

Article

A Survey on Mixed Traffic Flow Characteristics in Connected Vehicle Environments

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Abstract: Intelligent transportation has become a hot research field in recent years. The development direction of road traffic construction in the future, the relevant technologies and methods in the process of gradual promotion and application of intelligent connected vehicles continue to attract the attention of scholars and engineers. There are more and more relevant theories, methods and systems. This paper summarizes the current state of microscopic and macroscopic traffic models, characteristic analysis methods of mixed traffic flow, and lane management methods in connected vehicle environments. At the end of this paper, the conclusions of this work are presented, and possible future directions for safety warning research under connected vehicle environments are discussed. This paper represents the current research status of traffic flow characteristics under connected vehicle environments to some extent, which can provide references for future traffic flow characteristic research in terms of framework, methods and technologies, etc.

Keywords: connected vehicle environment; mixed traffic flow; traffic flow model; traffic management; characteristic analysis



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1. Introduction

The connected vehicle technology integrates on-board equipment, roadside equipment, cloud platform, wireless communication, and other technical means to realize accurate perception and intelligent management of vehicle information [1]. As a recent research hotspot of intelligent transportation, the future direction of road traffic construction, relevant technologies and methods in intelligent connected vehicles (ICV) application have attracted the interest of scholars and engineers, generating new theories, methods and systems [2–4]. Related research is summarized from the aspects of traffic flow model, traffic flow analysis method, and lane management, so as to clarify the research objectives and main contents of this paper.

This article is to provide a detailed reference by summarizing the research status of traffic flow in connected vehicle environments. Figure 1 shows that the number of articles on traffic flow characteristics in connected vehicle environments is increasing year by year (from 2001 to 2021). Figure 2 is the keyword co-occurrence analysis generated by VOSviewer (Leiden, The Netherlands) based on the literature reviewed in this paper, which shows the general keywords distribution. Among them, ‘cav’ is the most frequently focused keyword of most literature, followed by automated vehicle, characteristics, stability, platoon, optimization, etc. Based on the performance of these keywords, this article conducts a survey from the following aspects:

At the beginning of this paper, we introduce the development status of connected vehicle technology and its basic concepts. Second, the microscopic traffic models (including car-following and lane-changing) and macroscopic traffic models are introduced in detail. Next, based on this summary, an approach is proposed for characteristic analysis of mixed

traffic flow that combines numerical analysis, driving simulation study, and naturalistic driving study. Then, we examine the research on lane management from two aspects: speed control optimization and dedicate lane management. Finally, the conclusions of this study are presented and future research on traffic flow characteristics in connected vehicle environments is discussed in Section 6.

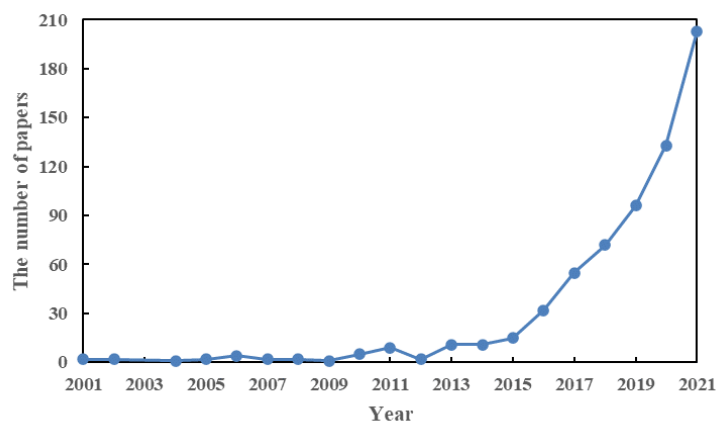


Figure 1. Schematic diagram of articles on connected vehicle technology.

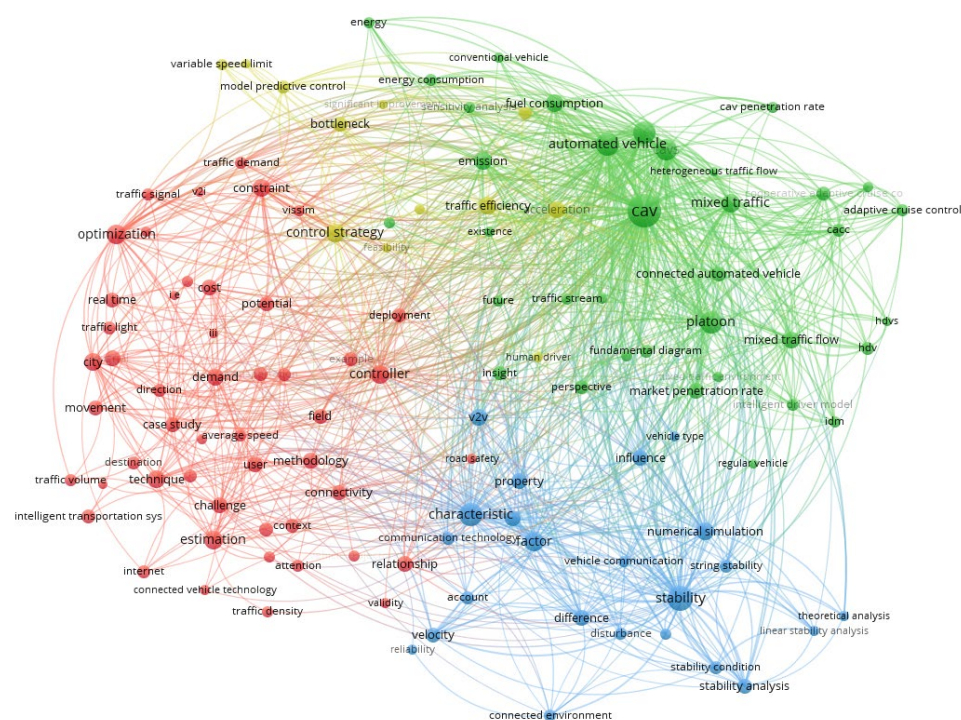


Figure 2. Diagram of the keyword co-occurrence analysis on connected vehicle technology.

2. Overview of Traffic Flow in Connected Vehicle Environments

Recent years have witnessed the gradual maturation of the intelligent transportation field, manifested by progressing driving assistant technology, communication technology, and automatic driving vehicle manufacturing technology, with intelligent connected vehicles being the direction of future development. However, there is still a long way to go before the intelligent transportation system reaches the advanced stage of “smart car, smart road”. In this process, vehicles with different levels of intelligence and networking will unavoidably mix with traditional human-driving vehicles, bringing a new type of mixed traffic flow. Before analyzing the characteristics of new mixed traffic flow, it is necessary to grasp the development status and trend of technology. Additionally, we need to clarify the composition and configuration distribution of traffic flow vehicles, and the connotation

of traffic flow in connected vehicle environments, and then the current research basis and existing problems.

2.1. The Development Situation and Trend of Connected Vehicle Technologies

The connected vehicle technology is the extension of the Internet of Things in an intelligent transportation system. The connected vehicle technology is an information interactive network composed of vehicle position, speed, and surrounding road environment information. It is based on advanced technologies in sensor, network, wireless communication, and large-scale parallel computing to carry out V2X (vehicle and vehicle, vehicle and roadside facilities, vehicle and traffic intelligent control center, vehicle and pedestrian, etc.) [5,6]. The real-time information interaction is a connected vehicle technology that can realize intelligent traffic management, intelligent dynamic information service, and intelligent vehicle control. Cooperative vehicle infrastructure technology is an important part of connected vehicle technology. It is an intelligent transportation technology to improve operational efficiency and traffic safety through information sharing and intelligent collaboration between vehicles and road facilities. The diagram shows the relationship of connected vehicle technology (CV), the internet of things (IOT), and intelligent transportation system (ITS). (Figure 3).

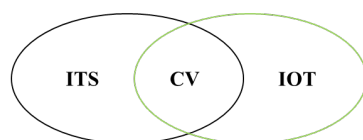


Figure 3. The relationship among CV, IOT, and ITS.

Since the mid-1980s, the United States started to research on intelligent vehicles and intelligent roads. In 1990, the U.S. Department of Transportation established the IVHS Organization (later renamed ITS America), and in 1991, the Congress passed the “Comprehensive Road Transportation Act” to provide financial support for research on intelligent vehicles and road systems. In 1997, the Federal Communications Commission authorized the 5.9 GHZ frequency band as the dedicated short-range communication band for vehicles. At the end of 2002, the special short-range communication standard ASTM e2213-02 based on this frequency band and using IEEE 802.11a as the underlying transmission technology was formulated. Since 2003, a series of vehicle road collaborative system projects have been carried out, such as VII, CVHAS, and IntelliDrive [7,8]. The Maryland University has developed a traffic monitoring device TrafficView connected vehicle technology, using the vehicle communication platform as the intermediary for traffic information collection and release to improve road safety and traffic efficiency [9]. The PATH project initiated by the University of California is on the cooperative control among vehicles, including adaptive cruise control (ACC), cooperative adaptive cruise control (CACC), and vehicle linkage control within a platoon [10–12].

In 1993, the ITS Promotion Committee, which is responsible for promoting intelligent transportation and other related work in Japan, was established. Many intelligent transportation projects carried out in Japan also focus on the application of connected vehicle technology. In the late 1990s, Japan started research on cooperative driving system projects. The two main CVIS projects are the ASV plan that focuses on V2V communication to improve driving safety, and the AHS project on safety driving assistance technology. In addition, Yuichi Morioka put forward a forward-collision warning system based on vehicle communication at intersections with poor sight [13].

Many organizations in Europe are also dedicated to promote the development of connected vehicle technology. ERTICO, an ITS organization, first proposed the basic concept of eSafety. Vehicle communication and collaborative control are regarded as the main directions in related research projects, such as PReVENT, CVIS, and CarTalk2000 [14]. In 1994, the European Committee on standards drafted the standard for dedicated short-range communication, and the standard came into force in 1997. In 2005, European vehicle

manufacturers, suppliers, and research institutions jointly founded the inter-vehicle communication alliance C2C-CC, focusing on the workshop communication interface, communication mode, and communication standards between vehicle and infrastructure. In 2019, in view of the increasing importance of networking concepts, European ERTRAC built the network-connected automatic driving technology roadmap on the previous version of the automatic driving roadmap referring to the European Union's STRIA CAT roadmap.

At the same time, in order to further promote the application of connected vehicle technology, more countries started to build test ground for intelligent connected vehicles. There are eight famous test sites abroad, namely M-City and GoMentum Station in the United States, AstaZero in Sweden and IDIAFA in Spain, Mira City Circuit in Britain, JARI test field in Japan, ACM test site in the United States, and K-City test site in South Korea (under construction). Among them, M-City, jointly constructed by the University of Michigan and the Department of Transportation of Michigan, is the world's first test site specially designed for testing automatic driving technology and connected vehicle technology. Another well-known test site in the United States is the GoMentum Station base, which has rich highway and urban road test scenarios. Astazero, the largest smart car test site in Europe, features the simulation test of ADAS scenarios. The Mira City Circuit test site in the UK is known for its networked test environment. At present, the China Ministry of Industry and Information Technology has approved two national-level pilot areas of connected vehicle tests and 10 demonstration areas of intelligent connected vehicles. Shanghai claims the first national demonstration area of intelligent connected vehicles in China. Additionally, Zhejiang Province claims the application demonstration area of intelligent transportation. China's national intelligent vehicle and information technology demonstration area and smart transportation demonstration area stretches in Beijing, Hebei, and Tianjin (Xiqing) also possess a national level connected vehicle pilot area. In addition, in 2017, Beijing established the first dedicated lane for connected vehicles in China.

The current status of connected vehicle technology tells us that vehicle network interconnection and intelligent collaborative control have become the main future direction for intelligent transportation systems. The major developed countries and regions have carried out a lot of research on it, and some technologies have grown mature. At the same time, communication standards for collaborative interaction have been issued, and a series of train networking scenarios have been defined [15–17]. However, there are still great challenges in realizing the collaborative decision-making of large-scale vehicle and group vehicle, as well as fully automatic driving control. The related research is still in the stage of laboratory research and experiment.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

2.2. Related Definitions

- Intelligent transportation system (ITS)

ITS is a general term that covers the application of advanced information technology, sensor technology, control technology, and computer technology in the field of transportation to improve current transportation system. It can improve the efficiency and safety of the traffic system through the cooperation of people, vehicles, and infrastructure, and thus alleviate traffic congestion, improve road capacity, and reduce traffic accidents.

- Intelligent cooperative vehicle infrastructure system

Intelligent cooperative vehicle infrastructure system refers to the high-precision real-time dynamic collection and fusion of road traffic environment information through advanced vehicles, roadside sensing equipment, wireless communication, and information interaction (I2X and V2X) technologies. It is subject to the agreed communication protocol and data exchange standard, and covers different vehicle automation levels. The

intelligent cooperative vehicle infrastructure system is constructed from three dimensions; vehicle automation, network interconnection, and system integration. Then, the road traffic perception, prediction, decision-making, and control functions can be implemented in a coordinated and efficient way. Finally, a new generation of ITS can be formed to integrate, coordinate, control, manage and optimize all vehicles, information services, facilities and equipment, active traffic safety control and road collaborative management, and fully realize the coordination among people, vehicles, and roads.

- **Advanced traffic management system**

The advanced traffic management system is based on intelligent technology, which is to ensure the integration of various traffic management systems with reliable, safe, and efficient utilization of road networks, and economic and practical traffic management systems. The related functions include event detection and emergency response, traffic management of special events, urban traffic control, traffic signal coordination control, demand management, path-changing navigation, long-distance traffic corridor management, weather warning system, law enforcement, etc. The contents include the computerized traffic management center and traffic control center. These centers are important data sources. Processed data are transferred to traffic participants, providing advice through the traffic information center.

- **Intelligent road network**

Intelligent network road refers to the road infrastructure equipment and information engineering facilities that provide traffic services for road traffic participants. It is a public service system to ensure the normal operation of traffic activities, mainly including road structures (subgrade, pavement, bridge, culvert, and tunnel, etc.), traffic engineering, and ancillary facilities along the line (road signs, marking lines, etc.), energy system, communication system, information platform, such as monitoring system, sensing system, toll system, traffic control, navigation, roadside system, and other modern equipment systems.

- **Intelligent connected vehicle**

Intelligent connected vehicle refers to a vehicle with advanced on-board sensors, controllers, and actuators. It integrates communication technology and information interaction technology, and exchanges and shares the information between V-X (vehicle and vehicle, vehicle and road, vehicle and people, vehicle and traffic facilities, vehicle and traffic control center, etc.). It features complex environment traffic perception, active safety control, collaborative control, and other functions. Meanwhile, it improves the safety, efficiency, comfort, energy-saving driving of vehicles, and accelerates the gradual replacement of human-driven vehicles.

- **Mixed traffic flow**

Although the intelligent network connection technology has become the future trend and direction of intelligent transportation systems, there is still much to improve in intelligent network transportation infrastructure and automatic vehicle control technology for larger market share. With the gradual maturity of connected vehicle technology, there will be novel mixed traffic flow that includes human-driven vehicles with traditional visual perception response operation mode, connected vehicles assisted with the help of information perception technology, autonomous vehicles, and connected and autonomous vehicles operating on the road.

3. Traffic Flow Models for Mixed Traffic Flow

Traffic flow theory develops from the basic theory of traffic engineering. It is a science to study the law of traffic flow with changing time and space under certain road conditions physically and mathematically. Traffic flow has interested many scholars and engineers with different academic backgrounds, including physics, mathematics, sociology, statistics, system engineering, control science, etc. The traffic flow model provides theoretical

support for the application of traffic planning, traffic engineering design, traffic control, and management, being an important basis for improving traffic flow theories. The study on traffic flow theory started in the 1930s. Studies on traffic phenomena and scales laid the groundwork for the emergence of traffic flow models, which can be roughly classified into three categories: macroscopic, middle, and mesoscopic traffic flow model. Among them, the microscopic traffic flow modeling describes the law of single-vehicle movement and multi-workshop interaction; while the macro traffic flow modeling describes neither individual motion characteristics nor individual interactions, but the set of vehicles on the road according to the evolution law of the overall operation of road traffic. The above two models are the two main directions of traffic flow research. This section mainly reviews the development of macro and micro models, and elaborates on the current development status of traffic flow study, providing theoretical support for further research and analysis.

3.1. Microscopic Traffic Flow Models

The micro traffic flow modeling uses the Lagrange method to model the single-vehicle movement law, describing the operation state of individual vehicles and vehicle–vehicle interaction. The micro traffic simulation system is based on a micro traffic flow model that predicts and evaluates the capacity of urban trunk roads, road network optimization scheme, traffic control strategy, etc., and provides technical support for traffic management departments in their decision-making process. The microscopic vehicle motion model includes the car-following model and lane-changing model. At present, as intelligent transportation develops, the intelligent network connection technology integrates advanced technologies in communication, information fusion, human–computer interaction, and automatic driving, to realize the real-time information perception of the road environment, intelligent control and information interaction between V–X (vehicle to vehicle, vehicle to the road, vehicle to pedestrian, vehicle to traffic facilities and vehicle to the traffic control center, etc.). At the same time, more and more scholars have been attracted to study on the micro model construction of vehicle movement in the intelligent connected vehicle environment, with many research results obtained.

3.1.1. Car-Following Model

(1) Car-following models under the traditional traffic environment (Figure 4 and Table 1).

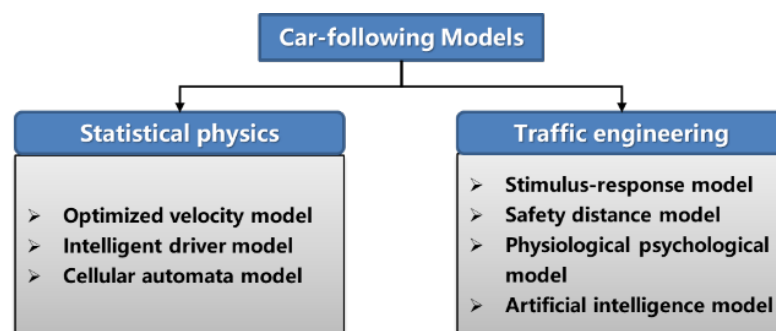


Figure 4. Car-following model classification.

In the early 1950s, the following theory was proposed. The mathematical model based on the theory of driver's following behavior is called the following model. After more than 60 years of development, the following theory has developed into a whole set of systems where a large number of the vehicle following models are proposed. The following theory is divided into seven categories from the perspective of statistical physics (Table 2) and traffic engineering [18].

Table 1. Car-following models from the perspective of traffic engineering.

Model Types	Model Characteristics	Base Models	Novelty	Limitations	Ref#
Stimulus-response model	The leading vehicle effect on the driver is expressed as a stimulus; the driver's perception is regarded as a sensitivity coefficient to the stimulus, and the driver's response can be expressed as the acceleration of the car following.	RV model. GM model. Newell model.	Simple traffic phenomena can be modeled, and the implementation effect is good.	For more complex traffic phenomena, the model will be very complex and the effect of model implementation is poor.	[19–24]
Safety distance model	The driver always expects to keep a safe headway with the leading vehicle. When the driver of the front guide car suddenly brakes, the driver of the following car is allowed enough time to slow down and stop, so as to avoid the collision.	CA model. FRESIM model. CARSIM model.	The model is practical and effective.	The safety distance of the model only ensures that collision will not occur in case of emergency braking.	[25–28]
Physiological and psychological model	Based on the driver's perception and reaction characteristics, this paper attempts to introduce more human factors into the car following behavior modeling to better adapt to real driving behavior.	Wiedemann74 model.	Nowadays, the popular driver psychological car following model often randomly generates the threshold for dividing various driving states according to a certain statistical distribution law, in order to expect to obtain the random characteristics of traffic flow more in line with the actual requirements.	The current driving psychological car following model cannot analyze and model all driving behavior characteristics.	[29,30]
Artificial intelligence model	It is difficult to accurately express the driver's characteristics with a mathematical model, so the artificial intelligence method is a better choice that can effectively describe the driver's characteristics. This is also one of the research hotspots of car-following behavior modeling in recent years.	The fuzzy MISSION model. TRAFFIC-JAM model. Artificial neural network model. Fuzzy neural network model.	It shows certain advantages in dealing with complex nonlinear problems, and shows good learning ability under large data samples.	The physical meaning of some models is not clear, the calibrated parameters change greatly under different conditions, and are greatly affected by the data. When the driving environment changes greatly, the fitting results are often far from the reality.	[25,31,32]

Table 2. Car-following models from the perspective of statistical physics.

Model Types	Model Characteristics	Base Models	Novelty	Limitations	Ref#
Optimized velocity model	In essence, it is similar to the stimulus-response model, but the stimulus is the difference between the vehicle speed and the optimized speed. The model is more intuitive, simple, and easy to analyze.	OV Model. FVD Model.	By using linear and nonlinear stability theory to analyze the optimal speed model, the stability conditions of the model and the propagation mechanism of traffic jam at the critical point can be obtained.	In the model simulation, there exist too fast acceleration, unreasonable acceleration and deceleration, and even reversing and collision.	[33–35]
Intelligent driver model	The model includes the acceleration trend in the free state and the deceleration trend considering the collision with the leading vehicle. The numerical simulation results are consistent with the measured data and can reproduce complex macroscopic traffic phenomenon.	Intelligent Driver Model.	It has parameter calibration. At the same time, unlike previous studies, a large number of parameters need to be calibrated. In this model, only a few parameters need to be adjusted, and the free flow and crowded flow can be expressed separately with the same expression.	It is difficult to obtain the simulation effect of intelligent control and cooperative driving.	[36–38]
Cellular automata model	In essence, it is defined as a dynamic system that evolves in discrete time dimension according to certain local rules in a cellular space composed of discrete and finite cells.	Wolfram 184 Model. Na Sch Model. FI Model.	In the process of simulation calculation, the calculation speed is relatively fast, which is especially suitable for traffic simulation of large-scale road networks. At the same time, based on the model, the reasonably designed evolution process can reproduce most common phenomena in traffic.	There are few such regular and consistent spatial systems in the real world. Some limitations of cell model restrict its ability to simulate the real world.	[39–45]

3.1.2. Car Following Models under Intelligent Connected Vehicle Environment

Connected vehicle technology can help drivers obtain the surrounding environment information of running vehicles, which is different from the previous situation where drivers only perceive the traffic environment through visual stimulation (Figure 5). Under the connected vehicle environment, drivers can obtain accurate information of the front vehicle and prepare in advance according to the suggestions from the driving assistance system. The subsequent driving operation is a kind of active psychological behavior. In a connected vehicle environment, driver's reaction time can be greatly reduced. With its development, driver participation in the whole driving process will gradually decrease, and the impact of human factors on traffic flow will be weakened. The intelligent connected vehicle has attracted much attention of scholars, and more and more researchers will study the car following model in the future. According to the degree of vehicle intelligence and network connection, the car following model can be divided into four categories: human-driven vehicle (HDV), connected vehicle (CV), autonomous vehicle (AV), and connected and autonomous vehicle (CAV). At the same time, due to the advantages of platoon organization in the field of traffic application and the enhancement of collaborative interaction between vehicles, the traffic flow configuration in road traffic will be more complex.

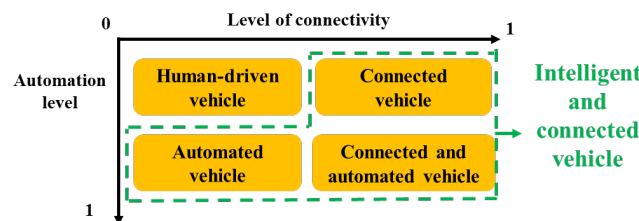


Figure 5. This is a figure. Schemes follow the same formatting.

According to Dr. Chai of the Beijing Institute of Technology, the trajectory of vehicles with real-time safety warnings can be predicted in a period of time under the connected vehicle environment [46]. By analyzing the NGSIM trajectory data which demonstrate the characteristics of connected vehicle data, researchers can extract the response time and minimum safety distance between vehicles to external stimuli based on Newell theory. Qin et al. [38] chose IDM as the car-following model and adjusted the parameters based on the characteristics of the connected vehicle, so they can accurately obtain the driving state of the front vehicle. The adaptive cruise control system (ACC) has become a hot spot. ACC system uses radar to monitor the current traffic situation around the vehicle, and the calibration value is the design distance between two vehicles. Building a ACC car following model requires the following three steps: Selecting appropriate parameter values to define the control mode under different car following states. Then, constructing the ACC car-following model and algorithm under different control modes. Finally, calibrating and evaluating the parameters of the improved ACC model under multiple control modes. To reduce headway for better traffic efficiency, Shladover et al. developed a CACC model based on the ACC model [11]. Through the literature review, it was found that the ACC model and CACC model were often used as the primary car following models of autonomous vehicle and connected automatic vehicle.

The PATH laboratory of Berkeley in California obtained real ACC vehicle trajectory data from four real vehicles equipped with the ACC control system, and calibrated the ACC car-following the model with a constant headway strategy. The ACC model is as follows:

$$a_n(t) = k_1(x_{n-1}(t) - x_n(t) - L_{n-1} - s_0 - t_a v_n(t)) + k_2 \Delta v_n(t) \quad (1)$$

where, t_a is the expected headway parameter of the ACC vehicle, k_1 is the error control coefficient of vehicle spacing, and k_2 is the control coefficient of the speed difference.

Through the long-term study on the characteristics of CACC traffic flow, the CACC car-following model based on nonlinear dynamic headway strategy proposed by PATH laboratory of the University of Berkeley in California is as follows:

$$\begin{cases} v = v_p + k_p e + k_d \dot{e} \\ e = h - l - s_0 - t_c v \end{cases} \quad (2)$$

where v is the current control speed of CACC. v_p is the speed of the previous control time. k_p is the control coefficient of vehicle spacing error. k_d is the control coefficient of the differential term of vehicle spacing error. e is the error between the actual vehicle spacing and the expected vehicle spacing at the previous control time. $\dot{e}$ is the differential term of e to time. t_c is the expected safe headway of CACC vehicle. s_0 is the minimum safe distance of vehicle braking. h is the equilibrium space headway of CACC vehicle.

3.1.3. Lane-Changing Model

Lane-changing behavior is a kind of driving behavior that drivers leave one lane and change into the adjacent lane to achieve driving purpose after comprehensively analyzing the surrounding vehicle status, including vehicle speed, vehicle spacing, road conditions, traffic control, and other affecting factors. There are three steps to complete a lane-changing: generation of lane-changing intention, feasibility judgment, and execution of the lane-changing operation. According to drivers' intentions, lane-changing behaviors include free lane-changing, cooperative lane-changing, and compulsory lane-changing. Compulsory lane-changing takes place when drivers must leave the lane before a certain point due to diversion, merging, or obstacles affecting normal driving in the lane. Free lane-changing occurs independently in pursuit of faster and larger free driving space, usually with slow vehicles ahead. Car-following behavior and lane-changing behavior are the two most important driving behaviors of vehicles and are also two important aspects of microscopic traffic flow simulation. Compared with the modeling process of car-following behavior, lane-changing behavior is more complex. However, it has been widely applied in micro traffic simulation, traffic capacity analysis, traffic safety assessment, and driving assistant decision support, attracting many scholars' attention. At the same time, in order to reflect the real state of traffic flow, many lane-changing models have been proposed, including the gap acceptance model [47], the acceptance model of acceleration (deceleration) [48], the trajectory planning model of lane-changing [49], and the optimized speed model of one-way multi-lane [50].

Under the connected vehicle environment, according to the real-time perception of the surrounding vehicle status, road traffic environment, and calculation results of a corresponding driving decision-making model, drivers can prepare in advance and deal with the complex traffic environment safely according to the generated trajectory planning. At present, scholars have made some achievements in the lane-changing decision-making model under the connected vehicle environment. Robin et al. [51] designed an automatic sensing system based on sensors and vehicle controller area network technology. They also used the Bayesian network model to evaluate vehicle traffic status, so as to provide lane-changing suggestions. Simon et al. [52] proposed a situation evaluation method for lane-changing strategy planning. Li et al. [53] summed up the critical safety time of lane-changing under various motion states and proposed the minimum safety distance lane-changing model based on the safety potential field theory. Using the distribution of the safety potential field, real-time intervention in the lane-changing process improves traffic safety and efficiency. It has an important theoretical significance for multi-vehicle coordinated lane changing, automatic driving, and vehicle group optimization control in the future.

3.2. Macroscopic Traffic Flow Models

Macro traffic flow modeling focuses on the overall characteristics of road traffic flow and does not specifically describe the interaction between individual vehicle movement

characteristics. The macroscopic traffic flow modeling is usually based on the lattice model and fluid mechanics theory. The vehicles that make up the traffic flow are regarded as the compressible continuous fluid medium. The macroscopic evolution law is characterized by the average speed, traffic flow, and density of the group vehicles, so as to reveal the main dynamic behaviors of traffic flow. The macroscopic traffic flow model originated from the LWR model proposed by Lighthill, Whitham, and Richards, namely the motion wave model, which can describe the nonlinear propagation characteristics of traffic flow according to the law of vehicle number conservation [54,55]. Since then, studies on the macro-level of traffic flow have been conducted. Payne proposed a speed gradient model based on Newell car-following model. Later, Whitham et al. improved the model, describing such phenomena as trend charts and traffic delay. Daganzo [56] proposed the cell transmission model, which is a discrete form of LWR model based on the trapezoidal relationship between traffic flow and density. The model discretizes the partial differential equations by finite difference method and simulates typical dynamic characteristics of traffic flow such as shock wave, congestion formation, and dissipation. Based on Bando's idea that traffic flow can be obtained with optimal speed and average density, Nagatani [45] proposed a discrete lattice hydrodynamic model to describe the nonlinear characteristics of traffic flow density wave. At present, the research of macro modeling for mixed traffic flow of vehicles with the intelligent network is mostly derived from the traditional macro traffic flow model of "small car-large truck". Daganzo et al. [57] proposed a multi-lane LWR macro model based on the first-order LWR macro model and proposed a multi-lane LWR macro model based on lane-changing behavior. Qian et al. [58] extended the cellular transmission model of single-vehicle traffic flow and proposed a multi-vehicle CTW model. The model was verified in the analysis of macro-evolution characteristics of traffic flow through numerical simulation experiments and measured data.

For the traffic flow mixed with intelligent connected vehicles and human-driven vehicles, Ngoduy et al. proposed macro traffic flow models based on the gas dynamics theory, and verified the characteristics of the proposed models through simulation experiments [59,60]. Qin et al. used the CACC model and IDM model to simulate the car following behavior of intelligent connected vehicles and human-driven vehicles, respectively [61–65]. Based on the basic graph model with different proportions of intelligent connected vehicles, a general analytical framework of LWR model was established, and the shock wave characteristics of the model were simulated and analyzed.

4. Methodology of Characteristics of Analysis for Mixed Traffic Flow

The analysis of mixed traffic flow under the ICV environment provides a scientific theoretical basis for the large-scale application of the intelligent connected transportation system in the future. On the other hand, it provides basic methodological support for traffic flow characteristics research and operation management control under the intelligent transportation system.

4.1. Numerical Simulation Analysis Method

Considering the characteristics of traffic flow in the environment of the autonomous highway system, Ran and Tsao derived the car-following model of platoon organization mode based on the traditional car-following model, and gave the general expression of three parameters relationship of macro traffic flow [66]. Based on numerical simulation, the influence of the platoon structure on the macro traffic flow was analyzed.

Vander et al. [67] used Monte Carlo simulation to estimate the impact of the proportion of ACC and CACC vehicles on freeway capacity and analyzed the sensitivity of headway parameters of ACC and CACC vehicles.

Talebbour and Mahmassani applied the car-following model, which distinguished the characteristics of network connection and automatic driving, to gain the scatter diagram of flow density speed under different traffic flow. When the value of penetration rate of intelligent connected vehicles is given, the influence of the proportion of intelligent connected

vehicles on traffic capacity is analyzed through numerical simulation experiments [68]. The research results are shown in Figure 6.

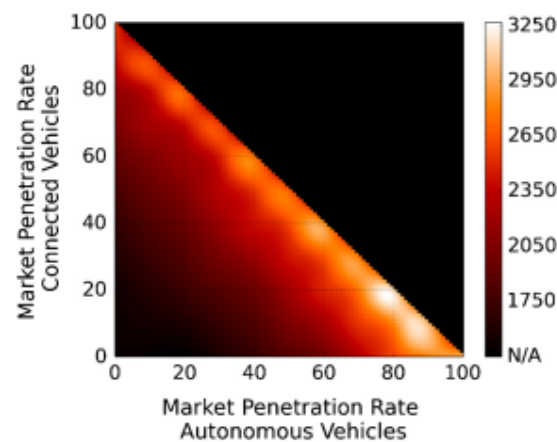


Figure 6. Maximum throughput (veh/h/lane) at different market penetration rates of connected and autonomous vehicles for a platoon of regular, connected, and autonomous vehicles with infinite length [68].

To analyze the characteristics of traffic flow mixed with IDM car-following model, CACC car-following model, and its degradation mode ACC car-following model, Chang et al. carried out numerical simulation experiments [69]. The results showed that an intelligent connected platoon could effectively improve the capacity of basic freeway sections [70,71]. Ye and Yamamoto established the traffic flow model of the dedicated lane and obtained the dedicated lane capacity by numerical simulation. The simulation results showed that the dedicated lane can improve traffic efficiency to a greater extent when the traffic flow is of low density [72]. Based on the relationship between speed and headway, Chen et al. analyzed the influence of the intelligent connected platoon penetration and platoon size restriction on traffic capacity with different lane management strategies by numerical simulation [73]. Bujanovic and Lochrane proposed the traffic capacity calculation model of traffic flow mixed with CACC and its degradation ACC vehicles at different CACC penetration rate and platoon size based on the analysis method in HCM2016 [74]. Chang et al. analyzed the stability of traffic flow mixed with intelligent connected vehicles by using the stability analytical framework of mixed traffic flow proposed by Ward. The influence of relevant parameters on traffic flow stability was analyzed through numerical simulation experiments, which provided a theoretical reference for the design of intelligent connected vehicle control parameters [75]. Qin et al. proposed the first-order traffic flow LWR model mixed with intelligent connected vehicles [76]. The results of theoretical analysis of the propagation characteristics of traffic wave and shock wave in the mixed traffic flow were verified by numerical simulation experiments. Lee et al. studied the real-time intersection control algorithm of cumulative travel time response under the connected vehicle environment and analyzed the effect of the penetration rate of connected vehicles on intersection delay and average speed through numerical simulation [24].

4.2. Simulation Experiment in a Software Virtual Environment

Fernandes and Nunes proposed the multi-platoon position and collaborative control strategy for the dedicated lane traffic flow of intelligent connected vehicles. Multi scenes and the algorithm were evaluated through the Matlab-Simulink simulation analysis (see Figure 7). The results showed that the proposed algorithm could ensure high traffic capacity and density, and avoid traffic congestion [77].

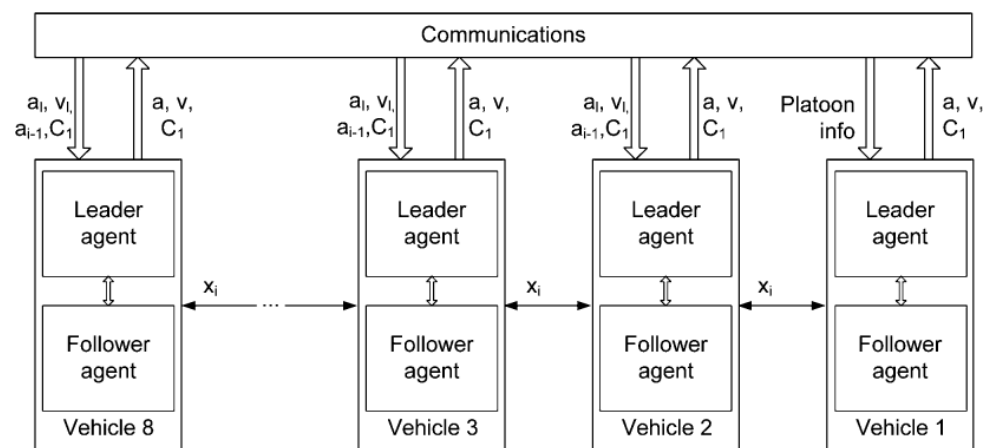


Figure 7. Information flow diagram of agent-based platoons [77].

Feng studied the system control strategy of the autonomous vehicle at intersections, and proposed the collaborative control algorithm for vehicles passing through the intersection. The simulation experiment was carried out with VISSIM. The results show that the proposed automatic driving vehicle control algorithm can effectively improve the traffic capacity at the intersection [78].

Rahman and Abdel evaluated the traffic flow safety under different lane management strategies and different penetration rates of intelligent connected vehicles using VISSIM software and its external interface C++ programming to simulate the intelligent connected vehicle environment. The results showed that the safety of intelligent connected vehicle dedicated lanes under the same penetration rate was better than other lane management strategies [79].

Zhao and Sun used the application programming interface of VISSIM to construct CACC platoon formation, adjustment, leaving the platoon, dissolution, and other simulation frameworks (see Figure 8). Through the simulation experiment, quantitative analysis of the impact of different penetration rates and platoon size restrictions on traffic capacity were carried out [80].

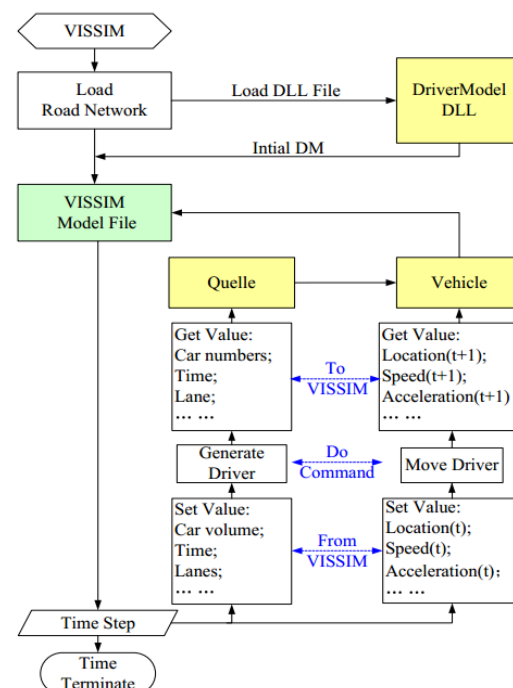


Figure 8. The diagram of interchanges between Driver Model DLL and VISSIM [80].

Amoozadeh et al. [81] proposed a CACC platoon management protocol based on wireless communication among connected vehicles. The effectiveness of the proposed protocol was verified by the comprehensive simulation platform VENTOS based on SUMO and OMNET++. The parameters under different platoon control strategies based on headway were calibrated.

4.3. Driving Simulator-Based Simulation Experiment

Based on a driving simulation experiment, Yue et al. studied the influence of the forward-collision warning system on driving behavior in the fog area. The experimental results showed that the forward-collision warning system could reduce the approaching collision events by 35% [82].

To study the influence of connected vehicle technology on driving behavior in the tunnel section, Vashitz et al. [83] evaluated the influence of HMI, a human–computer interaction equipment, on driver’s distraction in a driving simulation experiment. The results showed that the influence of HMI on driver’s distraction was very small, and HMI could relieve driving anxiety and boredom. Besides, based on driving simulation, Fu et al. [84] verified that the on-board HMI can improve driving safety in tunnel section and had different effects on improving safety in different positions.

Based on driving simulation, Chang et al. [85] studied the influence mechanism of longitudinal driving behavior and information action mechanism in tunnel section and evaluated driving safety and traffic flow smoothness under the connected vehicle environment. The CV environment design framework is shown in Figure 9.

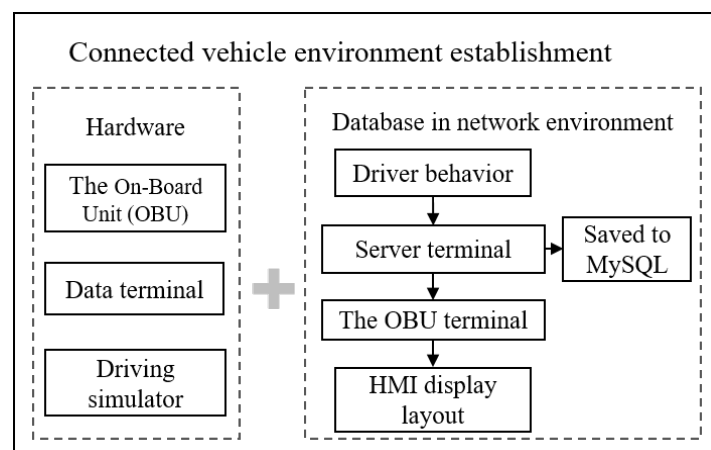


Figure 9. The CV environment design framework [85].

Walch et al. [86] proposed a cooperative interaction system between automatic vehicles and drivers to overcome the limitation of an automatic system or the uncertainty of the traffic environment, so as to avoid the full takeover state driven by the automatic driving system. The driving simulation experiments of 32 participants showed that participants feel very comfortable when dealing with random traffic events.

Vaezipur et al. [87] analyzed the impact of vehicle human–computer interaction design on traffic safety and eco-driving through a driving simulation experiment of 40 drivers. The results showed that when HMI provided information suggestion and feedback, it helped to realize eco-driving and improve safety.

To analyze the influence of cruise control CC and adaptive cruise control ACC on driving behavior, Mark Vollrath et al. conducted a driving simulation experiment at German Aerospace Center [88]. Participants drove different driving scenarios under three different conditions (ACC, CC, and manual driving without any system assistance), including secondary task conditions. The results showed that both systems could reduce speeding violations. There is no evidence that drivers paid more attention to secondary tasks when

driving with CC or ACC. However, drivers' response will be delayed in emergencies, such as in narrow bends or fog areas.

4.4. Naturalistic Driving Data-Based Statistical Analysis Method

Natural driving research refers to the research in which the driver's real driving process is observed and recorded by a high-precision data acquisition system under natural state (i.e., no interference, no interference of experimenters, and normal driving state). Chai [46] used the trajectory data of the NGSIM, which shares similar characteristics of high data acquisition frequency, relatively accurate data, and multiple data types. The Newell theory was applied to extract the reaction time and minimum safety distance of vehicles when drivers were responding to external environmental stimulation, and provided a theoretical basis for the construction of a safety early warning system under the connected vehicle environment.

Ben et al. [89] collected the data of car-following behavior when the forward warning system was open on the test road and found that drivers kept a longer following distance than the traditional environment (FCW off).

Farah et al. collected 35 test drivers who drove vehicles with or without COOPERS system. The COOPERS system vision is illustrated in Figure 10. The data related to driving behavior, physiological measurement, and user acceptance were collected. The impact of the infrastructure vehicle cooperative system on driver behavior was studied [90].

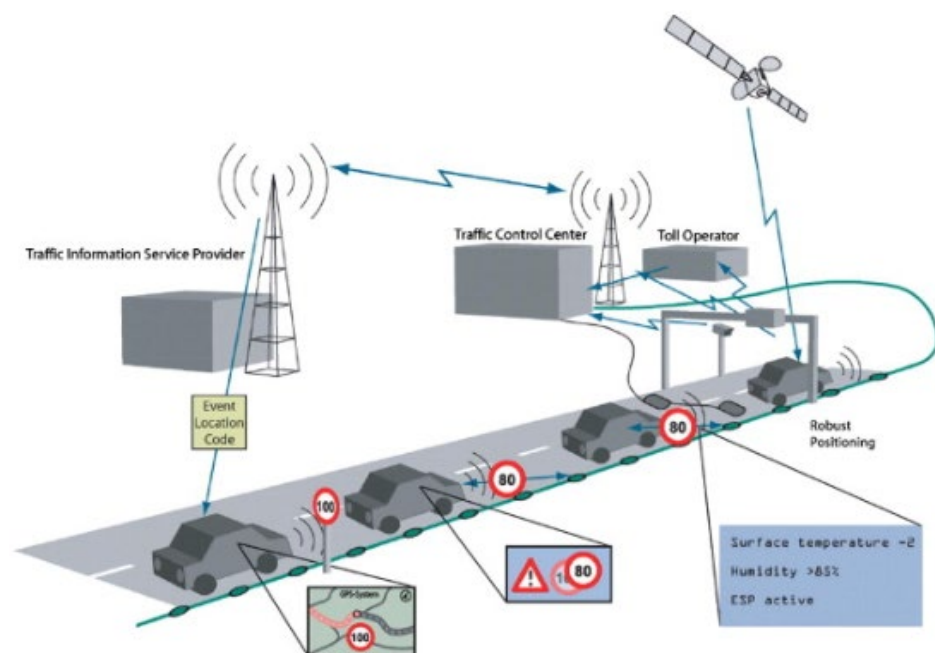


Figure 10. COOPERS vision of continuous bidirectional I2V communication along motorways (GPS = Global Positioning System, ESP = Electronic Stability Program) [90].

Farah and Koutsopoulos collected the trajectory data of test vehicles and the front vehicle with and without the I2V system, as well as sociodemographic characteristics of the test drivers. The results showed that the I2V system reduced the range of acceleration and deceleration differences among drivers, and its influence on elderly drivers was more significant [91].

Fu et al. [84] investigated the effects of in-vehicle navigation on drivers' perceptual behavior and driving behavior at tunnel entrance through natural driving experiments of 20 drivers in seven tunnel sections. The results showed that in-vehicle navigation significantly affected drivers' perceptual response, and the effects were varied in different areas of the tunnel entrance.

In order to verify the feasibility of the intelligent connected vehicle driving simulation test, Pariota et al. [92] compared and analyzed the stable car following state data of drivers

in the real road environment and two types of driving simulation virtual environments in the Italian DRIVE IN2 research project.

5. Lane-Management Methods for Mixed Traffic Flow

5.1. Speed Control Optimization Methods

Wu et al. [93] proposed a variable speed limit (VSL) feedback control framework (see Figure 11) considering the relationship between headway and sight distance under the connected vehicle environment. They evaluated the effect of proposed control strategy on traffic safety with two indicators: time to the collision while braking (TTC_{brake}) and total travel time (TTT). The results showed that VSL control performed an important role in reducing the risk of rear-end collision, and the control effect was affected by the compliance rate.

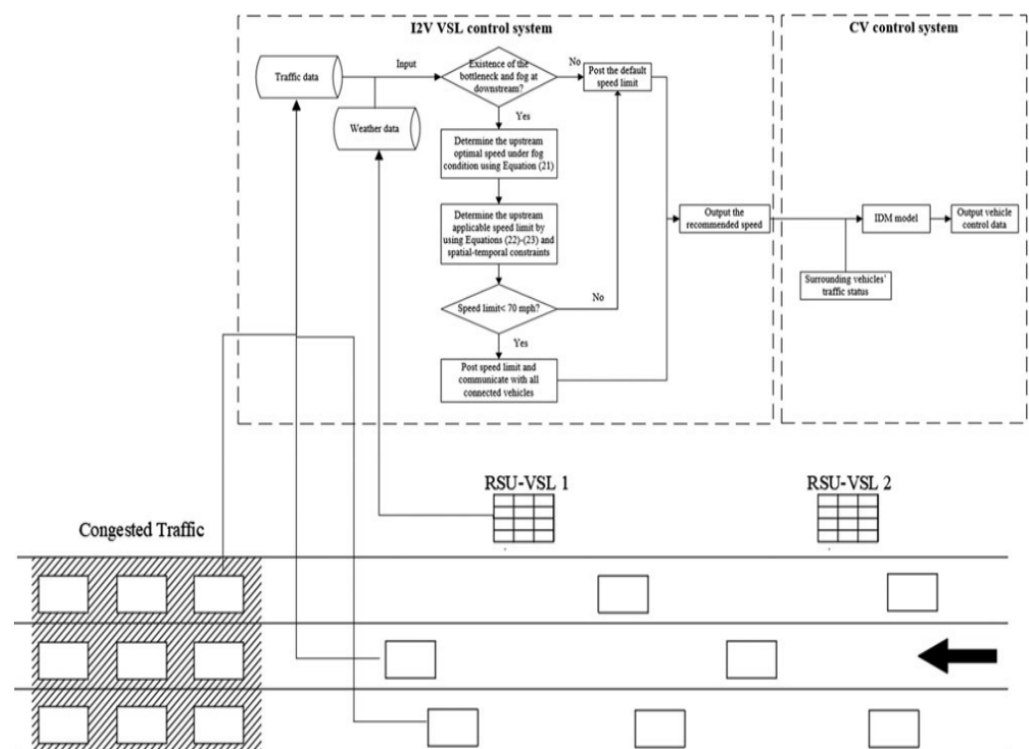


Figure 11. Implementing VSLs in CV environment [93].

Based on the driving simulation experiment platform, Yang et al. [94] evaluated the influence of the variable speed limit (VSL) warning system on the driving behavior of truck drivers under severe weather conditions in Wyoming. The results showed that the VSL warning system could reduce average speed and the speed difference of drivers with connected vehicle technologies, and could bring potential safety benefits.

Taking the variable speed limit system and real-time traffic information system of the vehicle navigation system as examples, Ackaah et al. [95] evaluated the effect of the advanced travel information system on driving behavior by analyzing the spatiotemporal regions of the real-time traffic conditions measured by the information broadcast.

To improve the traffic efficiency and traffic safety in ramp area, Wang [96] proposed a cooperative vehicle infrastructure system that regulated the traffic flow through variable speed limit control and on-ramp control.

5.2. Optimization Methods of Dedicated Lane-Management Strategy

Amir et al. [97] proposed a compact lane management model to determine the optimal number of lanes for intelligent connected vehicles considering different traffic demand levels, the penetration rate of intelligent connected vehicles, and the strength of CAV platoons. Thus, the lane management strategy could maximize the traffic capacity of multi-

lane highway sections, and the analytical method was determined for solving the optimal number of CAV lanes under certain headway setting.

Hu and Sun [98] proposed an online control algorithm for the merging area of multi-lane freeway based on lane-changing and car following trajectory optimization. Firstly, to ensure the safety and the smooth lane-changing process, a collaborative lane-changing control (CLCC) optimization model was proposed according to the rule-based lane-changing decision-making strategy. Then, the upstream traffic flow distribution of the merging point was adjusted, and the downstream traffic flow distribution was finally balanced. Secondly, the cooperative mixed control (CMC) model was used to be flexible near the merging point. Thirdly, a dynamic moving boundary point method was designed to coordinate the continuous execution of CLCC and CMC models.

Ma and Wang [99] introduced a basic graphic method to compare the performance of traffic flow mixed with autonomous vehicles under different lane numbers, which can reveal the advantages and disadvantages of dedicated lanes at different penetration rates of intelligent connected vehicles, and then determine the setting mode of dedicated lanes. In addition, they suggested that the traffic flow would exceed the operation results of the road without a dedicated lane in many cases (the penetration rate is between 10–90%). That is, unless the number of CAVs is too small or too large, there should be no dedicated lane.

Ghiasi et al. [100] believed that intelligent networked vehicles may operate with smaller longitudinal and lateral spacing than traditional human driving vehicles (HVS), thanks to the developing technologies in rapid and accurate control and cooperative mobility. Additionally, narrower expressway lanes can be allocated to intelligent networked vehicles to increase traffic capacity. Based on this, they put forward a lane management analysis framework, which determined the optimal number of lanes for intelligent connected vehicles to maximize the traffic capacity of highway sections, considering the application of the narrow CAV lane width.

Chen et al. [68] developed a general theoretical framework to study how the macroscopic capacity in equilibrium traffic would change with the introducing of AVs. They considered the scenario of a two-lane highway, and derived the capacity functions for three different lane policies in which lane 1 only allows AV platoons and lane 2 RVs; (M, R) policy, in which lane 1 allows both AV platoons and RVs (i.e., mixed traffic), and lane 2 allows RVs only; and (A, M) policy, in which lane 1 is dedicated to AV platoons and lane 2 has mixed traffic), see Figure 12.

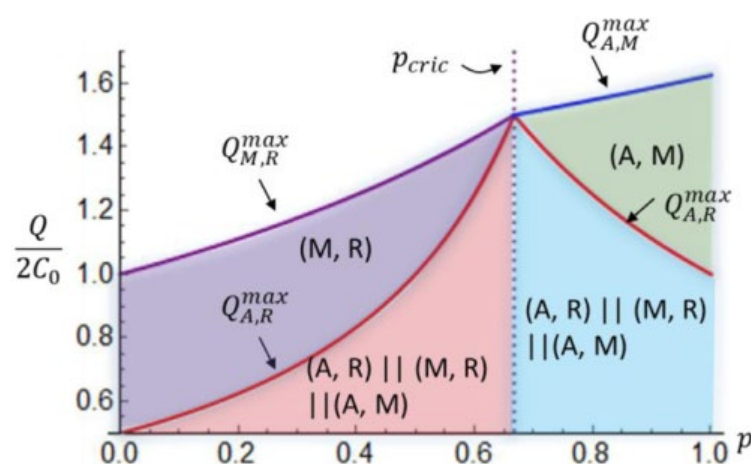


Figure 12. Implementing VSLs in CV environment [68].

6. Conclusions and Prospects

The study on characteristic analysis of traffic flow mixed with intelligent connected vehicles is very crucial for optimizing traffic control method under different ICV technology development stages and traffic flow states. Related research can not only provide a theoretical basis for constructing large-scale intelligent connected transportation infrastructure, but

also provide a reference for the establishment of connected and autonomous vehicle route maps. Moreover, it is also of great value in engineering applications. This paper introduces the current status and future trend of connected vehicle technologies, traffic flow models, the methods for the characteristic analysis of traffic flow, and lane management methods. This work represents the current research status of the characteristic analysis of traffic flow under a connected vehicle environment and provides references for related research.

Now, many models have been built on traditional methods. In the future, more traffic flow models should be studied, considering the reinforcement learning theory, transfer theory, etc. Advanced technologies will lead to a changes in the traffic operating environment. Thus, the car-following model, the lane-changing model, and the vehicle control model need to be updated iteratively [101]. In addition, the updating of traffic control technology will bring about a change in traffic management methods [102]. Moreover, the increased popularity and wide application of intelligent connected vehicle technology would help to obtain more actual operation data, and the traffic flow theory based on the statistical analysis of actual operation data will be a lasting academic hotspot. Besides, with the maturity and gradual application of the intelligent connected vehicle technology, it is of great significance to study the traffic management application scheme combining the theoretical analysis research results with the practical application of traffic engineering.

With the development of connected vehicle technology, the road traffic flow will be composed of many types of vehicles (including manual driving vehicles, take over vehicles, fully automatic driving vehicles, etc.) and traffic flow configuration, the traffic flow characteristics will be more complex. At present, the existing research rarely describes the micro driving behavior characteristics to the meso-traffic flow from the perspective of human factors. In addition, there is still a lack of systematically research on traffic flow characteristics mixed with intelligent connected vehicles, including the analytical expression of mixed traffic flow consisting of vehicles with different degrees of intelligence and connectivity, the construction of basic graph model, the capacity and stability analysis, and the analysis of the effect of intelligent connected vehicles on sustainability [102].

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References

1. Siegel, J.E.; Erb, D.C.; Sarma, S.E. A Survey of the Connected Vehicle Landscape—Architectures, Enabling Technologies, Applications, and Development Areas. *IEEE Trans. Intell. Transp. Syst.* **2018**, *19*, 2391–2406. [CrossRef]
2. Rios-Torres, J.; Malikopoulos, A.A. A survey on the coordination of connected and automated vehicles at intersections and merging at highway on-ramps. *IEEE Trans. Intell. Transp. Syst.* **2017**, *18*, 1066–1077. [CrossRef]
3. Dong-Fan, X.; Xiao-Mei, Z.; Zhengbing, H. Heterogeneous Traffic Mixing Regular and Connected Vehicles: Modeling and Stabilization. *IEEE Trans. Intell. Transp. Syst.* **2018**, *20*, 2060–2071.
4. Milakis, D.; Van Arem, B.; Van Wee, B. Policy and society related implications of automated driving: A review of literature and directions for future research. *J. Intell. Transp. Syst. Technol. Plan. Oper.* **2015**, *21*, 324–348. [CrossRef]
5. Amadeo, M.; Campolo, C.; Molinaro, A. Information-centric networking for connected vehicles: A survey and future perspectives. *IEEE Commun. Mag.* **2016**, *54*, 98–104. [CrossRef]
6. Parent, M.; Gallais, G. Intelligent transportation in cities with CTS. In Proceedings of the IEEE 5th International Conference on Intelligent Transportation Systems, Singapore, 6 September 2003.
7. Campbell, K.L. *Detailed Planning for Research on Making a Significant Improvement in Highway Safety*; Transportation Research Board: Washington, DC, USA, 2003.
8. Available online: <https://www.intelldriv usa.org/> (accessed on 4 April 2010).

9. Nadeem, T.; Dashtinezhad, S.; Liao, C.; Iftode, L. TrafficView: Traffic Data Dissemination using Car-to-Car Communication. *ACM SIGMOBILE Mob. Comput. Commun. Rev.* **2004**, *8*, 6–19. [\[CrossRef\]](#)
10. Available online: <http://www.path.berkeley.edu/Research/Safety-Ops.htm> (accessed on 1 January 2016).
11. Shladover, S.E.; Su, D.; Lu, X.Y. Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow. *Transp. Res. Rec.* **2012**, *2324*, 63–70. [\[CrossRef\]](#)
12. Milanés, V.; Shladover, S.E. Modeling cooperative and autonomous adaptive cruise control dynamic responses using experimental data. *Transp. Res. Part C Emerg. Technol.* **2014**, *48*, 285–300. [\[CrossRef\]](#)
13. Morioka, Y.; Sota, T.; Nakagawa, M. An anti-car collision system using GPS and 5.8 GHz inter-vehicle communication at an off-sight intersection[C]// IEEE VTS Fall VTC2000. In Proceedings of the 52nd Vehicular Technology Conference (Cat. No.00CH37152), Boston, MA, USA, 24–28 September 2000; IEEE: Piscataway, NJ, USA, 2000.
14. Toulminet, G.; Boussuge, J.; Laurgeau, C. Comparative synthesis of the 3 main European projects dealing with Cooperative Systems (CVIS, SAFESPOT and COOPERS) and description of COOPERS Demonstration Site 4. In Proceedings of the 2008 11th International IEEE Conference on Intelligent Transportation Systems, Beijing, China, 12–15 October 2008; IEEE: Piscataway, NJ, USA, 2008; pp. 809–814.
15. Maiti, S.; Winter, S.; Kulik, L. A conceptualization of vehicle platoons and platoon operations. *Transp. Res. Part C Emerg. Technol.* **2017**, *80*, 1–19. [\[CrossRef\]](#)
16. Jia, D.; Lu, K.; Wang, J.; Zhang, X.; Shen, X. A survey on platoon-based vehicular cyber-physical systems. *IEEE Commun. Surv. Tutor.* **2016**, *18*, 263–284. [\[CrossRef\]](#)
17. Hall, R.; Chin, C. Vehicle sorting for platoon formation: Impacts on highway entry and throughput. *Transp. Res. Part C Emerg. Technol.* **2005**, *13*, 405–420. [\[CrossRef\]](#)
18. Brackstone, M.; McDonald, M. Car-following: A historical review. *Transp. Res. Part F Traffic Psychol. Behav.* **1999**, *2*, 181–196. [\[CrossRef\]](#)
19. Chandler, R.E.; Herman, R.; Montroll, E.W. Traffic dynamics: Studies in car following. *Oper. Res.* **1958**, *6*, 165–184. [\[CrossRef\]](#)
20. Gazis, D.C.; Herman, R.; Rothery, R.W. Nonlinear Follow-the-Leader Models of Traffic Flow. *Oper. Res.* **1961**, *6*, 165–184. [\[CrossRef\]](#)
21. Newell, G.F. Nonlinear Effects in the Dynamics of Car Following. *Oper. Res.* **1961**, *9*, 209–229. [\[CrossRef\]](#)
22. Nagatani, T. Traffic behavior in a mixture of different vehicles. *Phys. A Stat. Mech. Appl.* **2000**, *284*, 405–420. [\[CrossRef\]](#)
23. Yang, Q.I.; Koutsopoulos, H.N. A Microscopic Traffic Simulator for evaluation of dynamic traffic management systems. *Transp. Res. C* **1996**, *4*, 113–129. [\[CrossRef\]](#)
24. Lee, G. A Generalization of Linear Car-Following Theory. *Oper. Res.* **1966**, *14*, 595–606. [\[CrossRef\]](#)
25. Kometani, S. Dynamic behavior of traffic with a nonlinear spacing-speed relationship. *Theory Traffic Flow* **1959**, 105–119. Available online: <https://ci.nii.ac.jp/naid/10004835989/> (accessed on 15 May 2022).
26. Gipps, P.G. A behavioural car-following model for computer simulation. *Transp. Res. Part B* **1981**, *15*, 105–111. [\[CrossRef\]](#)
27. Benekohal, R.F.; Treiterer, J. Car-following model for simulation of traffic in normal and stop-and-go conditions. *Transp. Res. Rec.* **1988**, *1194*, 99–111.
28. Sengupta, R.; Rezaei, S.; Shladover, S.E.; Cody, D.; Dickey, S.; Krishnan, H. Cooperative Collision Warning Systems: Concept Definition and Experimental Implementation. *J. Intell. Transp. Syst.* **2007**, *11*, 143–155. [\[CrossRef\]](#)
29. Michaels, R.M. Perceptual factors in car following. In Proceedings of the Second International Symposium on the Theory of Traffic Flow, London, UK, 25 June 1963.
30. Wiedemann, R. *Simulation of Road Traffic in Traffic Flow*; University of Karlsruhe: Karlsruhe, Germany, 1974.
31. Jia, H.F.; Juan, Z.C.; Wang, X.Y. Car-following model based on fuzzy inference system. *Transportation Research Record*. 2001. Available online: <https://onlinepubs.trb.org/Onlinepubs/trr/1992/1365/1365.pdf#page=86> (accessed on 15 May 2022).
32. Wang, Z.; Siwen, J.; Zhang, L. Developing a car-following model with consideration of driver's behavior based on an Adaptive Neuro-Fuzzy Inference System. *J. Intell. fuzzy Syst. Appl. Eng. Technol.* **2016**, *30*, 461–466. [\[CrossRef\]](#)
33. Bando, M.; Hasebe, K.; Nakayama, A.; Shibata, A.; Sugiyama, Y. Dynamical model of traffic congestion and numerical simulation. *Phys. Rev. E* **1995**, *51*, 1035–1042. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Helbing, D.; Tilch, B. Generalized force model traffic dynamics. *Phys. Rev. E* **1998**, *58*, 133–138. [\[CrossRef\]](#)
35. Jiang, R.; Wu, Q.; Zhu, Z. Full velocity difference model for a car-following theory. *Phys. Rev. E. Stat. Nonlinear Soft Matter Phys.* **2001**, *64*, 017101/1–017101/4. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Treiber, M.; Kesting, A.; Helbing, D. Delays, inaccuracies and anticipation in microscopic traffic models. *Phys. A Stat. Mech. Appl.* **2006**, *360*, 71–88. [\[CrossRef\]](#)
37. Treiber, M.; Hennecke, A.; Helbing, D. Congested traffic states in empirical observations and microscopic simulations. *Phys. Rev. E. Stat. Physics Plasmas Fluids Relat. Interdiscip. Top.* **2000**, *62*, 1805–1824. [\[CrossRef\]](#)
38. Qin, Y.; Wang, H.; Ran, B. Impact of Connected and Automated Vehicles on Passenger Comfort of Traffic Flow with Vehicle-to-vehicle Communications. *Ksce J. Civ. Eng.* **2019**, *23*, 821–832. [\[CrossRef\]](#)
39. Cremer, M.; Ludwig, J. A fast simulation model for traffic flow on the basis of boolean operations. *Math. Comput. Simul.* **2014**, *28*, 297–303. [\[CrossRef\]](#)
40. Wolfram, S. Statistical mechanics of cellular automata. *Rev. Mod. Phys.* **1983**, *55*, 601–644. [\[CrossRef\]](#)
41. Nagel, K.; Schreckenberg, M. A cellular automaton model for freeway traffic. *J. Phys. I* **1992**, *2*, 2221–2229. [\[CrossRef\]](#)

42. Benjamin, S.C.; Johnson, N.F.; Hui, P.M. Cellular automata models of traffic flow along a highway containing a junction. *J. Phys. A Gen. Phys.* **1996**, *29*, 3119–3127. [\[CrossRef\]](#)
43. Barlovic, R.; Santen, L.; Schadschneider, A.; Schreckenberg, M. Metastable states in cellular automata for traffic flow. *Eur. Phys. J. B-Condens. Matter Complex Syst.* **1998**, *5*, 793–800. [\[CrossRef\]](#)
44. Li, X.; Wu, Q.; Jiang, R. Cellular automaton model considering the velocity effect of a car on the successive car. *Phys. Rev. E Stat. Nonlin. Soft Matter Phys.* **2001**, *64*, 66128. [\[CrossRef\]](#)
45. Nagatani, T. Self-organization and phase transition in traffic-flow model of a two-lane roadway. *J. Phys. A Math. Gen.* **1993**, *26*, L781–L787. [\[CrossRef\]](#)
46. Chai, R. *Research on Driving Behavior Characteristics under Connected Vehicle Environment*; Beijing Institute of Technology: Beijing, China, 2016.
47. Kimber, R. Gap-Acceptance and Empiricism in Capacity Prediction. *Transp. Sci.* **1989**, *23*, 100–111. [\[CrossRef\]](#)
48. Gipps, P.G. A model for the structure of lane-changing decision. *Transp. Res. Part B Methodol.* **1986**, *20*, 403–414. [\[CrossRef\]](#)
49. Li, L.; Wang, F.Y.; Kim, H. Cooperative driving and lane changing at blind crossings. In Proceedings of the IEEE Intelligent Vehicles Symposium, Las Vegas, NV, USA, 6–8 June 2005.
50. Gu, G. *Intelligent Vehicle Collaborative Lane Change Trajectory Planning Considering Driving Characteristics*; South China University of Technology: Guangzhou, China, 2018.
51. Schubert, R.; Schulze, K.; Wanielik, G. Situation Assessment for Automatic Lane-Change Maneuvers. *IEEE Trans. Intell. Transp. Syst.* **2010**, *11*, 607–616. [\[CrossRef\]](#)
52. Ulbrich, S.; Maurer, M. Situation Assessment in Tactical Lane Change Behavior Planning for Automated Vehicles. In Proceedings of the IEEE International Conference on Intelligent Transportation Systems, Gran Canaria, Spain, 15–18 September 2015.
53. Li, L.; Gan, J.; Zhou, K.; Qu, X.; Ran, B. A novel lane-changing model of connected and automated vehicles: Using the safety potential field theory. *Phys. A Stat. Mech. Appl.* **2020**, *559*, 125039. [\[CrossRef\]](#)
54. Richards, P.I. Shock Waves on the Highway. *Oper. Res.* **1956**, *4*, 42–51. [\[CrossRef\]](#)
55. Lighthill, M.J.; Whitham, G.B. On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads. *Proc. R. Soc. A Math. Phys. Eng. Sci.* **1955**, *229*, 317–345.
56. Daganzo, C.F. A continuum theory of traffic dynamics for freeways with special lanes. *Transp. Res. Part B Methodol.* **1997**, *31*, 83–102. [\[CrossRef\]](#)
57. Daganzo, C.F. A behavioral theory of multi-lane traffic flow. Part I: Long homogeneous freeway sections. *Transp. Res. Part B Methodol.* **2002**, *36*, 131–158. [\[CrossRef\]](#)
58. Qian, Z.; Li, J.; Li, X.; Zhang, M.; Wang, H. Modeling heterogeneous traffic flow: A pragmatic approach. *Transp. Res. Part B Methodol.* **2017**, *99*, 183–204. [\[CrossRef\]](#)
59. Ngoduy, D.; Jia, D. Multi anticipative bidirectional macroscopic traffic model considering cooperative driving strategy. *Transp. B Transp. Dyn.* **2016**, *5*, 100–114. [\[CrossRef\]](#)
60. Ngoduy, D. Application of gas-kinetic theory to modelling mixed traffic of manual and ACC vehicles. *Transportmetrica* **2012**, *8*, 43–60. [\[CrossRef\]](#)
61. Qin, Y.-Y.; Wang, H.; Ran, B. Car-following Model of Connected and Autonomous Vehicles Considering Multiple Feedbacks. *J. Transp. Syst. Eng. Inf. Technol.* **2018**, *18*, 48–54.
62. Qin, Y.-Y.; Wang, H.; Wang, W.; Ni, D.-H. Review of car-following models of adaptive cruise control. *J. Traffic Transp. Eng.* **2017**, *17*, 121–130.
63. Qin, Y.; Wang, H.; Ran, B. Stability analysis of connected and automated vehicles to reduce fuel consumption and emissions. *J. Transp. Eng. Part A Syst.* **2018**, *144*, 04018068. [\[CrossRef\]](#)
64. Qin, Y.-Y.; Wang, H.; Wang, W. LWR Model for Mixed Traffic Flow in Connected and Autonomous Vehicular Environments. *Chin. J. Highw. Transp.* **2018**, *31*, 147–156.
65. Qin, Y.; Wang, H.; Wang, W. Analysis on stability and safety for mixed traffic flow with connected auxiliary driving. *J. Southeast Univ. Nat. Sci.* **2018**, *48*, 188–194.
66. Ran, B.; Tsao, H.-S.J. Traffic Flow Analysis for an Automated Highway System. 1996. Available online: <https://journals.sagepub.com/doi/10.3141/1588-18> (accessed on 15 May 2022).
67. Vander Werf, J.; Shladover, S.E.; Miller, M.A.; Kourjanskaia, N. Effects of adaptive cruise control systems on highway traffic flow capacity. *Transp. Res. Rec. J. Transp. Res. Board* **2002**, *1800*, 78–84. [\[CrossRef\]](#)
68. Talebpour, A.; Mahmassani, H.S. Influence of connected and autonomous vehicles on traffic flow stability and throughput. *Transp. Res. Part C Emerg. Technol.* **2016**, *71*, 143–163. [\[CrossRef\]](#)
69. Chang, X.; Li, H.; Qin, L.; Rong, J.; Lu, Y.; Chen, X. Evaluation of cooperative systems on driver behavior in heavy fog condition based on a driving simulator. *Accid. Anal. Prev.* **2019**, *128*, 197–205. [\[CrossRef\]](#)
70. Chang, X.; Li, H.; Rong, J.; Zhao, X.; Wang, Y. Analysis of Capacity for Mixed Traffic Flow with Connected Vehicle Platoon on Freeway. *J. South China Univ. Technol. Nat. Sci.* **2020**, *48*, 142–148.
71. Chang, X.; Li, H.; Rong, J.; Qin, L.; Yang, Y. Analysis on fundamental diagram model for mixed traffic flow with connected vehicle platoons. *J. Southeast Univ. Nat. Sci.* **2020**, *50*, 782–788.
72. Ye, L.; Yamamoto, T. Modeling connected and autonomous vehicles in heterogeneous traffic flow. *Phys. A Stat. Mech. Appl.* **2018**, *490*, 269–277. [\[CrossRef\]](#)

73. Chen, D.; Ahn, S.; Chitturi, M.; Noyce, D.A. Towards vehicle automation: Roadway capacity formulation for traffic mixed with regular and automated vehicles. *Transp. Res. Part B Methodol.* **2017**, *100*, 196–221. [\[CrossRef\]](#)
74. Pavle, B.; Taylor, L. Capacity Predictions and Capacity Passenger Car Equivalents of Platooning Vehicles on Basic Segments. *J. Transp. Eng. Part A Syst.* **2018**, *144*, 04018063.
75. Chang, X.; Li, H.; Rong, J.; Zhao, X.; Li, A. Analysis on Traffic Stability and Capacity for Mixed Traffic Flow with Platoons of Intelligent Connected Vehicles. *Phys. A Statist. Mech. Appl.* **2020**, *557*, 124829. [\[CrossRef\]](#)
76. Fernandes, P.; Nunes, U. Multiplatooning Leaders Positioning and Cooperative Behavior Algorithms of Communicant Automated Vehicles for High Traffic Capacity. *IEEE Trans. Intell. Transp. Syst.* **2015**, *16*, 1172–1187. [\[CrossRef\]](#)
77. Qi, F. *Coordinated Control Strategy for Autonomous Vehicle Intersections*; Harbin Institute of Technology: Harbin, China, 2017.
78. Rahman, M.S.; Abdel-Aty, M. Longitudinal safety evaluation of connected vehicles' platooning on expressways. *Accid. Anal. Prev.* **2018**, *117*, 381. [\[CrossRef\]](#) [\[PubMed\]](#)
79. Zhao, L.; Sun, J. Simulation Framework for Vehicle Platooning and Car-following Behaviors under Connected-Vehicle Environment. *Procedia-Soc. Behav. Sci.* **2013**, *96*, 914–924. [\[CrossRef\]](#)
80. Amoozadeh, M.; Deng, H.; Chuah, C.N.; Zhang, H.M.; Ghosal, D. Platoon management with cooperative adaptive cruise control enabled by VANET. *Veh. Commun.* **2015**, *2*, 110–123. [\[CrossRef\]](#)
81. Yue, L.; Abdel-Aty, M.; Wu, Y.; Wang, L. Assessment of the safety benefits of vehicles' advanced driver assistance, connectivity and low level automation systems. *Accid. Anal. Prev.* **2018**, *117*, 55–64. [\[CrossRef\]](#)
82. Vashitz, G.; Shinar, D.; Blum, Y. In-vehicle information systems to improve traffic safety in road tunnels. *Transp. Res. Part F Traffic Psychol. Behav.* **2008**, *11*, 61–74. [\[CrossRef\]](#)
83. Fu, X.; He, S.; Du, J.; Ge, T. Effects of In-Vehicle Navigation on Perceptual Responses and Driving Behaviours of Drivers at Tunnel Entrances: A Naturalistic Driving Study. *J. Adv. Transp.* **2019**, *2019*, 9468451. [\[CrossRef\]](#)
84. Chang, X.; Li, H.; Rong, J.; Qin, L.; Zhao, X. Spatiotemporal Characteristics of Vehicle Trajectories in a Connected Vehicle Environment—A Case of an Extra-Long Tunnel Scenario. *IEEE Syst. J.* **2020**, *99*, 1–12. [\[CrossRef\]](#)
85. Walch, M.; Sieber, T.; Hock, P.; Baumann, M.; Weber, M. Towards Cooperative Driving: Involving the Driver in an Autonomous Vehicle's Decision Making. In Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Ann Arbor, MI, USA, 24–26 October 2016.
86. Vaezipour, A.; Rakotonirainy, A.; Haworth, N.; Delhomme, P. Enhancing eco-safe driving behaviour through the use of in-vehicle human-machine interface: A qualitative study. *Transp. Res. Part A Policy Pract.* **2017**, *100*, 247–263. [\[CrossRef\]](#)
87. Schleicher, S.; Gelau, C. The influence of Cruise Control and Adaptive Cruise Control on driving behaviour—A driving simulator study. *Accid. Anal. Prev.* **2011**, *43*, 1134–1139.
88. Ben-Yaacov, A.; Maltz, M.; Shinar, D. Effects of an in-vehicle collision avoidance warning system on short-and long-term driving performance. *Hum. Factors* **2002**, *44*, 335–342. [\[CrossRef\]](#) [\[PubMed\]](#)
89. Farah, H.; Koutsopoulos, H.N.; Saifuzzaman, M.; Koelbl, R.; Fuchs, S.; Bankosegger, D. Evaluation of the effect of cooperative infrastructure-to-vehicle systems on driver behavior. *Transp. Res. Part C* **2012**, *21*, 42–56. [\[CrossRef\]](#)
90. Farah, H.; Koutsopoulos, H.N. Do cooperative systems make drivers' car-following behavior safer? *Transp. Res. Part C Emerg. Technol.* **2014**, *41*, 61–72. [\[CrossRef\]](#)
91. Pariota, L.; Bifulco, G.N.; Markkula, G.; Romano, R. Validation of driving behaviour as a step towards the investigation of Connected and Automated Vehicles by means of driving simulators. In Proceedings of the 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), Naples, Italy, 26–28 June 2017; pp. 274–279.
92. Wu, Y.; Abdel-Aty, M.; Wang, L.; Rahman, M.S. Combined connected vehicles and variable speed limit strategies to reduce rear-end crash risk under fog conditions. *J. Intell. Transp. Syst.* **2020**, *24*, 494–513. [\[CrossRef\]](#)
93. Yang, G.; Ahmed, M.M.; Gaweesh, S. Impact of Variable Speed Limit in a Connected Vehicle Environment on Truck Driver Behavior under Adverse Weather Conditions: Driving Simulator Study. *Transp. Res. Rec. J. Transp. Res. Board* **2019**, *2673*, 132–142. [\[CrossRef\]](#)
94. Ackaah, W.; Bogenberger, K.; Bertini, R.L. Empirical evaluation of real-time traffic information for in-vehicle navigation and the variable speed limit system. *J. Intell. Transp. Syst.* **2019**, *23*, 1–14. [\[CrossRef\]](#)
95. Wang, C.; Zhang, J.; Xu, L.; Li, L.; Ran, B. A New Solution for Freeway Congestion: Cooperative Speed Limit Control Using Distributed Reinforcement Learning. *IEEE Access* **2019**, *7*, 41947–41957. [\[CrossRef\]](#)
96. Ghiasi, A.; Hussain, O.; Qian, Z.S.; Li, X. A mixed traffic capacity analysis and lane management model for connected automated vehicles: A Markov chain method. *Transp. Res. Part B Methodol.* **2017**, *106*, 266–292. [\[CrossRef\]](#)
97. Hu, X.; Sun, J. Trajectory optimization of connected and autonomous vehicles at a multilane freeway merging area. *Transp. Res. Part C Emerg. Technol.* **2019**, *101*, 111–125. [\[CrossRef\]](#)
98. Ma, K.; Wang, H. Influence of Exclusive Lanes for Connected and Autonomous Vehicles on Freeway Traffic Flow. *IEEE Access* **2019**, *7*, 50168–50178. [\[CrossRef\]](#)
99. Ghiasi, A.; Hussain, O.; Qian, Z.S.; Li, X.S. Lane Management with Variable Lane Width and Model Calibration for Connected Automated Vehicles. *J. Transp. Eng.* **2020**, *146*, 04019075.1–04019075.12. [\[CrossRef\]](#)

100. Guo, Y.; Zhang, H.; Wang, C.; Sun, Q.; Li, W. Driver lane change intention recognition in the connected environment. *Phys. A Stat. Mech. Appl.* **2021**, *575*, 126057. [[CrossRef](#)]
101. Zhang, P.; Yue, H.; Shao, C.; Zhang, X.; Ran, B. Modelling the road network capacity considering residual queues and connected automated vehicles. *IET Intell. Transp. Syst.* **2022**, *16*, 543–570. [[CrossRef](#)]
102. Ortúzar, J.D.D. Future transportation: Sustainability, complexity and individualization of choices. *Commun. Transp. Res.* **2021**, *1*, 100010. [[CrossRef](#)]