Impact of Automated Vehicle Eco-Approach on Human Driven Vehicles

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ABSTRACT In urban areas, traffic signals cause unnecessary stops and delays to vehicles resulting in excessive energy consumptions and emissions. The eco-approach technology has been introduced to achieve environmentally friendly driving behaviors and to improve energy efficiencies with reduced rapid accelerations or decelerations. However, it is not clear how the behavior of drivers would change while following an eco-approaching vehicle. Especially in the mixed traffic, dynamics behind the interactions between the human-driven vehicle and connected automated vehicle (CAV) that perfectly achieve the eco-approach, and the impacts on energy consumptions are not transparent. This research designs a driving simulation environment for the mixed traffic to assess the benefits of the eco-approach. In the experiments, a straight roadway with four signaled intersections equipped with communication devices is developed. An eco-guidance algorithm for human drivers and an eco-approach control algorithm of CAV with the I2V communication system are designed and compared, where each scenario is tested 50 times with a human driver using a driving simulator. The results indicate that both eco-guidance scenario and following CAV with the eco-approach scenario could reduce over 6% of fuel consumptions compared to the base-case scenario, which is normal-driving without guidance. This indicates the energy efficiency benefit of the eco-approach of CAVs and its impact on surrounding vehicles in the mixed traffic.

INDEX TERMS Road Transportation, Traffic Flow, Connected and Automated Vehicle, Eco-approach, Human Factor.

I. INTRODUCTION

Connected and automated vehicles (CAVs) have been actively researched with significant momentum and being advertised for their potentials for improving with respect to mobility, safety, energy, and greenhouse gas (GHG) emissions. With the emerging CAV technology, it is necessary to consider the interactions between human-driven vehicles and CAVs and their impacts on the transportation system. It is expected that the mixed traffic of human-driven vehicles and CAVs would present new challenges and hopefully a room for improvement opportunities. However, it is still difficult to affirm the benefits or risks of CAVs in the mixed traffic flow. The influence of CAVs on the energy consumption and greenhouse gas (GHG) emissions would be one of the most meaningful topics to explore.

Facing the climate challenges, many governments around the world have started paying more attention to energy consumptions and greenhouse gas emissions. According to the report by the United States Environmental Protection Agency (EPA), the energy consumptions and emissions from...
transportation sector cover about 29% and 28% of the total US energy consumptions and emissions [1, 2], which is the second largest contributor. The pollutants emitted from the motor vehicles add significant air quality problems, especially in the cities. The traffic lights in urban areas typically result in unnecessary stops which further contribute to extra energy consumptions and emissions. To deal with this issue, the concept of eco-driving has been introduced. Eco-driving is defined as decision-making processes which influence the fuel economy and emissions of vehicles to reduce the environmental impact [3]. The decisions include the strategic decisions on vehicle selection and maintenance, the tactical decisions such as route selection and vehicle load, and the operational decisions of on-road driver behaviors [3].

Compared to the terminology “eco-driving” with a general meaning of energy-efficient driving, the word “eco-approach” refers to one of the eco-driving operational applications, which uses the Infrastructure-to-Vehicle (I2V) communication system to provide the vehicles with real-time Signal Phase and Timing (SPaT) to improve energy efficiencies at the signalized intersections [4]. This strategy has been proven to have 10-20% potential reductions in energy consumption [5].

However, when the eco-approach is recommending the optimal speed to drivers, it is evident that the driver’s behavior (i.e., how closely the driver follows the guidance) would be more critical to the effectiveness of eco-driving technology than the other factors, such as specifications of the vehicle (i.e., model and weight), or the eco-approach algorithms. The reason is that the drivers would decide whether to follow the guidance or not, how to follow it, tightly or loosely, and the energy consumptions and emissions would eventually depend on their behaviors. Furthermore, when the human-driven vehicles and CAVs equipped with the eco-approach driving closely on the same road, the behavior of human drivers would be affected by the ideal eco-approach-based behavior of CAVs. That is to say; how will CAVs influence their surrounding vehicles in terms of energy efficiencies? For example, if a CAV with eco-approach travels in front of the human-driven vehicle, the human driver’s behavior should also be affected in terms of the energy consumption.

To answer these questions, this research assesses the impacts of the CAV equipped with the eco-approach on the behaviors and the energy consumptions of human-driven vehicles using a human-in-the-loop simulation (HILS) environment. The simulation environment uses a driving simulator software PreScan (developed by TASS International, TNO), which is designed for Advanced Driver Assistance Systems (ADAS) and Intelligent Vehicle (IV) systems with different sensors equipped to the vehicles and the infrastructures [6]. This platform has been validated by means of evaluations on its reliability in the eco-driving application by comparing it with the field tests [7]. In addition, a guidance of eco-approach for human driver and a decision principle of eco-approach for CAV under I2V communication system are designed to enhance the driving experiments for the mixed traffic.

The rest of this paper consists of following parts: the eco-driving technology related papers are reviewed in the next part; then the experimental design is introduced in details, including the roadway network design, the scenario design, and the eco-approach design; then the experiment implementation and results are presented; in the end, the conclusions, as well as future studies are discussed.

II. LITERATURE REVIEW

The first eco-driving project was conducted in 2007 by several European countries in order to answer how eco-driving was addressed in learners and novice drivers’ training and test [9]. Based on the results, the project gave recommendations on eco-driving behaviors mainly as: to maintain a steady speed and to decelerate smoothly. Since then, many researchers have been applying various speed control strategies to improve the environmental performances such as reducing the energy consumptions and emissions.

With more advanced technologies being available in the transportation systems, many analytical models combined with various technologies have been proposed to improve the energy efficiency and to reduce the emissions. For example, by using Variable Speed Limit (VSL), Zegeye et al. [10, 11] integrated a macroscopic traffic flow model METANET and a microscopic fuel consumption model VT-Micro to optimize the fuel efficiencies of vehicles on freeways. A model predictive control (MPC) framework was adopted to achieve the balanced trade-off between conflicting traffic control objectives, such as minimizing energy consumption and travel time. He et al. [12] and Xie et al. [13] designed a jam-absorption driving strategy by guiding the vehicles to move slowly when approaching a shockwave. The simulation results revealed that the traffic flow oscillations and the emissions could be effectively reduced. Qian and Chung [14] proposed a strategy for the eco-driving styles – to moderate and smooth the accelerations. They used a microscopic traffic simulator Aimsun to evaluate the energy consumption as well as the travel time at the traffic intersection level. However, the before-and-after comparison results showed the potential negative impacts of using eco-driving. This was caused by the moderate acceleration, which slowed down the average speed at start-up of green light and reduced the discharge flow rate of queuing vehicles. A dynamic eco-driving concept was proposed by Barth and Boriboonsomsin [15]. In this system, the drivers would receive real-time advice based on the surrounding traffic conditions. They evaluated the performance of the dynamic advising system with simulation first. The simulation results showed that around 10-20% reductions in energy consumption could be realized, where
less congested scenarios had higher reduction rates. Then in the real-world experiment, a slightly smaller energy saving was achieved when compared to the simulation tests. Saboohi and Farzaneh [16] developed an optimal driving strategy to avoid excess fuel consumption and minimize the fuel consumption in given routes. The control variables in this eco-driving model were vehicle speed and gear ratio. By estimating the speed profile in different traffic congestion patterns, the results showed the potential fuel consumption savings of 1.5L/100km in mixed intense traffic flow. Their focuses were mainly on the eco-driving on freeway systems.

Many studies have investigated the eco-approach (i.e., eco-driving on signalized arterial) as well. Barth et al. [17, 18] proposed a dynamic eco-driving system for an arterial corridor with traffic signals. The SPaT information of a traffic light is provided to the driver to adjust the speed and minimize the energy consumption when approaching the signalized intersections. The simulation results showed a wide range of reductions (around 10-15%) in fuel consumption depending on different parameters such as traffic flow rate and speed. They also concluded that significant indirect network-wide fuel savings on the overall traffic were achieved, even at low penetration rates of eco-approach vehicles (e.g., approximately 5% with 20% penetration rate) [19]. Rakha and Kamalanathsharma developed an optimal framework using the simplified microscopic fuel consumption model as the objective function. [5]. This research focused on the development of a more explicit objective function to find the most fuel-optimal speed profile for signalized intersections.

It is noticed that these studies are mainly dealing with the eco-approach of an individual vehicle. Therefore, some researchers turned their attention to a platoon-based eco-approach at signalized intersections. Chen et al. [20] presented an eco-driving speed control algorithm for platoons in which the acceleration-deceleration profile was used to prevent the drivers from idling and passing the platoon as much as possible. The algorithm considered the impact of the downstream platoon as well as the mixture of vehicles that obey or disobey the system guidance. Ma et al. [21, 22] designed a parsimonious shooting heuristic algorithm to cluster the vehicles in platoons to occupy the green phases properly by considering kinematic vehicle models, arrival patterns, and signal operations. With numerical experiments, the studies showed the potential benefit of transformative trajectory optimization approach using advanced CAV technologies (around 29% of fuel consumption reductions). Unlike the aforementioned platoon-based eco-driving studies that assume all the vehicles to be CAVs, some of the studies have considered the mixed traffic flow and simulated with different penetration rates of CAVs [18, 23, and 24].

However, in the eco-driving technology, the human factors can play one of the most significant roles and result in a wide range of energy savings [25, 26]. The reason is that the human driving behaviors would ultimately decide the energy consumptions and emissions. That is why many researchers tried to implement the eco-driving technology in the field or test with the driving simulator to evaluate the actual effectiveness. As mentioned above, Barth and Boriboonsomsin [15] implemented their eco-driving system with real-time advice in real-world and verified that the system could successfully reduce the fuel consumption (by 13%). Oscar et al. [27] also investigated the fuel consumption and emission impacts of Intelligent Speed Adaptation (ISA) system which provides the real-time advice in forms of recommendation speeds to the drivers. The speed advice was decided based on the location and speed of the vehicle. ISA system has been proven to reduce both fuel consumptions and emissions without significantly affecting travel times compared to normal vehicles. Boriboonsomsin et al. [28] proposed an eco-driving device to provide an instantaneous fuel economy feedback information and tested it in Southern California. With twenty drivers, they analyzed the fuel economy improvements due to the influence of eco-driving devices and concluded that 6% of reduction on city streets and 1% of reduction on highways were achieved. Another test of an eco-approach using SPaT and intersection map information was presented by Xia et al. [4]. The system calculated and provided the speed recommendation to the drivers to allow them to pass through the signals on the green time by adjusting the speed. They found that both simulation tests and field tests could achieve the reductions in fuel consumptions and emissions (around 14%). Hiraoka et al. [29] and Cui and Park [26] used a driving simulator to evaluate the driving behaviors with eco-driving strategies. Ko et al. tested the eco-driving system and eco-signal system with the field test as well as the driving simulator test and observed that both tests could effectively improve the energy efficiency [7]. Kirsten also used a driving simulator to simulate the driving behavior by influencing the green wave with advice and analyze the acceptance level of the corresponding system [30]. The system was concluded to be promising for improving traffic flow and driver comfort level in addition to the energy consumption.

There have been many studies that explored the benefits of eco-driving strategies from the aspect of human drivers. However, with the emerging technologies of CAV, it is important and timely to quantify the impact of CAVs to fuel consumptions of the surrounding vehicles including human-driven vehicles. To bridge this gap, this study focuses on evaluating the energy impact of the CAV on the human driver behaviors under different eco-approach scenarios. Meanwhile, the impact of CAV with the eco-approach to the human driver is compared with the impact of the eco-approach guidance for the human driver.
III. EXPERIMENTAL DESIGN

The purposes of this experiment are as follows:
- To design a driving simulation environment of mixed traffic to assess the interactions between CAVs and human-driven vehicles based on the previous version of eco-driving evaluation [7], by adding an eco-approach controller of CAV
- To assess the benefit of eco-approach considering the actual response of the human driver
- To evaluate the impacts of a CAV to its following human-driven vehicle from the aspect of fuel efficiency

The experimental design, including the roadway network and the scenario settings, and eco-approach system designs for CAV and human driver are described in this part.

A. Roadway network design

To implement the experiments, a hypothetical four-lane arterial roadway network is designed in the driving simulator software, PreScan. The roadway network and the view of the human driver are as shown in Figure 1. In this roadway, the human driver would travel through four signalized intersections. The speed limit is set as 35mi/h (around 15m/s, a typical speed limit on minor arterial), and this is informed to the driver with a traffic sign on the roadside. The total travel distance is around 0.75 mi (=1.2 km).

The antenna sensors are equipped at the traffic signal and the vehicles to send and receive the SPaT information and the location information through the I2V communication system. The communication range is set as 100m (i.e., 328ft). The simulation updates in the frequency of 200Hz.

Among the four intersections, the first intersection is used to control the departure time of the vehicles using the green light. The time for departure from the first intersection is uniformly distributed between 20–70s. For the rest of intersections, the cycle length is fixed at 50 seconds, assuming light traffic (the phase volume per lane is supposed to be 400 veh/h/ln). The signal consists of 18 seconds of green time, 3 seconds of yellow time, and 29 seconds of red time. To avoid the case in which the driver can pass through the intersections without any stops, the offsets of the third and the fourth intersections relative to the second intersection are set as 10 and 5 seconds, respectively.

B. Scenario design

The scenarios considered in this research are based on the existence of a CAV with the eco-approach as a leading vehicle and of the guidance for the human driver. The guidance means to guide the driver with recommendation speed in real-time to minimize the energy consumptions based on the eco-approach. This guidance is called as “eco-guidance” here, and its mechanism is described in next part. The scenario descriptions are as follows:

- Base case: The driver drives as usual without the eco-guidance. There are no other vehicles on the road.
- With CAV: The driver drives as usual without the eco-guidance, but there is a CAV with the eco-approach in front of the human-driven vehicle.
- With guidance: The driver drives with the eco-guidance on the driving simulator display. There is only the subject vehicle on the road without any other vehicles.

The CAV and the human-driven vehicle depart from their starting points, with an offset distance of 30 meters to make sure the leading and following mechanism occurs (Rittger et al. [32]).

C. Eco-approach controller design for CAV

A cruise controller is designed for CAV, which is equipped with the I2V communication system, to drive through the roadway by following the eco-approach principle. The eco-approach principle is shown in Figure 2. It should be noted that this model is assuming that no other vehicles are ahead of the CAV. The behavior decision module consists of two major parts: “out of signal control” and “in signal control.” The eco-approach controller is designed to improve the fuel consumption and to ensure realistic behaviors of CAVs and comfort of the occupants. The ultimate goal is to let the CAV cruise with fewer accelerations or decelerations, which cause...
most of the unnecessary fuel consumptions at the intersections. When approaching the intersections and the CAV needs to stop, the eco-approach is supposed to let the CAV slowdown in advance so that it arrives at the stop line just in time when the signal turns green. This method is used in many studies and is proven to be effective in reducing fuel consumptions [5, 7, 17]. More details on the principles are described below.

“Out of signal control” is active when the vehicle is not in the communication range of any traffic signals. In this module, the vehicle would cruise with the speed limit, which is called the “target speed” in Figure 2. If the current speed $v_t$ is not the same as the target speed $v_r$, the vehicle will accelerate or decelerate to reach the speed. This may happen when the vehicle leaves the intersections. The acceleration or deceleration profile follows a sine function in order to ensure a realistic and smooth speed trajectory, to minimize the fuel consumption, and to consider the comfort of the passengers ([17-18]). The sine function here is of a half-cycle ($180^\circ$, from 0 to $\pi$ radians), with the amplitude of 2.5m/s², which is the maximum comfort acceleration rate [34]. Therefore, once the difference between the current speed and target speed is calculated, the duration of the acceleration or deceleration can be decided.

“In signal control” is triggered when the vehicle is within the communication range. When this module is active, the vehicle follows a dynamic speed plan of the eco-approach, which is modified from the model of Xia et al. [18] by using the sine-shaped acceleration and deceleration profile. The decision of maintaining current speed, accelerating or decelerating is made by comparing the current speed $v_t$ and the recommendation speed $v_r$. If the vehicle cannot pass the intersection with current speed, the recommendation speed is calculated by considering the distance, remaining green time or red time, and the acceleration or deceleration profile is generated. The smooth acceleration or deceleration is based on the sine function profile which is mentioned above. The recommendation speed is the marginal speed that can pass the intersection during the current signal phase. That is to say, when the current signal is green, the vehicle should cruise with speed no less than the recommendation speed to pass through before the signal turns red. If the current signal is red, the vehicle should use the recommendation speed to avoid a full stop. In the case of recommendation speed during green phase exceeds the maximum speed $v_{\text{max}}$, which is related to the speed limit, the vehicle would discard the original recommendation speed that is calculated with remaining green time and update the recommendation speed $v'_r$, which is targeting to pass the intersection after the upcoming red signal.

**FIGURE 2** Driving behavior decision principle of eco-approach for CAV

### D. Eco-guidance design for human driver

The guidance is realized by giving a recommendation speed $v_r$ so as to guide the human driver to adjust the speeds. The difference between the eco-guidance and the eco-approach for CAV is that the eco-approach for CAV provides a speed plan, which is a proactive system, while the eco-guidance updates the recommendation speed every time interval and is reactive to real-time information. This is because the CAV is expected to follow the speed plan exactly and thus, a speed trajectory can be planned based on the distance, current speed, and signal phase, once the vehicle approaches the intersection within the communication range. However, such speed plan is impossible for the human drivers to follow since it is hard to predict or control the trajectory of the human-driven vehicle. Therefore, the eco-guidance updates the recommendation speed with real-time distance and signal phase (i.e., in the frequency of 200 Hz).

The recommendation speed is calculated as the distance to the signal over the remaining green time ($t_{\text{grn}_{\text{left}}}$) or remaining red time ($t_{\text{rd}_{\text{left}}}$). The speed limit is also considered in the recommendation speed calculation in order to avoid giving an unrealistic recommendation. For example, if the traffic signal is green, and the recommendation speed is calculated as a far higher value than the speed limit with the current remaining green time, the algorithm uses the remaining green time + red time to calculate a new recommendation speed, which guides the driver to drive through during the next green phase.

The recommendation speed is displayed on a screen under the human driver view with two-dimensional temporal plots (Figure 3). The interface shows the current speed of the subject vehicle with yellow plots and the recommendation speed with red or green points. It should be noted that because the driver view in Figure 3 is captured after the simulation ended, the numerous points shape lines. In the eco-guidance interface, the red points come up when the recommendation speed is for the red signal, i.e., when the signal is red or current remaining...
green time is too short to pass through. It indicates that when the recommendation speed is given in red points, the human driver should travel at speed below the recommendation speed. If the recommendation speed is lower than 10mi/h (=5m/s), the driver is recommended to stop by the stop line. When the recommendation speed points are given in green, which means the minimum speed to pass through the intersection, the driver should travel at speed above the recommendation speed unless the recommendation speed is too high. Besides, if the current speed satisfies the recommendation speed, there is no need to take any actions.

![Diagram](image)

**FIGURE 3 Driving simulator display of the eco-guidance interface for the driver**

Figure 3 shows actual and recommended speeds under the eco-guidance given to a human driver that ended up avoiding a complete stop. Current speed and the recommendation speed are updated in real-time. In this case, when the human-driven vehicle is approaching the intersection, the recommendation speed is lower than the current speed at the beginning, which requires a deceleration. Then the driver starts to decelerate after a reaction time and maintains the speed near the recommendation speed, which was near 10 m/s until the signal turned to green light. The recommendation speed increases, as the remaining red time nears zero, which is the denominator in calculating the recommendation speed. Since the recommendation speed in red color indicates that the human driver should travel at speed below the recommendation speed, the driver can ignore the infinite recommendation speed. Therefore, the driver accelerates back to the target speed after a certain perception-reaction time and passes through the intersection.

**IV. EXPERIMENTAL RESULTS**

In the experiments, the human driver drove on the straight roadway with four signalized intersections under three scenarios. To obtain an adequate sample size, each scenario was tested for 50 times. For each simulation run, the speed and acceleration data were collected, and then the fuel consumptions were calculated with the VT-CPFM model [8]. The average (AVE), standard deviation (STD), maximum (MAX) and minimum (MIN) fuel consumptions of the CAV and the human-driven vehicle in different scenarios are presented in Table I. The relative change is calculated as the fuel consumption differences divided by the reference fuel consumption:

\[
\text{Relative change}(x, x_{\text{reference}}) = \frac{x - x_{\text{reference}}}{x_{\text{reference}}}
\]

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Fuel consumption (ml)</th>
<th>Relative change (%) compared to:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AVE</td>
<td>STD</td>
</tr>
<tr>
<td>Human-driven vehicle</td>
<td></td>
<td></td>
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<tr>
<td>With CAV</td>
<td>93.1</td>
<td>12.0</td>
</tr>
<tr>
<td>With guidance</td>
<td>92.8</td>
<td>12.6</td>
</tr>
<tr>
<td>CAV</td>
<td>88.4</td>
<td>9.5</td>
</tr>
</tbody>
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* indicates the mean difference is significant at the 0.05 level.

Within the distance of 800m (counting from the middle point of the first and second intersections), the base case fuel consumption is 99.1ml on average and the fuel consumption of CAV with eco-approach is 88.4ml, which is 10.80% less. Besides, CAV with eco-approach consumed 5.05% and 4.74% less than the human-driven vehicle in “with CAV” and “with guidance” scenarios, respectively. All of the fuel consumption reductions are statistically significant. The fuel consumption reduction of 10.80% is showing the potential benefit of the eco-approach controller in CAV because CAV can follow an ideal eco-approach with its precise controls. This is significantly higher than the benefit of providing eco-guidance to the human drivers, i.e., “with guidance” scenario, due to the reaction time, distraction, and the willingness to follow the guidance system.

The standard deviation, maximum and minimum fuel consumptions are showing that the performance of CAV is most stable. The fuel consumptions of human driver “with CAV” and “with guidance” have slightly bigger standard deviations than the base and CAV cases, but the minimum fuel consumption is as low as that of CAV. In the base case, even though the standard deviation is small, both the minimum and maximum fuel consumptions are the largest among the scenarios.

Besides, it can be observed that the human-driven vehicle consumed 6.05% less fuel when following a CAV with the eco-approach compared to the base case. This reduction is also proved to be statistically significant. The fuel consumptions are similar between “with CAV” scenario and “with guidance” scenario. This indicates that the benefit of following CAV is
similar to the improvement that is achieved by providing the eco-guidance to the human driver. Therefore, the CAV with the eco-approach in mixed traffic is expected to have positive impacts on surrounding vehicles, especially on a closely following vehicle. The impacts may vary by the willingness to follow, driving behaviors, the relative distance of the vehicles, and traffic conditions.

V. CONCLUSIONS

In this research, a driving simulation environment for the mixed traffic to assess the benefits of eco-approach is developed. An eco-approach control algorithm for CAV and an eco-guidance for the human driver are designed with I2V to improve the fuel consumption efficiencies. Then the influences of the eco-approach for CAV and the human driver are evaluated on a signalized arterial. This research implemented three scenarios – “base case,” “with guidance,” and “with CAV” – on a straight arterial roadway with four intersections using the driving simulator software PreScan. Each scenario is tested for 50 times to acquire an adequate amount of data for analysis.

The test results showed that a CAV with the eco-approach could help its following human-driven vehicle to save the fuel significantly with a reduction of 6.05%. This benefit is similar to the improvement that was achieved by providing an eco-guidance to a human driver which resulted in a fuel reduction of 6.36%. The main reason is that the CAV operated under the influences of an ideal set of eco-approach behaviors, leading to the following human-driven vehicle to mimic the behaviors of the CAV and reduce the fuel consumption. The CAV with the eco-approach consumed the least fuel compared to the human-driven vehicle in different scenarios. The potential benefit of the eco-approach controller is 10.80% reduction in fuel consumptions, which is difficult for the human drivers to achieve due to the reaction time, distraction, and the willingness to follow the guidance system.

For future research, additional factors related to the eco-approach technology, including the communication range, weather condition, traffic condition, and signal timing, should be explored. The results could help in designing communication range, eco-driving strategies, and traffic signal timing plan. Furthermore, the road conditions including the curve or upgrade, downgrade, and road type should be considered as a factor that might influence the benefit of eco-approach in mixed traffic. Besides, an enhanced eco-approach algorithm for CAV needs to be developed which considers its preceding human-driven vehicles. Due to the uncertainty of the human driver behaviors, CAVs may have low energy efficiencies when following human-driven vehicles. Therefore, an enhanced algorithm is necessary for CAVs to ensure high energy efficiencies in the mixed traffic.
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