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Influences of Single-Lane Automatic Driving Systems on Traffic Efficiency and CO_2 Emissions on China's Motorways

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Abstract: There are big differences between the driving behaviors of intelligent connected vehicles (ICVs) and traditional human-driven vehicles (HVs). ICVs will be mixed with HVs on roads for a long time in the future. Different intelligent functions and different driving styles will affect the condition of traffic flow, thereby changing traffic efficiency and emissions. In this paper, we focus on China's expressways and secondary motorways, and the impacts of the 'single-lane automatic driving system' (SLADS) on traffic delay, road capacity and carbon dioxide (CO_2) emissions were studied under different ICV penetration rates. Driving styles were regarded as important factors for scenario analysis. We found that with higher volume input, SLADS has an optimizing effect on traffic efficiency and CO_2 emissions generally, which will be more significant as the ICV penetration rate increases. Additionally, enhancing the aggressiveness of driving behavior appropriately is an effective way to amplify the benefits of SLADS.

Keywords: intelligent connected vehicle; single-lane automatic driving system; China's motorway; traffic efficiency; CO_2 emissions

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1. Introduction

With the empowerment of the new round of information technology revolution represented by the Internet, big data, cloud computing, artificial intelligence, fifth-generation mobile communications, etc., traditional vehicles are gradually developing in the direction of intelligence and connectivity [1]. Intelligent connected vehicles (ICVs), on the one hand, are equipped with advanced on-board sensors, controllers and actuators, which can assist or even replace human drivers in completing tasks like complex environmental perception, intelligent decision-making and control. On the other hand, they are equipped with modern communication modules, making it possible to realize intelligent information interactions with roads, pedestrians, and cloud platforms [2]. Therefore, ICVs are expected not only to provide safer, more efficient, more comfortable, and more energy-saving travel experiences, but also to serve as links to open up smart cities, smart transportation and smart energy systems, solving the problems caused by rapid urban development, such as traffic congestion and environmental pollution [3,4]. Scientific evaluation of ICV benefits in transportation efficiency, energy saving and emissions reduction will help to: (1) provide reference for top-level design and important strategic deployment in the fields of automobiles, cities, transportation, energy, etc.; (2) correctly grasp the development direction of automobile, city, transportation, energy technologies; (3) alleviate urban traffic and environmental problems, and promote the improvement of social productivity; (4) optimize travel experience and improve quality of life.

Unlike new energy vehicles that make changes to powertrains, which directly affect energy consumption and emissions, the impacts of ICVs on energy consumption and emissions are on the basis of the change in the traffic condition, which is due to alterations in driving behaviors and route selection. Therefore, one can regard traffic efficiency as having a direct impact on ICVs and an indirect impact on energy consumption and emissions [5]. At present, many scholars have conducted studies on the influences of ICVs on transportation efficiency, energy consumption and emissions, but the conclusions are significantly different. Based on the Kalman filter algorithm, Shanglu He et al. developed a method to estimate the average speed of expressway sections using data from ICVs with low penetration rate (not more than 10%), but unfortunately it did not further analyze the specific impacts [6]. Davis et al. believe that when the penetration rate of the adaptive cruise system (ACC) reaches 50%, ICVs can increase the traffic volume by 20% at expressway merging areas and improve the total travel distance per unit time by 3.6 km [7]. Focusing on the basic two-lane section of the expressway, Arash Olia et al. analyzed the impacts on the road capacity of two kinds of ICVs under different penetration rates. The two kinds of ICVs are autonomous vehicles and cooperative vehicles, which are developed with different technical routes. It was found that autonomous vehicles have almost no impact on the road while the cooperative vehicles can effectively shorten the car following distance so as to improve road capacity [8]. Pengfei Liu et al. have the same views as Arash Olia et al. on the mechanism of the impact of ICVs on traffic flow. Through simulation research, they found that, as for expressways, ICV will exert a negative impact on road capacity when its penetration rate is lower than 40%. However, the road capacity will be significantly improved if the ICV penetration rate is over 40% and the improvement effect will be more apparent with the increase of the road speed limit [9]. In order to promote the rapid implementation of ICVs, Ke Ma et al. studied the impact of dedicated lanes for ICVs on expressways' traffic flow in terms of traffic control. They claimed that the number of dedicated lanes should correspond to the ICV penetration rate [10]. Considering the road safety law and the huge expressway mileage, however, laying a large area of dedicated lanes for ICVs is probably not realistic in China in a short period of time. Christos Stogios et al. studied the impact of ICVs on traffic flow characteristics and energy consumption from multiple dimensions such as technical routes, powertrain types, penetration rates, driving styles and road scenes. They found that ICVs with an aggessive style can reduce carbon dioxide (CO_2) emissions by 26%, increase the average speed, reduce travel delay, and improve traffic capacity. On the contrary, ICVs with a conservative style will have the opposite effect [11]. Ricardo et al. found that self-driving vehicles can appropriately reduce greenhouse gas and pollutant emissions on the expressway when their penetration rate is smaller than 30%, but the impact when the penetration rate exceeds 30% was not given [12]. Yanyan Qin et al. announced that as the ICV penetration rate with connected adaptive cruise control (CACC) continues to increase up to 100%, the fuel consumption can be reduced by 10.74% at the maximum degree on expressways [13]. Jackeline et al. believed that in merging areas of expressways, ICVs with vehicle-to-vehicle (V2V) functions can significantly reduce travel time and fuel consumption through coordinated control between vehicles on the main roads and the ramps [14]. Iman Mahdinia et al. claimed that, on expressways, ICVs with CACC can form fleets, which can reduce the fuel consumption and emissions of the ICVs in the fleets by 3.7% on average compared to ICVs with non-connected ACC. However, it will increase the average fuel consumption and exhaust emissions of other ICVs integrated into the fleets by 0.54% and 4.1%, respectively [15]. As a result, there have been many related previous studies but they mainly focused on the function of the Internet of Vehicles (IoV). On the contrary, realizing V2V information interaction is faced with various restrictions at present such as laws and regulations, technologies, and differences between different vehicle products. In addition, the estimation results of the impacts of IoV on traffic efficiency, energy conservation and emissions reduction are likely to be different from the current results with technological updates, traffic demands and changes in travel modes in the future.

The popularization of ICVs cannot be achieved overnight. Firstly, the development of automation and connection technologies of ICVs requires adequate accumulation, studies, iteration and verification [16]. Secondly, it is necessary to explore effective business models for innovative travel modes based on ICVs. Thirdly, ICVs have to be supported by policies and regulations if they are driven on roads. As a result, traditional human-driven vehicles (HVs) and different levels of ICVs are likely to coexist on roads for a long period of time in the future [8]. At present, high-level ICVs cannot be applied immediately because the specific product forms and technologies, as well as the business models, have not yet been determined. Therefore, the accuracy and guidance value of the assessment of the impacts due to ICVs may not be sufficient. However, the technology of low-level and medium-level ICVs equipped with the advanced driver assistance system (ADAS) is relatively mature and has a relatively higher market penetration rate. As a result, the impact estimation of the low-level and medium-level ICV impacts is expected to be more accurate and valuable in guidance. This paper is expected to fill the gap.

ACC and automatic emergency braking (AEB) are the main functions of ADAS to control the longitudinal driving behavior [17]. Based on the distance between the self-vehicle and the preceding vehicle, the motion state, and the artificial operation instructions of the self-vehicle, ACC controls the longitudinal speed of the self-vehicle and the time gap between the self-vehicle and the preceding vehicle to improve the driving experience and safety [18]. AEB can monitor the front driving environment in real time, and automatically brake when a collision risk may occur, so as to avoid or reduce the collision [19]. Both of the two functions change longitudinal driving behavior, consequently affecting the state of the traffic flow. Therefore, it is advisable and reasonable to define the concept of 'single-lane automatic driving system' (SLADS) to fully characterize the comprehensive changes in the longitudinal driving behavior due to the two functions. SLADS is a comprehensive driving assistance function for a vehicle used in a single lane, i.e., in the longitudinal direction of the vehicle. If the distance between the vehicle with SLADS and its leading vehicle in the same lane exceeds the maximum car following distance, it will accelerate to its desired speed according to its desired acceleration. Once the distance mentioned above is within the range of the car following state, it will follow the leader with ACC. As the distance between it and its leader is lower than the safety threshold, which is brought about by emergency braking of the leader for instance, it will decelerate with the help of AEB with the safe deceleration or even the maximum deceleration to avoid a rear-end collision. ICV contains many advanced driver assistance functions to help human drivers and even has an automated driving system to fully realize automated driving. Almost all of the current ICVs on Chinese roads only offer driving assistance to human drivers and still require human drivers to complete driving tasks. SLADS has advanced driver assistance functions only available in ICVs. It influences the longitudinal driving behavior directly. Since the research object of this article is SLADS, and the composition of traffic flow represents the different types of traffic participants, it may be agreed that 'ICVs' mentioned in the experimental research parts of this paper represents vehicles equipped with SLADS. The penetration rate of ICV mentioned in the following text is on behalf of the penetration rate of SLADS.

In this article, VISSIM, a traffic simulation software, is used to evaluate the impacts of ICVs equipped with SLADS on traffic efficiency, energy consumption and emissions under two typical motorway scenarios in China, which are expressways and secondary motorways. Changes in traffic delay, road capacity and CO_2 emissions are assessed in order to provide suggestions for promoting the development and application of ICVs to maximizing the relevant social benefits. Additionally, SLADS is still a function of driving assistance and the main controller of a vehicle is still the human driver. Therefore, the impacts of driving style and distracted driving behavior are also considered in order to obtain more realistic and accurate evaluation conclusions.

2. Methodology

2.1. Driving Behavior Models of Vehicles

In order to research the impact of ICV with SLADS on traffic efficiency and energy consumption with simulation methods, driving behavior models are of great necessity.

They depict the longitudinal and lateral driving behaviors through mathematical methods such as kinetic equations, machine learning, statistics and so on, which makes it possible for computers to calculate.

2.1.1. Longitudinal Driving Behavior Models of Vehicles

The longitudinal driving behavior of vehicles mainly involves the free-driving behavior and the car following driving behavior. As for the free-driving behavior, just like HVs, ICVs will accelerate to their desired speeds with the maximum desired accelerations. However, with the application of SLADS, there are obvious differences in car following behavior between ICVs and HVs. Consequently, it is of great significance to select a suitable car following model to characterize these differences. It is generally believed that when the time headway of two neighboring vehicles is less than 6 s or the distance headway is less than 125 m, the following vehicle is in a state of car following, which means the speed and acceleration (or deceleration) will be adjusted with the change of the motion state of the preceding vehicle [20]. The car following models are relatively mature including 'Irritation Response Model', 'Safe Distance Model', 'Desired Speed Model', 'Psycho-physiological Model', 'Cellular Automata Model' and 'Artificial Intelligence Model' [20]. Considering the characteristics of various models, the Wiedemann 99 model, a kind of 'psycho-physiological Model', was selected [21]. The main reasons for this are given as follows.

(1) For ICVs with SLADS, it is still the human drivers who complete driving tasks. Under the overlap of the driving assistance functions and the driving experience of human drivers, vehicles probably exhibit extremely complex driving behaviors. Some nonlinear and stochastic driving behavior characteristics are difficult to depict through fixed kinematic equation descriptions. Wiedemann 99 model abstracts driving behaviors into 10 parameters. By adjusting the values of these parameters, driving behaviors of ICVs and HVs can be described from the dimensions of intelligent functions and driving styles. The specific model principle will be introduced later.

(2) The Wiedemann 99 model has been used by many scholars in their research [6,11,22], and many sorts of famous traffic simulation software such as VISSIM and SUMO also use it as a built-in model. Therefore, reliability and accuracy of the Wiedemann 99 model can be guaranteed.

The Wiedemann 99 model constructs the vehicle state space with the speed difference Δv between the leading and following vehicles as the abscissa and the head distance Δx between them as the ordinate. This state space is divided into four main areas by a number of thresholds, namely, free driving zone, car following zone, emergent braking zone and collision zone. These thresholds are calculated from 10 model parameters shown in Table 1 [11]. The state of each vehicle at each moment can be represented by point (Δv, Δx) that will obviously belong to one of the four different areas. According to the current state space area of the vehicle, the Wiedemann 99 model calculates and outputs the acceleration at the next moment for each vehicle to achieve real-time control. Since the reaction speed and execution accuracy of sensors, computing platforms and intelligent actuators are higher than those of human drivers, ICVs can accurately capture the movement states of vehicles in front and react to them in time. Therefore, compared with HVs, ICVs with SLADS are expected to adjust their speed more smoothly when following a vehicle, which could reduce the sensitivity to changes in the acceleration and deceleration of the preceding vehicle, and weaken speed fluctuations caused by "restraint" and "hysteresis" of car following behavior. These differences will affect the parameters in the Wiedemann 99 model, which are CC2, CC4, CC5 and CC6 [22,23].

Table 1. Parameters of the Wiedemann 99 model.

Model Parameter	Meaning	Unit	Explanation
CC0	Standstill distance	meter	The desired distance between stopped vehicles
CC1	Headway time	s	The time gap that a vehicle keeps
CC2	Following variation	m	The distance in addition to the allowed safety distance that is permissible before the vehicle-drive unit moves closer to the preceding vehicle
CC3	Following entering threshold	-	The threshold for entering the car following state, which controls whether the vehicle starts to decelerate
CC4	Negative following threshold	-	Control negative speed differences during car following
CC5	Positive following threshold	-	Control positive speed differences during car following
CC6	Speed dependence of oscillation	-	Influence of distance on speed oscillation
CC7	Oscillation acceleration	m/s^2	Influence of vehicle acceleration during car following oscillation
CC8	Standstill acceleration	m/s^2	Desired acceleration when starting from standstill
CC9	Acceleration at 80 km/h	m/s^2	Desired acceleration from a speed of 80 km/h

As mentioned before, ICVs with SLADS and HVs are all mainly controlled by human drivers. The parameters in SLADS like activation speed and expected time headway can be adjusted by human drivers according to their personal preferences. Consequently, the driving style of different drivers is also an important factor changing the impacts of SLADS on traffic efficiency and CO_2 emissions. The driving style is mainly determined by drivers' personality, which is divided into three categories: aggressive style, moderate style and conservative style. Drivers with the aggressive style are easily affected by external factors, become irritated, and show aggressive driving behaviors. They prefer higher driving speeds than the limit, high longitudinal acceleration and a large opening degree of accelerators and brakes. Drivers with the conservative style usually choose a low-speed and smooth driving mode to ensure safety. They tend to drive at the lower driving speed within the limit, show lower longitudinal acceleration and a small opening degree of accelerators and brakes. The behavior of drivers with the moderate driving style are between that of the aggressive and conservative drivers, which is more appropriate and safer. They are partial to the speed limit, medium longitudinal acceleration and moderate opening degree of accelerators and brakes. In order to simplify the research variables, we define the unaggressive driving style as including the moderate and the conservative driving style.

Some scholars have conducted studies on the distribution of Chinese drivers' driving styles through driving simulators, big data from IoV and so on. Qingjun He et al. selected 27 experienced drivers and studied their driving style distribution on the expressway through a driving simulator [24]. The simulation scenes consisted of two types of climatic environments (sunny and foggy) and three types of traffic conditions (free flow, congested flow and blocked flow) (six types in total). Driving styles were obtained by clustering vehicle indicators such as speed, acceleration, accelerator force, brake force, time headway and distance headway. This research was scientific and involved rich scenes and comprehensive evaluation indicators. Therefore, based on the research results, it is believed that the distribution of Chinese driving styles is: aggressive style:unaggressive style = 25.9%:74.1%. As for the model parameters of Wiedemann 99, the differences in driving styles have an impact on CC0, CC1, and CC7 [23].

Considering the differences in driving behaviors between ICVs with SLADS and HVs, as well as drivers with different driving styles (including SLADS used by them), aggressive ICVs, unaggressive ICVs, aggressive HVs and unaggressive HVs are studied.

The parameter values of the Wiedemann 99 model for different types of vehicles are shown in Table 2.

Table 2. Parameter values of the Wiedemann 99 model.

Parameters	Aggressive ICVs	Unaggressive ICVs	Aggressive HVs	Unaggressive HVs
CC0	0.50	2.17	0.50	2.17
CC1	0.50	1.70	0.50	1.70
CC2	1.00	1.00	4.00	4.00
CC3	−1.00	−3.33	−8.00	−8.00
CC4	0.00	0.00	−0.35	−0.35
CC5	0.00	0.00	0.35	0.35
CC6	0.00	0.00	11.44	11.44
CC7	0.45	0.12	0.45	0.12
CC8	3.50	3.50	3.50	3.50
CC9	1.50	1.50	1.50	1.50

2.1.2. Lateral Driving Behavior Models of Vehicles

The lateral driving behavior models of vehicles mainly involve the lane changing model and the lateral behavior model. The process of lane changing contains four steps, which are lane changing decision, lane selection, clearance selection, and lane changing action [25,26]. Lane changing decision is the driver's judgment of whether lane changing is necessary. If it is extremely necessary, such as changing to the correct lane or avoiding an accident, it is regarded as forced lane changing; otherwise, it is free lane changing, which is to obtain higher speed or better position. Lane selection is to select the target lane according to the lane changing purpose. After determining the target lane, the target clearance in the target lane will be found on the premise of safety. Finally, lane changing operations will be performed through acceleration and speed adjustment. At present, the commonly used lane changing models in computer simulation are cellular automata models, rule-based models, discrete choice-based models and excitation-based models. Since SLADS does not have the function of intelligent lane changing, the lateral driving behavior model of ICVs in this article should be consistent with that of HVs. The rule-based lane changing model built in VISSIM is selected because it can truly characterize the behaviors of free lane changing and forced lane changing, the parameter values of which are listed in Table 3.

Table 3. The meanings and values of the parameters of the vehicle lane changing model.

Parameters	Meaning	Value
Maximum deceleration	The upper limit of the deceleration of the driver or preceding vehicle	Overtaking other vehicles: -4.00 m/s^2
		Overtaken by other vehicles: -3.00 m/s^2
-1 m/s^2 per distance	The maximum deceleration is reduced with increasing distance from the emergency stop position	Overtaking other vehicles: 200.00 m/s^2
		Overtaken by other vehicles: 200.00 m/s^2
Accepted deceleration	The initial deceleration taken by the driver or preceding vehicle	Overtaking other vehicles: -1.00 m/s^2
		Overtaken by other vehicles: -0.50 m/s^2
Waiting time to dissipate	The maximum time the vehicle waits for the appearance of lane change clearance in the emergency parking position	60.00 s
Minimum headway distance	The minimum headway distance required for the vehicle behind to successfully overtake the vehicle in front	0.50 m
Safety distance reduction factor	The ratio of the safety distance when changing lanes to the original safety distance	0.60
Maximum deceleration for cooperative braking	The maximum accepted deceleration taken by the driver when another vehicle changing to the current lane he (or she) is driving on	-3.00 m/s^2

The vehicle lateral behavior model includes the position of the vehicle in a lane and the target lane choice when overtaking the vehicle in front. In terms of the position in a lane, taking the driving habits of most drivers and the requirements of driving training in driving schools into account, it is supposed that all vehicles tend to move in the center of the lane. As for overtaking lane selection, this paper allows the vehicle to overtake the preceding vehicle from the left, right and even its own lane (if the lane is wide enough) as long as ensuring safety. It is necessary to explain that overtaking and lane changing are not the same. When a vehicle plans to overtake the vehicle in front, as long as it maintains a sufficient safe distance laterally from the overtaken vehicle and does not affect the driving of other vehicles, the overtaking can be performed. Therefore, when a lane is wide enough, the vehicle has the opportunity to make full use of the remaining lateral space in the lane to complete overtaking.

2.1.3. Distracted Driving Behavior Model

Distracted driving behavior is when the driver's attention is partially or completely transferred from the driving task to other matters, which reduces the perception, judgment, and control capabilities and extends the response time to road conditions of drivers and raises the security risk as a result [27]. Distracted driving behavior can be divided into visual distraction, auditory distraction, physical distraction and cognitive distraction according to its nature, referring to the driver's attention being distracted respectively by some things, sound, action and thoughts not related to driving [27]. Among them, visual distraction will cause drivers' sight to shift to other directions, which makes them unable to respond in time to the road conditions ahead, while other distracting behaviors will not change their sight direction. Studies have shown that visual distraction such as WeChat typing could cause significant speed fluctuations and reductions, the impact of which is much more significant than that of non-visual distraction such as phone and WeChat chatting [27,28]. Thus, this paper only takes visual distraction into account. It should be noted in this paper that only distracted driving behavior of HVs is considered and there is no distracted driving behavior in ICVs because although drivers of ICVs may also have distracted driving behaviors, due to the auxiliary control and safety warning function of SLADS, ICVs are not completely out of control.

Distracted driving behavior will appear with a certain probability, which is 15.3% in this paper [28]. At the same time, once distracted driving behavior occurs, it will continue for a certain period of time. The duration of distracted driving behavior can be obtained by subtracting the reaction time without distraction from the reaction time with distraction. At present, most scholars have measured the duration of drivers' distracted driving behaviors through driving simulator experiments, but the results are different because the driver samples and distraction tasks are quite different. As a result, this paper integrates the measurement results of multiple documents and uses the average value of them as the reference value, which is 0.71 s [20,29–31].

2.2. The Model of CO_2 Emissions

In order to couple with the micro-traffic models and make full use of the speed and acceleration data of each vehicle output in the simulation to accurately calculate CO_2 emissions, the VT-Micro model developed by Virginia Tech was selected [32]. This model is a statistical model based on the instantaneous speed and acceleration of vehicles. It is suitable for estimating CO_2 emissions of light passenger cars or light trucks under high-speed and high-acceleration driving conditions [33], which can satisfy the research needs.

The VT-Micro model is able to directly calculate the rate of CO_2 emissions of a vehicle at a certain moment, as shown in Formula (1):

$$\ln(\text{MOE}_e) = \begin{cases} \sum_{i=0}^{3} \sum_{j=0}^{3} L_{i,j}^{e} \cdot v^i \cdot a^j, \ a \geq 0 \\ \sum_{i=0}^{3} \sum_{j=0}^{3} M_{i,j}^{e} \cdot v^i \cdot (-a)^j, \ a < 0 \end{cases} \tag{1}$$

In Formula (1), MOE_e represents the rate of CO_2 emissions, the unit of which is 'kilograms per second'. $L_{i,j}^{e}$ and $M_{i,j}^{e}$ are respectively on behalf of the correlation coefficients for the acceleration greater than or equal to 0 and the acceleration less than 0, which are commonly obtained by carrying out road trials in different regions. v^i denotes the vehicle instantaneous speed to the power of i. a^j means the vehicle instantaneous acceleration to the power of j. In addition, the model distinguishes between positive and negative vehicle acceleration to ensure its applicability to vehicle working conditions of acceleration, deceleration and constant speed. The overall CO_2 emissions of the traffic flow on the entire road can be obtained by accumulating the CO_2 emissions rate of each vehicle at each moment recorded during the entire simulation time period. And the average CO_2 emissions of vehicles on the entire road is eventually worked out by dividing the overall CO_2 emissions by the number of vehicles passing by during this period. In order to make the model suitable for Chinese scenarios, model parameter $L_{i,j}^{e}$ and $M_{i,j}^{e}$ are determined according to Table 4 [34]. The impact of vehicle electrification on CO_2 emissions is not taken into account and only fuel passenger vehicles are considered. However, this does not mean that the influences of electric vehicles cannot be included in this research. They can be calculated by recalibrating parameters of the VT-Micro model, or by multiplying the current result by a conversion factor.

Table 4. Parameter values of the VT-Micro model.

Acceleration Working Condition		Deceleration Working Condition	
Correlation Coefficient	**Value**	**Correlation Coefficient**	**Value**
L0,0	−0.67	M0,0	−0.67
L0,1	0.2974	M0,1	0.0166
L0,2	−0.017	M0,2	−0.0086
L0,3	−0.0019	M0,3	−0.0007
L1,0	0.0121	M1,0	0.0258
L2,0	0.0004	M2,0	−0.0002
L3,0	−0.00000376	M3,0	−0.00000227
L1,1	0.0283	M1,1	0.0043
L2,1	−0.0009	M2,1	0.00043
L3,1	0.00000944	M3,1	−0.00000462
L1,2	−0.0077	M1,2	0.0007
L2,2	0.0003	M2,2	−0.0000561
L3,2	−0.00000373	M3,2	−0.000000511
L1,3	0.0007	M1,3	−0.0000339
L2,3	−0.0000265	M2,3	−0.00000128
L3,3	−0.000000338	M3,3	−0.000000000761

3. Simulation Modeling

Under the scenarios of Chinese expressways and secondary motorways and based on the traffic simulation software VISSIM, the research on the impact of SLADS on traffic efficiency and CO_2 emissions was carried out. The basic road sections of expressways and secondary motorways, which are both 1 km in length, were chosen to be the specific scenes. Ramps, intersections and signals were not included. There were 3 and 1 lanes in one direction on the road sections of the two types of roads separately and the width of the lanes was all set to 3.75 m. Three types of traffic conditions were set initially, which were free, congested and forced condition. The traffic volume input of each condition is shown in Table 5. The lane reduction coefficients of the expressway, which was used to depict the volume distribution on different lanes, were set to 1, 0.89 and 0.78 for the first, second and third lanes [35]. Except for them, the values of road structure parameters and traffic volume above were all set according to China's 'Expressway Engineering Technical Standards' [36].

Table 5. Traffic volume on the expressway and the secondary motorway.

Road Type	Traffic Volume Input (pcu/h)				
	Free Condition		Congested Condition	Forced Condition	
	First Service Level	Third Service Level	Saturated Service Level	Oversaturated 20% Service Level	Oversaturated 40% Service Level
Expressway	2003	4406	5874	7049	8224
Secondary motorway	420	1120	2800	3360	3920

The service level was mainly used to characterize traffic input. Within the designed service level, i.e., the designed traffic input of a road, the service level was divided into five degrees. The higher the level was, the greater the traffic input was. At each service level of the two kinds of motorways listed in Table 5, the penetration rate of ICVs with SLADS was set to 20%, 40%, 60%, 80%, and 100% respectively. In terms of driving styles, it was assumed that the proportion of the aggressive style of HVs is equal to that of Chinese aggressive styles, which is 25.9%, while the proportion of the aggressive style of ICVs with SLADS was set to 0, 20%, 40%, 60%, 80%, and 100% separately considering that the functional parameters of the SLADS can be adjusted. The changes in traffic efficiency and CO_2 emissions were specifically studied when HVs were gradually transitioning to ICVs with SLADS under the actual driving style ratios in China. In summary, 36 groups of simulation experiments were set for each type of road, which means that there were 72 groups of simulation experiments in total. Each group of experiments was repeated 5 times and each time was 600 s. The simulation step was set to 0.1 s.

4. Results and Discussion

In this study, the average traffic delay and the road capacity were selected as the evaluation indicators of traffic efficiency. Traffic delay refers to time lost for vehicles while running due to interference from other vehicles that the driver cannot control, or obstruction from traffic control facilities. Because the research scenarios of this paper are the basic sections of the expressway and the secondary motorway, this paper only considers operation delay caused by the mutual interference from various traffic components. It includes interference from the vertical and horizontal direction, as well as external and internal parts, such as traffic congestion, continuous parking and so on.

In order to avoid systematic errors, the results of each group of experiments were the average of 5 repeated experiments in each group. The average CO_2 emissions of a vehicle in traffic flow was chosen to be the evaluation index for CO_2 emissions. To work out this value, the group whose average speed value was closest to the average speed of each group of 5 repeated experiments was taken as the analysis object, and the acceleration and speed values of each vehicle in the analyzed group at each moment were input in the VT-Micro model for calculation.

4.1. The Impact of SLADS on Traffic Efficiency and CO_2 Emissions

4.1.1. The Impact of SLADS on Traffic Delay

Under the real distribution of Chinese driving style, the impacts of SLADS on traffic delay on the expressway and the secondary motorway were analyzed with the ICV penetration rate changing from 0 to 100%. As for the expressway, it is shown in Figure 1a that at the first and the third service level, no matter how the ICV penetration rate changes, SLADS does not have a significant impact on traffic delay. At the saturated service level, however, SLADS has the most significant impact on traffic delay. The average delay per vehicle can be reduced by 3.30 s, which is 26.81%, if the ICV penetration rate reaches 100%. As the volume input meets the service level, which is oversaturated by 20% and 40%, it declines The maximum benefits are both obtained when the ICV penetration rate reaches 80%, reducing the delay by 2.56 s and 2.58 s, which are 14.57% and 13.86%.

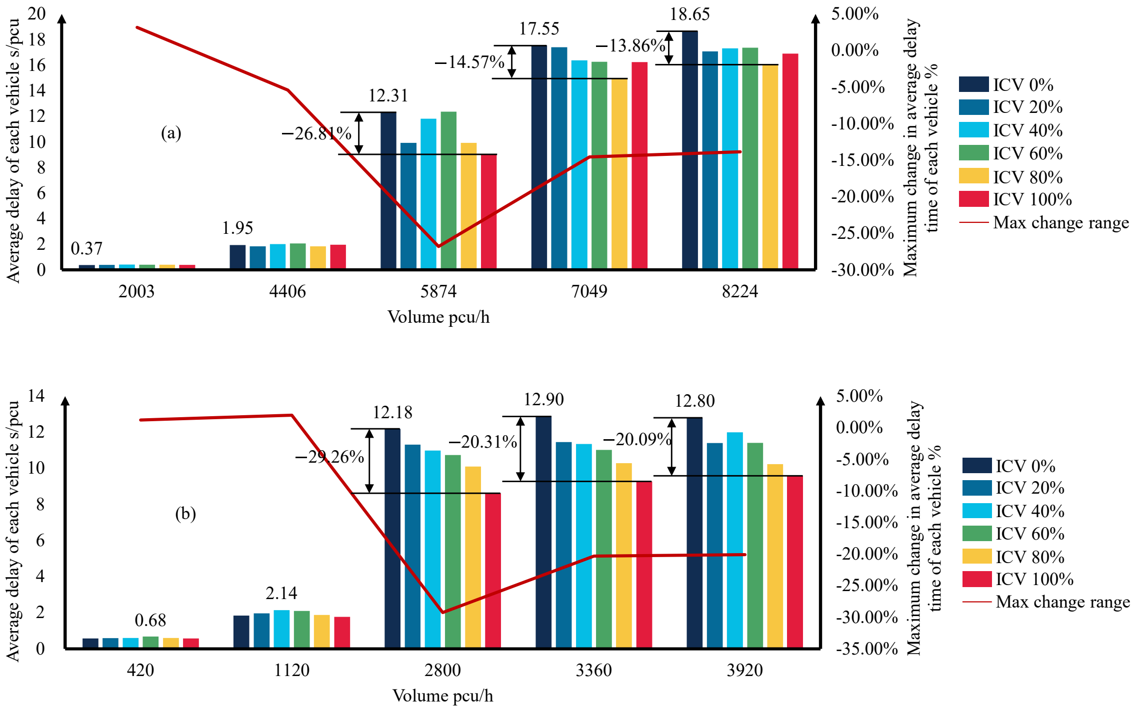

Figure 1. The impacts of SLADS on traffic delay on the expressway (**a**) and the secondary motorway (**b**).

In terms of the secondary motorway, a similar tendency can be found. It is shown in Figure 1b that at the first and the third service level, no matter how the ICV penetration rate changes, SLADS does not exert an apparent impact on traffic delay. At the saturated service level, however, SLADS has the most significant impact on traffic delay. The average delay per vehicle can be reduced by 3.30 s, which is 29.26%, if the ICV penetration rate reaches 100%. As the volume input increases to the 20% and the 40% oversaturated service level, the impacts of SLADS on traffic delay declines. The maximum benefits are both realized when the ICV penetration rate reaches 80% that it can be reduced by 2.56 s and 2.58 s, which are 20.31% and 20.09%.

It is interesting that although SLADS has different ratios of impacts on the expressway and secondary motorway traffic delay, the absolute values of the impacts are almost the same. It is deduced that the difference in driving behaviors of ICVs reflected in traffic delay with SLADS and HVs may not change with road scenarios, but more experiments are needed to verify this.

4.1.2. The Impact of SLADS on Road Capacity

Under the real distribution of Chinese driving style, the impact of SLADS on the road capacity on the expressway and the secondary motorway were analyzed by changing the ICV penetration rate from 0 to 100%. In order to find the upper limit, simulation studies for the 60% oversaturated service level and the 80% oversaturated service level were also conducted. For the expressway, as shown in Figure 2a, when the volume input is within the range of the designed service level (the saturated level), SLADS cannot improve the road capacity. But if the volume input exceeds the design service level, SLADS is able to improve the road capacity to some degree, as shown in the red circle in the left picture of Figure 2a. It is indicated in the right picture enlarged from the red circle in the left picture that SLADS can increase it by 256.50 pcu/h on average, which is 4.37% and by a maximum of 283.20 pcu/h, which is 4.81%.

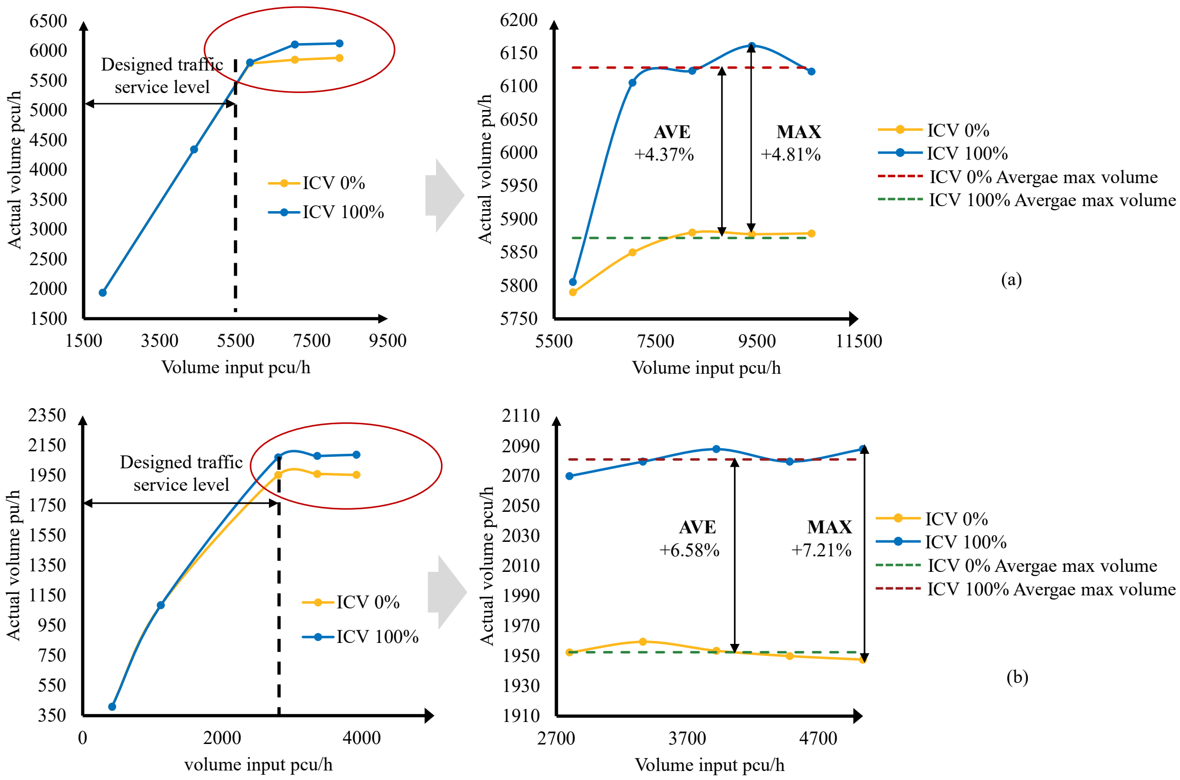

Figure 2. The impacts of SLADS on the road capacity on the expressway (**a**) and the secondary motorway (**b**).

In terms of the secondary motorway, as depicted in the red circle in the left picture of Figure 2b, SLADS can appropriately improve the road capacity as long as the volume input is higher than the third service level. We found that SLADS is able to raise the road capacity by 117.60 pcu/h, which is 6.02%, as shown in the right picture, enlarged from the red circle in the left picture. The road capacity does not reach the saturated service level even though the ICV penetration rate is 100%. The single-lane structure and the relatively low aggressive ratio style of ICVs may account for this, which will be explained in detail in Section 4.2.2. When the volume input exceeds the saturated service level, SLADS can increase it by 128.40 pcu/h on average, which is 6.58%, and by 140.40 pcu/h at most, which is 7.21%.

4.1.3. The Impact of SLADS on CO_2 Emissions

Under the real distribution of Chinese driving style and the scenarios of the expressway and the secondary motorway, the impact of SLADS on CO_2 emissions was analyzed by changing the ICV penetration rate from 0 to 100%. As shown in Figure 3a, on the expressway, SLADS does not have apparent influence on the average CO_2 emissions per vehicle at the first service level, and it even increases them by 19.11% at the third service level since the traffic flow is in free condition at this service level and the increase of ICV penetration rate will improve the average speed of the traffic flow. As the volume input is equal to the saturated traffic service level, the 20% oversaturated service level, and the 40% oversaturated service level, SLADS can significantly reduce the average CO_2 emissions per vehicle by 10.05%, 22.94% and 28.73%, respectively, when the ICV penetration rate reaches 80%, 100%, and 100% separately. This is because the increment of ICV penetration rate could make each vehicle in the traffic flow move smoothly so that the working conditions of acceleration and deceleration would decrease.

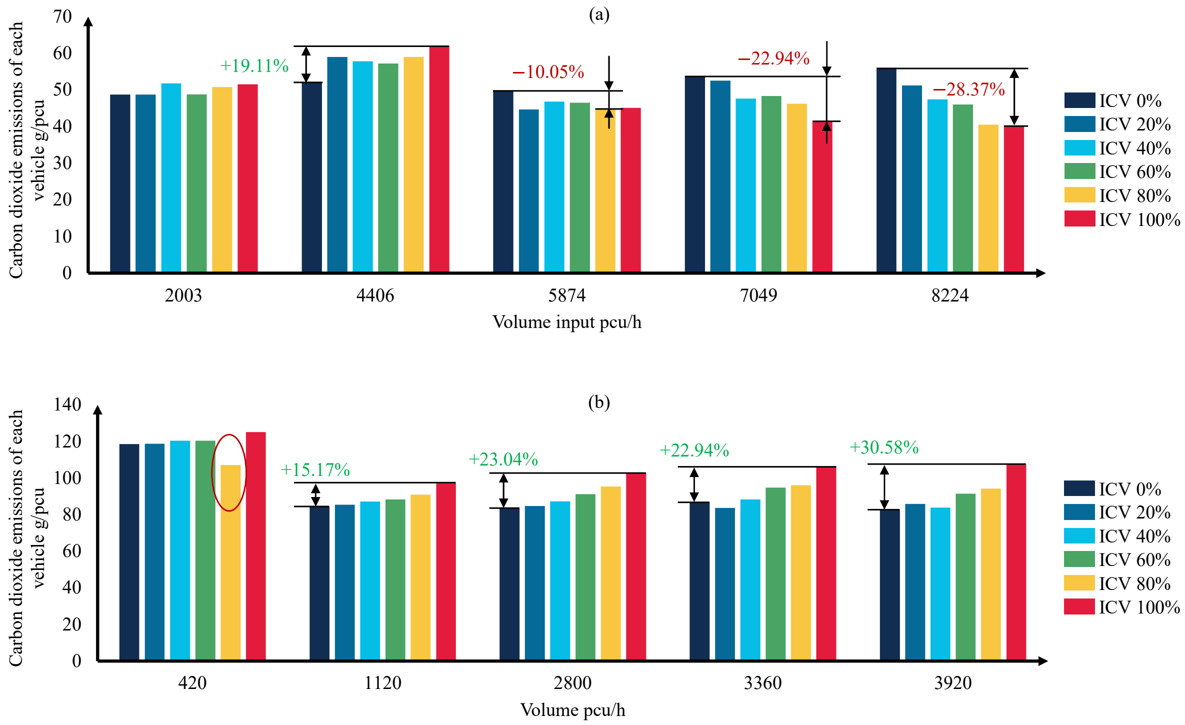

Figure 3. The impacts of SLADS on the average CO_2 emissions per vehicle on the expressway (**a**) and the secondary motorway (**b**).

On the secondary motorway, as depicted in Figure 3b, a quite different result from the expressway scenarios was obtained. At the first service level, SLADS has no significant impact on the average CO_2 emissions per vehicles, but slightly increases it. It should be noted that there is a trough of CO_2 emissions in the red circle in Figure 3b, which is probably caused by the difference in vehicle input distribution in the simulation algorithm and should be ignored. When the volume input is not lower than the third service level, as the ICV penetration rate becomes increasingly large, SLADS increases the CO_2 emissions per vehicle, which is even more significant when the volume input becomes larger. As the volume input is at the saturated traffic service level, and the 20% and 40% oversaturated service levels, SLADS can significantly reduce the CO_2 emissions per vehicle at most by 10.05%, 22.94% and 28.73%, respectively. Although the increase in ICV penetration rate can improve the traffic efficiency, the working conditions of acceleration and deceleration within the traffic flow cannot be improved because the secondary road has only one lane in one direction so that vehicles cannot change lanes and overtake other vehicles.

4.2. Scenario Analysis: The Impact of SLADS under Different Driving Styles on Traffic Efficiency and CO_2 Emissions

4.2.1. The Impact of SLADS on Traffic Delay under Different Driving Styles

The influence of SLADS on traffic delay on the expressway and the secondary motorway under different aggressive style ratios of ICVs is shown in Figures 4 and 5, respectively. It is indicated in the Subgraph (a)–(e) in the two figures that the volume input in corresponding road types is the first service level, the third service level, the saturated service level, and the 20% and 40% oversaturated service level. For the expressway, when the aggressive style ratio of ICVs was lower than China's actual value (25.9%), shown by the regions above the red curve in each subfigure in Figure 4, SLADS did not show an improvement in traffic delay and even increased it. As the aggressive style proportion of ICV increased, however, SLADS could reduce traffic delay markedly, but this benefit gradually decreased after the volume input outnumbered the saturated service level. Under the five different volume inputs in Figure 4a–e, when the aggressive style ratio and the penetration rate of ICVs both reached 100%, the average delay per vehicle was reduced by 40.01%, 57.03%, 89.44%, 85.86% and 45.51% separately, that is, 0.15 s, 1.11 s, 11.01 s, 15.06 s, and 8.49 s, respectively.

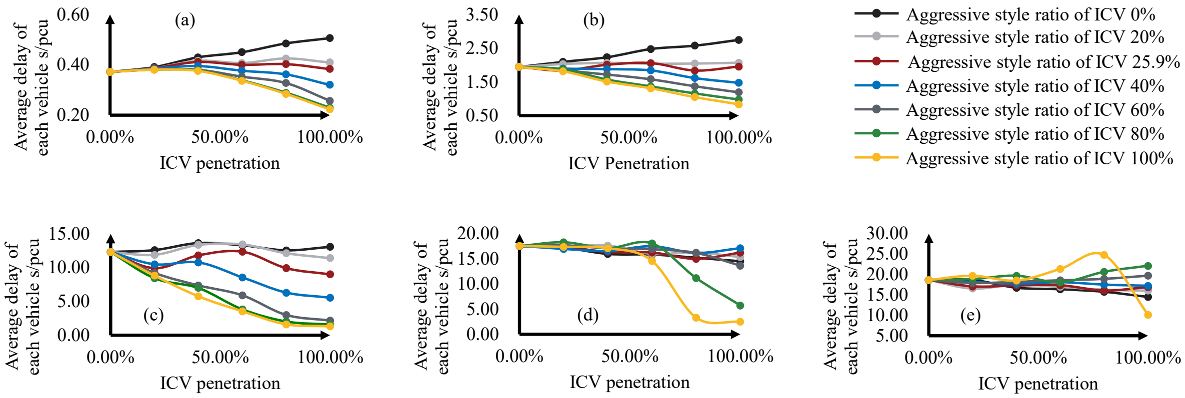

Figure 4. The impacts of SLADS on traffic delay on the expressway under different driving styles with the volume input being equal to the first service level (**a**), the third service level (**b**), the saturated service level (**c**), the 20% (**d**) and 40% (**e**) oversaturated service level.

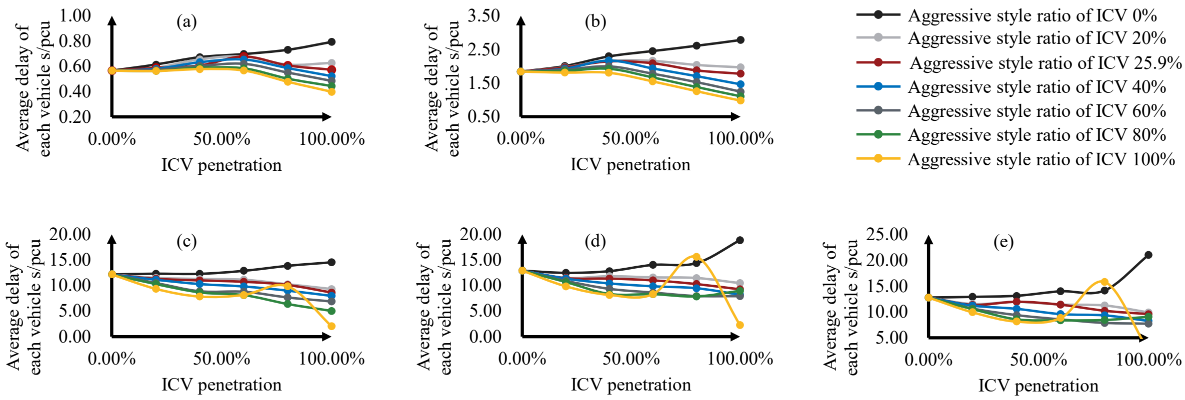

Figure 5. The impacts of SLADS on traffic delay on the secondary motorways under different driving styles with the volume input being equal to the first service level (**a**), the third service level (**b**), the saturated service level (**c**), the 20% (**d**) and 40% (**e**) oversaturated service level.

At the same time, it can be observed that when the volume input is lower than the third service level and the aggressive style ratio of ICVs has reached a certain level, the delay reduction is achieved as long as the ICV penetration rate is bigger than 30%. When the volume input outstrips the saturated service level, although the aggressive style proportion of ICVs reaches the threshold for traffic delay reduction at low-to-medium service level (not higher than the third level), the traffic delay does not decrease quickly until the ICV penetration rate reaches a high level. This is because under the oversaturated service levels, the traffic density increases and the average traffic speed decreases. Vehicle lane changing, emergency braking or cautiously driving are likely to cause a moving bottleneck, which probably make the traffic flow enter a congested state. In addition, it is difficult for vehicles to achieve higher driving efficiency by changing lanes. Therefore, in order to significantly reduce traffic delay, the proportion of conservative styles in the traffic flow must be small enough and the driving style consistency of the entire traffic flow tends to be uniform.

For the secondary motorway, when the volume input reached the first service level and the third service level, ICVs could not reduce traffic delay until the aggressive ratio exceeds 40%. When the volume input was not lower than the saturated service level, the traffic delay could be reduced as long as the aggressive style ratio of ICVs outstripped 20%. At the same time, it is easy to find that once the aggressive style proportion of ICVs reaches the threshold for reducing the average traffic delay, the increase in ICV penetration rate can significantly reduce the average traffic delay. Under the five different volume inputs, as shown in Figure 5a–e, when both the aggressive style ratio and the penetration rate of ICVs reached 100%, the average vehicle delay of each vehicle decreased by 0.17 s, 0.86 s, 10.14 s, 10.64 s, 10.40 s separately, that is, 29.64%, 46.85%, 83.29%, and 82.52%, respectively.

There were some similar results on the expressway and the secondary motorway. First of all, at the first and the third service level, when the aggressive style ratio of ICVs exceeds the threshold for reducing the traffic delay, the benefit rises at first and then decreases as the ICV penetration rate increases, the inflection points of which appear when the ICV penetration rate is equal to around 50%. This could be attributed to the introduction of ICV making the heterogeneity of traffic flow firstly decrease and then increase. Next, at the oversaturated service levels, as the aggressive style ratio of ICVs reached 100%, the average traffic delay increased inversely with the ICV penetration rate being around 80%. Although the difference in vehicle distribution in VISSIM may account for this phenomenon, it can also be inferred that the stability of ICV's ability to reduce traffic delay is reduced at oversaturated service levels due to the deterioration of traffic flow.

4.2.2. The Impact of SLADS on Road Capacity under Different Driving Styles

The influences of SLADS on the road capacity of the expressway and the secondary motorway under different aggressive style ratios of ICVs are shown in Figures 6 and 7, respectively. In view of the fact that the impact of SLADS on the road capacity mainly appears above the saturated service level, as shown in a–c of the two figures, only three different volume inputs were studied, which were the saturated service level, and the 20% and 40% oversaturated service levels. For the expressway, when the volume input is at the saturated service level, the capacity can be maintained near the designed service level as long as the ICV aggressive rate is more than 40%, while a decreasing interval exists in the road capacity if the ICV penetration rate is lower than 40%. In particular, if there is no aggressive ICV on the road, the road capacity will drop significantly as the ICV penetration rate increases. When the volume input reaches the 20% and 40% oversaturated service level, the road capacity is significantly improved as the aggressive style proportion of ICVs increase, and the benefit could be increasingly more apparent as ICV penetration rate increases. Compared with the actual Chinese driving style distribution, when the volume input is at the 20% and 40% oversaturated service level, the road capacity can be promoted by 919.20 pcu/h and1982.40 pcu/h, respectively, as the aggressive ratio of ICVs increases, which is 15.06% and 31.49%, respectively.

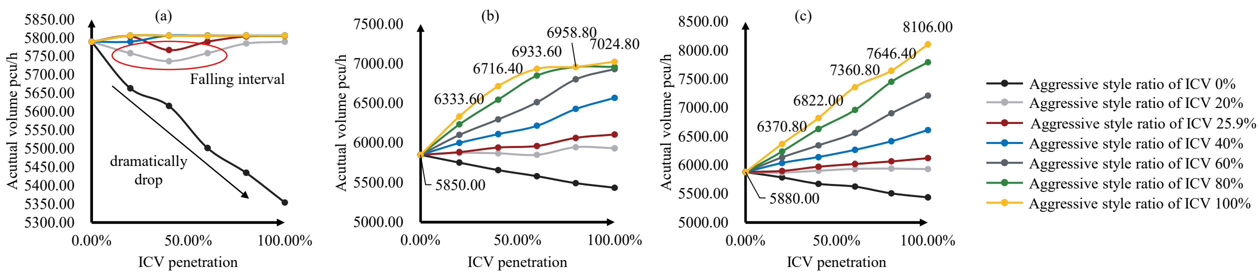

Figure 6. The impacts of SLADS on road capacity of the expressway under different driving styles with the volume input being equal to the saturated service level (**a**), 20% oversaturated service level (**b**) and 40% oversaturated service level (**c**).

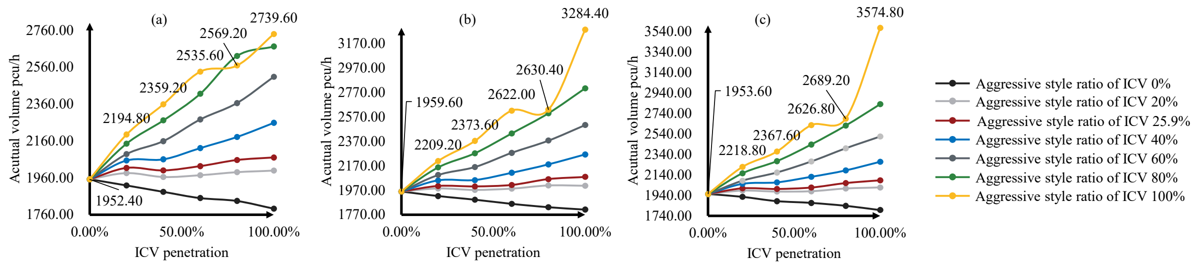

Figure 7. The impacts of SLADS on road capacity of the secondary motorway under different driving styles with the volume input being equal to the saturated service level (**a**), 20% oversaturated service level (**b**) and 40% oversaturated service level (**c**).

For the secondary motorway, when the volume input was not lower than the saturated service level, the higher the aggressive style proportion of ICVs was (not less than 20%), the more obvious the improvement of road capacity was under the same ICV penetration rate. When the aggressive style proportion of ICVs exceeded 20%, a similar improvement trend of the road capacity was observed with the ICV penetration rate becoming larger. Compared with the actual Chinese driving style distribution, when the volume input reached the saturated service level, and the 20% and 40% oversaturated service level, the road capacity could be promoted by 669.00 pcu/h, 1204.80 pcu/h and 1486.80 pcu/h, respectively as the aggressive ratio of ICVs increased, which were 32.35%, 57.93% and 71.21%, respectively. Additionally, as shown in Figure 7a, at the saturated service level, when both the aggressive style ratio and the penetration rate of ICVs reached 100%, the road capacity was close to the actual volume input. This is a reasonable explanation for the phenomenon mentioned in Section 4.1.2 that the actual volume cannot be raised to the volume input under the saturated service level of the secondary road even though the ICV penetration rate has reached 100%. However, as the volume input continues to increase, such a phenomenon will still exist, as depicted in Figure 7b,c.

4.2.3. The Impact of SLADS on CO_2 Emissions under Different Driving Styles

The influences of SLADS on CO_2 emissions on the expressway and the secondary motorway under different aggressive style ratios of ICVs are shown in Figures 8 and 9 separately. Subgraph (a)–(e) of the two figures show the volume input in the corresponding road type for the first service level, the third service level, the saturated service level, and the 20% and 40% oversaturated service level. On the expressway, when the volume input is at the first and the third service level, no matter how the aggressive style proportion of ICVs changes, SLADS cannot reduce the average CO_2 emissions per vehicle and may even cause an increase. It is observed in Figure 8a that there is fluctuation in the curves for the average CO_2 emissions per vehicle for different aggressive style ratios of ICVs. However, the fluctuation ranges under the same aggressive style ratios do not exceed 10% of the benchmark value, which can be attributed to the difference in vehicle distribution in VISSIM. At the saturated service level, with the gradual increase of ICV penetration rate, the average CO_2 emissions per vehicle could be remarkably reduced by about 10.05% if the aggressive style proportion of ICVs reached the Chinese actual value. When the volume input was equal to the 20% and 40% oversaturated service level, it could be significantly reduced by appropriately raising the aggressive style ratio (up to 60%). Compared with the standard situation where the ICV penetration rate is 0 and the aggressive style ratio is the same with the Chinese actual value, it could be reduced by up to 25.03% and 42.58%, respectively.

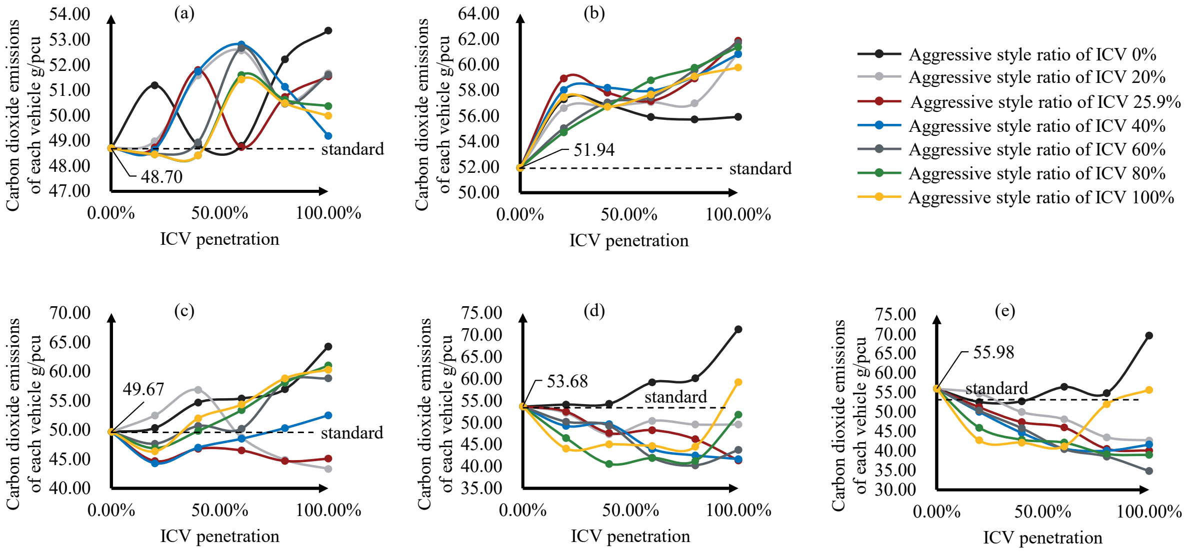

Figure 8. The impacts of SLADS on the average CO_2 emissions per vehicle of the expressway under different driving styles with the volume input being equal to the first service level (**a**), the third service level (**b**), the saturated service level (**c**), and the 20% (**d**) and 40% (**e**) oversaturated service level.

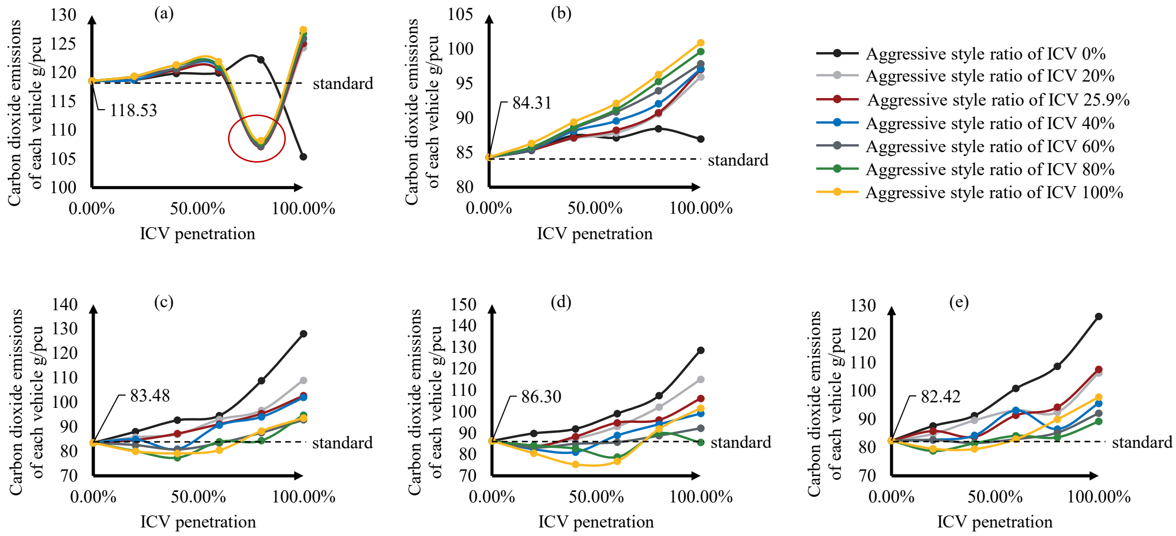

Figure 9. The impacts of SLADS on the average CO_2 emissions per vehicle of the secondary motorway under different driving styles with the volume input being equal to the first service level (**a**), the third service level (**b**), the saturated service level (**c**), and the 20% (**d**) and 40% (**e**) oversaturated service level.

For the secondary motorway, when the traffic input was at the first and the third service levels, there was an upward trend in the average CO_2 emissions per vehicle as the aggressive style proportion of ICVs increased. What has to be noted is that there is a regular abnormal drop in the average CO_2 emissions per vehicle shown in the red circle in Figure 9a. This is probably caused by the difference in vehicle distribution in the simulation software, the results of which should consequently not be adopted. When the volume input was at the saturated service level, the 20% oversaturated service level and the 40% oversaturated service level, there were decreasing intervals in the average CO_2 emissions per vehicle if the aggressive style ratio was not smaller than 40%. In the decreasing interval, compared with the standard situation where the ICV penetration rate is 0 and the aggressive style ratio is the same as the Chinese actual value, it could be reduced by 7.24%, 12.64%, and 4.40%, respectively.

In addition, regardless of the road types, when the traffic input was not lower than the saturated service level, the average CO_2 emissions per vehicle declined at first but then increased with the increase of ICV penetration rate. This is because, on the one hand, when the traffic flow is in a congested or blocked state with a large volume input, the introduction of ICV can optimize the car following behavior, overcome driving distraction, and reduce acceleration and deceleration working conditions, which will decrease the average CO_2 emissions per vehicle. On the other hand, when the ICV penetration rate was further increased to a higher level, the average speed of the traffic flow greatly improved, so it would have a reverse upward trend [37].

5. Results and Suggestions

Under the scenarios of the expressways and secondary motorways in China, the impacts of ICVs with SLADS on traffic efficiency and CO_2 emissions were studied in this paper. It was indicated that ICVs with SLADS can remarkably reduce traffic delay and improve road capacity under high volume input while these benefits are not significant under low-to-medium volume input. Under high volume input, ICVs with SLADS can significantly reduce the CO_2 emissions per vehicle on expressways (three lanes in one direction), but the opposite effect is obtained on secondary motorways (one lane in one direction). Additionally, the impacts of the aggressive style ratio of ICVs were also discussed. We found that adjusting the parameters of SLADS to appropriately increase the aggressive style ratio of ICVs can make full use of the SLADS advantages, which is expected to reduce traffic delay and the CO_2 emissions per vehicle and improve road capacity.

It is concluded that with the rise in ICV penetration rate, SLADS shows more considerable benefits in complex and high-volume traffic scenarios. When the volume input is not lower than the saturated level, the traffic optimization effects of SLADS is much higher than that of the volume input at low-to-medium service level. Furthermore, improving the aggressive style proportion of ICVs can further amplify the optimization effect. Therefore, we suggest that drivers should be encouraged to turn on SLADS on expressways, secondary motorways or similar road types with high volume, and avoid overly conservative driving behaviors, which can not only reduce commuting time and optimize travel experience, but also save energy and reduce emissions, and contribute to the country's "carbon neutral" goal. The conservative driving style of human drivers in China, however, accounts for close to 50% due to personal characteristics and the strict traffic laws and complex traffic conditions in China. As driving schools are still the only places for human drivers to learn driving and apply for a driver license, the state can try to urge driving schools to increase the explanation of the relationships between driving style, traffic efficiency and energy consumption for trainees. They are supposed to not only obey the laws and ensure safety, but also to improve the efficiency and avoid becoming a "mobile bottleneck" on the road.

In addition, it is indicated that SLADS shows the ability to improve road capacity. In the future, with the maturity of more functions of advanced driver assistance and IoV and the continuous rise of ICV penetration rate, ICVs themselves can not only realize the high level of intelligence, but can also interconnect with other vehicles, infrastructures, and cloud platforms to make swarm intelligence come true. As a result, ICVs are likely to exert much more remarkable influences on road capacity in the future. Therefore, it can be boldly speculated that the road construction standards will also alter. For instance, when the ICV penetration rate reaches a certain level, a road that is reduced by a lane may also be able to meet the travel demand, so that the costs of road infrastructure and maintenance can be greatly reduced. Furthermore, it can also reduce the land occupation area and increase the green area, promoting the absorption of the greenhouse gases.

As for the research directions in the future, on the one hand, the effects of both horizontal and lateral intelligent functions of ICVs will be studied in richer traffic scenarios, and the functions of the IoV will be considered so as to depict the intelligent and connected functions of ICVs more comprehensively. On the other hand, discussions on ICV powertrain types will also be included since electric vehicles are much more likely to be carriers of ICVs, which will have new influences on vehicle power performance and energy consumption. Last but not least, a comprehensive evaluation model for the benefits from ICVs in transportation efficiency, energy saving and emission reduction will be built to make a more systematic evaluation at a more macro level, based on which more detailed and practical suggestions are expected to be put forward.

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