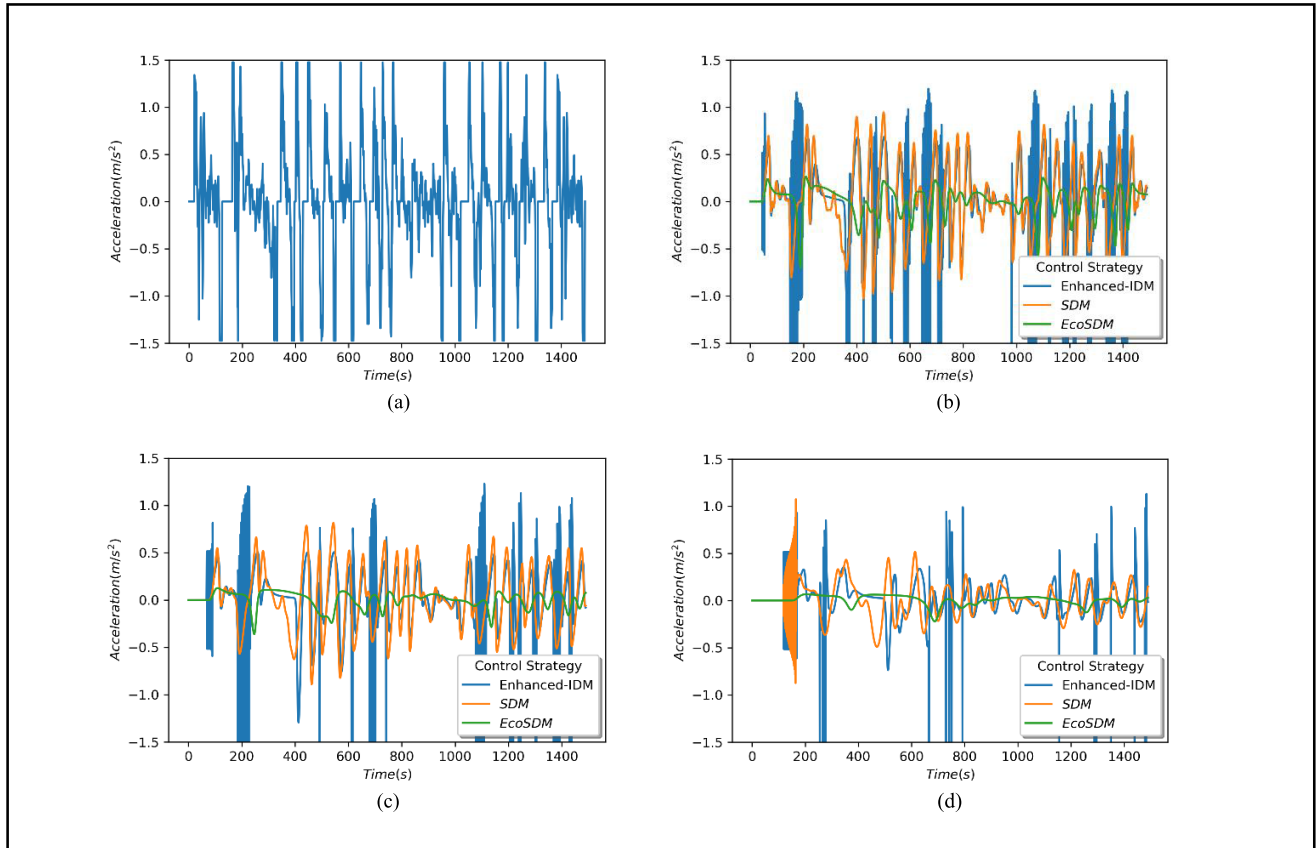


FIGURE 7. Acceleration profiles of 1st, 25th, 50th, and 100th vehicle equipped with Enhanced-IDM, SDM and EcoSDM. (a) 1<sup>st</sup> Vehicle. (b) 25<sup>th</sup> Vehicle. (c) 50<sup>th</sup> Vehicle. (d) 100<sup>th</sup> Vehicle.

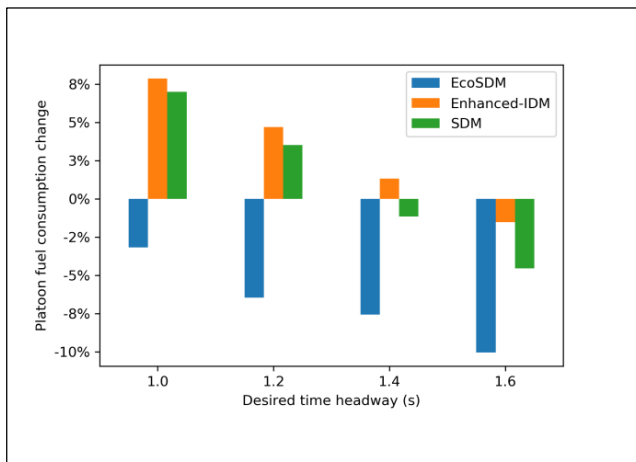


FIGURE 8. Impact of desired time headways of CAVs on platoon-level fuel consumption.

of the platoon. Moreover, EcoSDM outperforms SDM and Enhanced-IDM in terms of stabilization effect on homogeneous traffic flow. In other words, EcoSDM is able to provide smoother deceleration and acceleration compared to SDM and Enhanced-IDM.

As shown in FIGURE 8, the impact of CAV control strategies on platoon-level fuel consumption is investigated by considering different desired time headways.

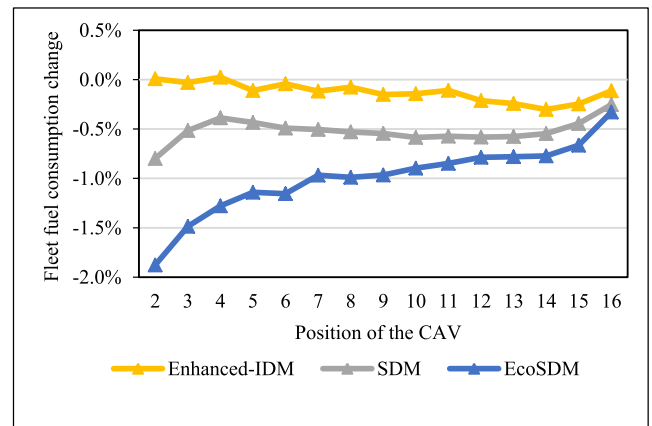


FIGURE 9. Impact of CAV position on platoon-level fuel consumption.

EcoSDM outperforms Enhanced-IDM and SDM in terms of fuel economy when the desired time headway is larger than 1 sec.

To examine the impact of CAV location on the platoon-level fuel consumption, a mixed platoon with one CAV and 15 manually driven vehicles is simulated. The position of the CAV in the platoon varies from immediately following the lead vehicle to the end of the platoon. As shown in FIGURE 9., all the CAV control strategies reduce platoon-level fuel consumption with only one CAV in the platoon.



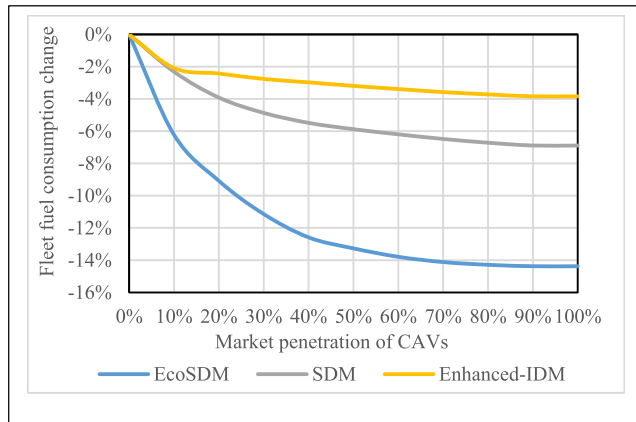


FIGURE 10. Impact of CAV market penetration on fuel consumption.

An EcoSDM-equipped vehicle towards the front of the platoon reduces more platoon-level fuel consumption than the case when CAV towards the end of the platoon. When place an EcoSDM-equipped vehicle can result in up to 2% reduction in platoon-level fuel consumption if placed at the front of the platoon. However, with SDM and Enhanced-IDM, there is no obvious relationship between the location of CAV and fuel consumption.

Additionally, a mixed traffic stream with CAVs and human-driven vehicles is simulated to investigate the impact of different market penetration of CAVs on fuel consumption. Different scenarios are run for each control strategies by varying CAV market penetration and location of CAVs in the platoon. The mean fuel consumption reduction of the entire fleet, compared to the all manually driven vehicle scenario, is shown in FIGURE 10. In general, the higher market penetration of CAVs results in better fuel efficiency of the fleet. With EcoSDM, the marginal improvement in fuel efficiency decreases when the market penetration of CAVs exceeds 30%.

## VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed the Ecological Smart Driver Model to control CAVs in the mixed traffic stream which considered the location of a CAV relative to other CAVs and manually driven vehicles. By adjusting the desired spacing between the following and leading vehicle, EcoSDM can provide smooth deceleration and acceleration and better linear stability. The linear stability of EcoSDM is investigated theoretically and numerically. Moreover, the impact of EcoSDM on fuel consumption is investigated by using the VT-Micro model.

To verify the results of linear stability analysis, numerical simulations were conducted for cut-in and open boundary conditions. The result of the cut-in case is consistent with the results of linear stability analysis. Moreover, considering a platoon without cut-in, the simulation result shows that the EcoSDM outperforms Enhanced-IDM and SDM in terms of the stabilization effect of the homogeneous traffic flow.

Moreover, single-lane vehicle dynamics in mixed traffic are simulated by considering different market penetration

rates of CAVs. The result shows that CAVs have better fuel economy than human-driven vehicles, which is consistent with existing studies. Moreover, EcoSDM outperforms Enhanced-IDM and SDM in terms of vehicle-level and platoon-level fuel consumption. Moreover, higher market penetration of CAVs results in better fuel efficiency of the fleet. When the market penetration of EcoSDM equipped CAVs exceeds 30%, the marginal improvement of fuel efficiency decreases. Moreover, the impact of the CAV location in a platoon on fuel consumption is investigated. The result shows that one EcoSDM-equipped vehicle may result in up to 2% reduction in platoon-level fuel consumption if placed at the front of the platoon.

The present paper has the following limitations. First, lane-changing behavior is not considered in the model. In future research, a fuel-efficient two-dimensional control strategy will be designed for the CAVs. Second, the stochastic nature of human driving behavior is not considered. In a future study, car-following models that consider the stochastic nature of human driving behavior will be used to simulate the human-driven vehicle in the mixed traffic stream. Third, the numerical simulations in this only considered cut-in and single-lane condition. In the future, different traffic states with the multi-lane condition need to be simulated to investigate the impact of EcoSDM under different congestion levels.

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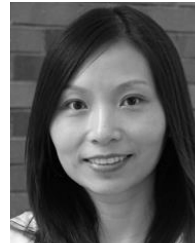
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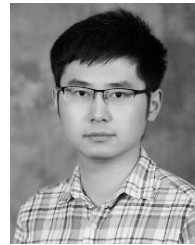
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