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Review Article

A review of vehicle speed control strategies

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ABSTRACT: Currently, traffic problems in urban road traffic environments remain severe, traffic pollution and congestion have not been effectively improved, and traffic accidents are still frequent. Traditional traffic signal control methods have little effect on these problems. With the continuous improvement of communication technology and network connections, vehicle speed guidance provides a new idea for solving the above problems and has gradually become a popular topic in academic research. However, its generalization has shortcomings. Therefore, this paper summarizes the research on vehicle speed control strategies in urban road environments and provides suggestions for future research. In this paper, we summarize the existing research in four parts. First, we categorize existing research based on vehicle type. Second, the vehicle speed guidance problem is divided according to the problem research scene. Third, we summarize the existing literature regarding vehicle speed. Finally, we summarize the methods used for speed guidance. Through an analysis of the existing literature, it is concluded that there is a deficiency in the existing research, and suggestions for the future of vehicle speed guidance research are suggested.

KEYWORDS: speed guidance, vehicle control, vehicle trajectory planning, intelligent transportation

1 Introduction

At present, with the economic development of various countries worldwide, the level of urbanization has continued to increase, urban residential population has grown rapidly, and number of motor vehicle has increased annually. However, compared with the growth rate of motor vehicle ownership, the development rate of urban road resources is significantly lagging behind, and traffic congestion and environmental pollution are also serious concerns. For example, in USA, the transportation department accounts for 75% of oil consumption, and the emission of carbon dioxide accounts for 30% of the total discharge, which is the second largest source of carbon emissions (EPA, 2016). It is expected that in the future, because of the continuous extension of road networks, continuous increase in the amount of motor vehicle ownership, and increase in the mileage of annual driving, the energy consumption of road traffic will continue to increase (Leard et al., 2019), making the pollution problem more serious. And expected to increase traffic congestion by 60% in 2030 (Rafter et al., 2017). At present, relevant government departments, research institutes, and various types of enterprises have conducted significant research to solve traffic congestion and pollution. The current research is mainly focused on improving the level of urban cross-port traffic control and increasing the sharing rate of public transportation in urban transportation systems (Bashiri and Fleming, 2017; Lak et al., 2022; Malandraki et al., 2015).

With the development of communication technology, artificial intelligence, vehicle intelligence, and other auxiliary technologies, research on intelligent vehicle-road network linkage systems is gradually becoming more practical in countries around the world (Autili et al., 2021; Barbaresso et al., 2014; Guanetti et al., 2018; Lam et al., 2022). Using various sensors and communication devices, an intelligent vehicle-road network linkage system can obtain the operation status of various vehicles and road facilities in real-time and realize information sharing between vehicles and vehicles (V2V) and vehicles and roads (V2I) through advanced communication technology, which provides a massive database for the implementation of traffic control in all time and space. This is used to achieve the collaborative optimization of multiple operational parameters in the traffic system and realize flexible and fine-tuned control and decision-making of multiple traffic subjects, thus achieving the goal of improving the efficiency of road traffic resource utilization from a system perspective (Malakorn and Park, 2010). Improving traffic efficiency in intersection areas and reducing vehicle fuel consumption emissions through V2V and V2I has become a major focus for researchers and scholars. These include signal intelligence control, vehicle speed guidance, and collaborative vehicle control at light-free intersections, among which speed control for vehicles has received widespread attention owing to its good implementation and prospects (Chen et al., 2018; Ma et al., 2016). Through V2V and V2I communication, the vehicle can obtain vast information, such as the front intersection traffic signal timing information, vehicle location, and operating status information comprehensive consideration, so that the vehicle can ensure traffic efficiency while reducing the number of stops and energy emissions and achieving optimal operating strategy. Through the vehicle precision implementation of the resulting control strategy, it can improve the signal intersection road mobility, reduce urban road traffic pollutant emissions, and improve the efficiency of fuel and traffic

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(Chen et al., 2015; Muñoz-Organero and Magaña, 2013).

At present, the number of articles on vehicle speed control is increasing annually; for example, in a "Web of Science" search with the subject term "vehicle speed control" , as shown in Fig. 1, it is obvious that the research on vehicle speed control is increasing in both publication and citation frequency, and the growth rate is gradually accelerating. However, there have been few reviews of vehicle speed control strategies. Mintsis et al. (2020) conducted a literature review on different methods to determine the dynamic eco-driving speed of vehicles near signal intersections and discussed the advantages and shortcomings of existing eco-driving models. However, the research in that paper was singular, and speed guidance was performed only in terms of eco-driving, without considering other research objectives and scenarios. Asadi et al. (2021) conducted an analysis of different driving objectives, such as eco-driving, safety and travel time improvement, and advanced objectives achieved by speed assist systems, but there were also shortcomings, and the research scenarios scenarios, objects, etc., needs to be further improved. Wu and Qu (2022) reviewed the control of network-connected self-driving vehicles at intersections, but there are still some deficiencies in the research.

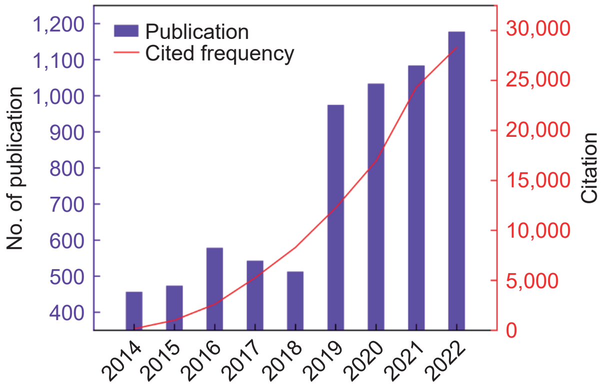

Fig. 1 Publications and citation frequency distribution.

The above reviews of the vehicle speed guidance problem all address a particular aspect and have certain limitations; therefore, the review of the vehicle speed guidance problem needs to be further improved, and further scientific suggestions can be made to provide insights for future research directions. Therefore, this article focuses on the study of vehicle speed control strategies on urban roads and organizes relevant research in depth from the three most important aspects of vehicle speed control impact: research objects, scenarios of research problems, and methods of speed guidance research.

The remainder of this paper is organized as follows: Section 2 explains the methodology of this review, Section 3 classifies the scenarios of speed-guided problems and conducts the corresponding literature review, Section 4 categorizes the research objectives, Section 5 reviews the research objectives, and Section 6 discusses and analyzes the previous literature review and provides suggestions for future research.

2 Research methodology

To provide a scientific, quantitative, and conclusively reliable review and analysis of the literature related to vehicle speed guidance, this paper follows the review paper writing criteria described by Kitchenham and Charters (2007) and Boland et al. (2020).

The language of the literature collection was limited to English, and the literature sources included Web of Science and Engineering village. The search was conducted in November, 2022. Therefore, the literature retrieved in this paper includes research conducted prior to 2022. To ensure relevance of the retrieval results, abstracts, titles, and keywords were limited to "speed management", "speed advisory", "speed recommendation", "speed assistance", "speed assistant", "speed harmony", and "speed guidance". After screening, 88 papers were identified for review.

Based on previous studies, the literature on vehicle speed control strategies can be visualized using VOSviewer metric visualization analysis, as shown in Fig. 2. An author co-occurrence network was drawn for the English literature in the retrieval library, where a node represents an author, and the size of the node represents the number of papers published by that author. Links between nodes indicate collaboration; therefore, a larger link width indicates closer collaboration.

3 Types of vehicles for speed guidance

Based on a summary analysis of the existing literature, in the urban road environment, the problem of vehicle speed guidance is often expanded for different models. For example, the frequent start and stop of buses will make it difficult for the speed guidance strategy of cars to be applied to buses. At present, the speed guidance of vehicles in urban road environments is mainly targeted at cars and buses. Therefore, this section reviews the literature on speed guidance for these two models.

3.1 Car

The weight of a car is generally lighter, its power is strong, and the number of cars is large. Research on car-speed guidance began earlier. Ahn et al. (2002) judged the driving of cars by calculating the cross-port driving time. Whether the speed of the vehicle must be changed, the transmission time is the parameter, and the cross-sectional speed guidance model is established with the goal of minimizing fuel consumption. Kamal et al. (2013) used the model prediction method (MPC) to detect whether there are vehicles and considered the state of the signal light at the intersection to adjust the vehicle speed to improve the fuel economy of the car and used a simulation test to prove it. Under certain conditions, fuel consumption was reduced compared with actual driving. Yang et al. (2016) proposed a collaborative adaptive cruise control system for addressing the cross-port queuing problem. When the penetration rate of a car with vehicle equipment was 100%, the overall fuel consumption could be reduced by 40%. Zhang and Yao (2015) combined vehicle status information and cross-port road information, built a car ecological driving model, and proved the effect of emission reduction of the model through examples. De Nunzio et al. (2013) studied an intelligent eco-driving model to guide small cars to reach intersections at green lights with a faster computational speed than traditional dynamic planning algorithms. However, the abovementioned research scenarios for guiding the speed of a small car are relatively simple, and none of them consider the influence of other vehicles. Therefore, on the basis of this, Amirgholy et al. (2020) studied optimal traffic control at smart intersections and developed a stochastic traffic analysis model so that the headway time spacing between vehicles lined up at the intersection could meet the smooth crossing of the convoy in the conflicting direction. Although this method considers the influence of other vehicles, its practical value needs to be further improved because it only has a single target. Sun et al. (2022) also

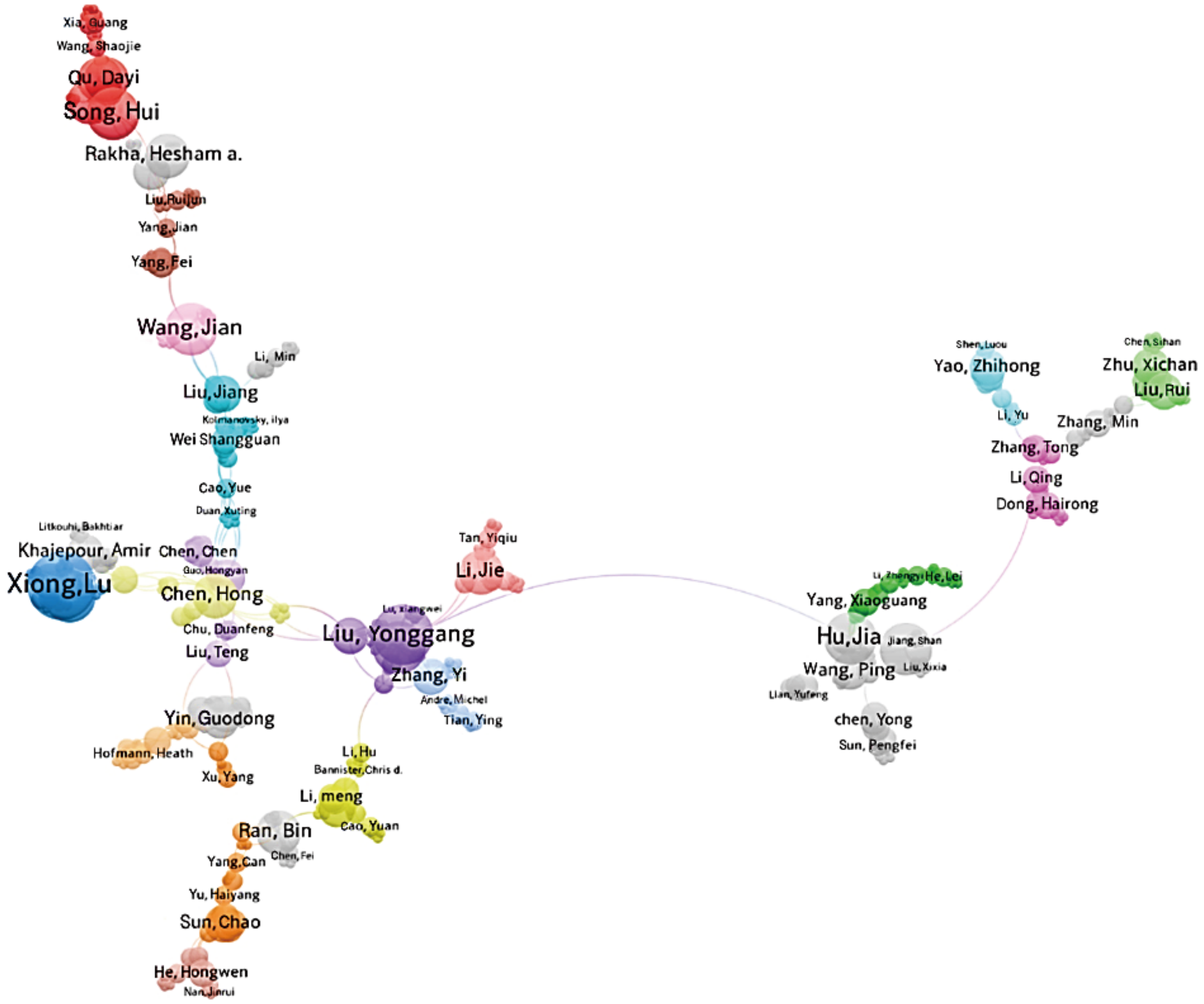

Fig. 2 Co-occurrence network of vehicle speed control strategy research authors.

designed an eco-driving algorithm based on telematics technology. The results showed that the algorithm can improve the capacity and travel speed at intersections, in addition to saving fuel.

3.2 Bus

As a significant component of urban transportation systems, most countries have prioritized the development of public transportation to reduce traffic pollutant emissions owing to its high capacity, environmental protection, and energy-saving characteristics. To continuously improve the attractiveness of buses and the share of public transportation in residents' trips, operation departments are constantly optimizing the operating environment and improving the quality of bus services. Among them, speed guidance of public transportation is an important technical tool, and a series of studies have been conducted by researchers on speed guidance of public transportation.

Furth and Muller (2000) demonstrated that the delay variation with the bus guidance model was much smaller than that without bus guidance model by comparing the delay variations with and without bus guidance control. Abu-Lebdeh (2002) proposed a dynamic intersection signal timing algorithm based on adjustable intersection signal timing by varying the bus travel speed, and they proved the viability of the algorithm. The model applies to buses with a dedicated right-of-way and does not consider queuing vehicles. In contrast, Girianna and Benekohal (2004) considered the case of saturated intersections and added a genetic algorithm to the intersection area cooperative guidance control model to improve the model. Head et al. (2006) used a project management-related theory to consider the problem of multiple bus arrival priorities, proposed a priority control model, and demonstrated that the model outperformed the first-come-first-served guidance model in terms of reducing vehicle delays. Daganzo and Pilachowski (2011) designed a coordinated bus control strategy based on adaptive cruise control, which can balance the headway and improve the average speed. Thus far, speed guidance for buses has primarily focused on reducing delays. To improve the quality and attractiveness of buses further, the comfort and stability of buses during operation have become the focus of scholarly attention. Based on the analysis of bus trajectory data, Zhang et al. (2019) realized a balanced distribution of bus head time distance and improved the reliability of bus operations. Hao et al. (2020) developed a dynamic control method that not only improved the punctuality of public transportation but also minimized the impact on private cars. Deng et al. (2020) established a dynamic speed control model that can realize the real-time regulation of vehicles under different road infrastructure configurations and congestion conditions. Xue et al. (2022) proposed a single-line real-time control strategy that increased the stability of bus operation by controlling the speed, parking time, and load rate of buses.

3.3 Others

The speed guidance problem for vehicles has basically been developed with small cars and public transit vehicles as the research objects; however, there are few studies on heavy trucks. For example, Mahmud (2014) evaluated the impact of freight signal priority control models on intersections using the VISSIM software, and the simulation analysis showed that extending the green light time can reduce overall road traffic delays and stops.

4 Research scene of vehicle speed guidance problem

In an urban road environment, owing to the existence of an intersection, the traffic flow will form an intermittent current and frequently start and stop, resulting in traffic problems that are particularly serious at intersections. Therefore, intersections are an important breakthrough for easing traffic problems. Among them, research on the speed guidance of vehicles is a popular issue. Research from a single cross-port to multiple cross-port trunk lines has achieved certain results.

4.1 Vehicle speed guidance at a single intersection

At intersections, as nodes of the road network, the problems of traffic congestion and environmental pollution are particularly serious, as vehicles are in a “stop and go” traffic operation mode due to the periodic disturbance of signals. This results in reduced intersection throughput efficiency and increased vehicle delays, fuel consumption, and pollutant emissions. Controlling the speed of vehicles in advance in a certain area before an intersection enables them to cross the intersection smoothly. Fig. 3 is a schematic diagram of vehicle speed guidance at a single intersection.

With the maturity of vehicle-road cooperation, the intersection control mode will change in the direction of intelligence and refinement and realize the change from traffic flow control to vehicle control. Regarding this trend, scholars concerned with the intersection vehicle speed control problem have conducted research and successively put forward intersection vehicle operation control strategies based on gap theory, signal reservation, and green wave optimization, which is based on speed guidance so that the vehicle can ensure traffic safety, efficiency, and speed through the intersection.

Several studies have been conducted to address the vehicle speed guidance problem at intersections. Asadi and Vahidi (2011) predicted the speed trajectory of a vehicle, allowing the vehicle to reach an intersection in time for the green period, while avoiding deceleration as much as possible and maintaining a safe distance to cruise at the predicted speed range. However, the forecast results are vulnerable to changes in the traffic environment. Rakha and Kamalanathsharma (2011) proposed environmentally friendly driving using signal cross ports with V2I communication. Although they considered combining motor vehicle emissions with signal cross-port control, they only used simple space-time relationships as a target function to obtain the corresponding speed value of optimal motor vehicle emissions. The function does not create detailed control strategies at the same time, so the speed value obtained is not the best possible. Yang et al. (2016) proposed a flat cross-port vehicle control model in response to the mixing of intelligent and non-intelligent connected vehicles, inspired by signal control strategy switching based on different vehicle types. The algorithm plans the optimal driving trajectory of the vehicle to minimize delays. Zhou et al. (2017) developed a targeted heuristic optimization theoretical model that can be solved efficiently while finding intersections under fixed signal timing conditions, with minimum delay and safety risk as the optimization objectives of the vehicle optimal speed trajectory scheme under fixed signal timing conditions. However, the optimization-related indicators are not obvious when the signal timing of fixed intersections remains unchanged. Odekunle et al. (2018) considered the vehicles in front and behind as a vehicle queue and used information from traffic signals to minimize the idle time of the vehicle queue. An optimal state feedback controller was developed without any prior knowledge to regulate the speed, acceleration, and headway time distance of each vehicle

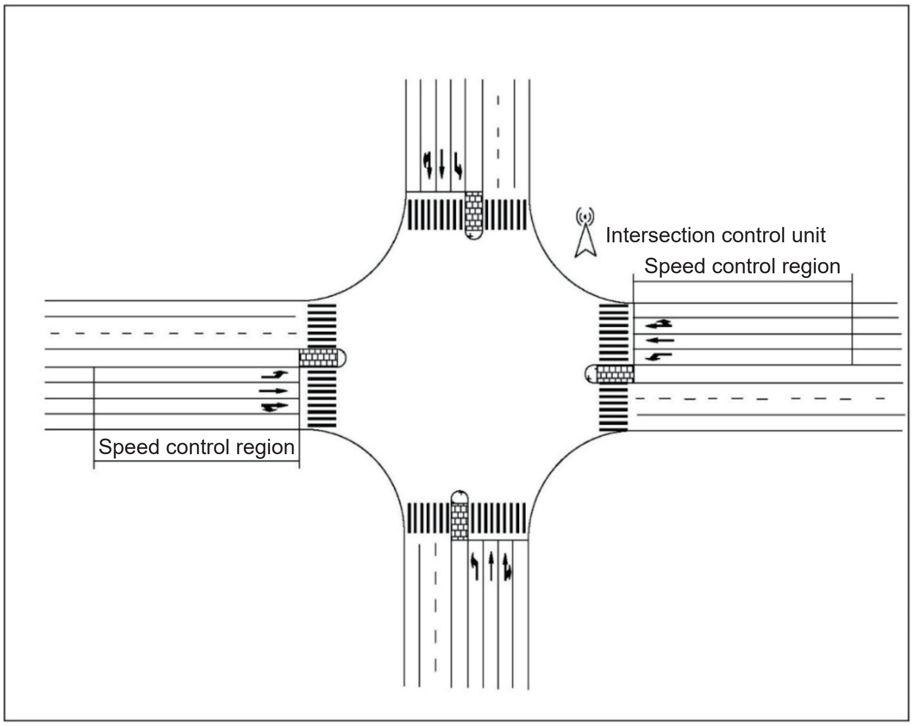

Fig. 3 Schematic of intelligent intersection control system architecture.

in the vehicle queue.

However, the implementation of speed guidance alone cannot control vehicles effectively; therefore, researchers have considered signal intersection signal control and approaching vehicles to guide the speed of synergistic control to further improve the control effect of the vehicle.

Guler et al. (2014) chose a simplified two-way intersection as the target scene, evaluated an intersection traffic control algorithm involving vehicle formation in an intelligent and connected environment, and realized the coordinated control of vehicle trajectory and traffic signals. Li et al. (2014) designed a simplified collaborative control algorithm for vehicle speed and traffic signals, including fixed acceleration and deceleration parameters and macro-traffic characteristics, which was solved by a simple enumeration method. However, it could only deal with relatively simple scenes, and fixed acceleration and deceleration speeds and macroscopic traffic characteristics are of little practical significance. Therefore, these models are not suitable for more complex problems.

Extensive research has been conducted to adapt to more complex vehicle speed guidance scenarios. Feng et al. (2018) used the speed trajectory of intelligent network vehicles as control variables when matching with traffic signals and used the average delay and fuel emissions as the control target to build a dual-layer model. To optimize the signal with minimum delay, the upper layer was optimized in the lower layer to consider the vehicle trajectory with the lowest fuel emissions. Yu et al. (2018) further proposed a collaborative optimization model for traffic signals and vehicle trajectories based on mixed-integer linear programming, assuming 100% occupancy of networked autonomous vehicles, and traffic details, such as left turn, straight ahead, right turn, and turnaround, were analyzed and considered. With the objective of minimizing the average delay, the signal timing, lane change behavior, and arrival time are collaboratively optimized; however, 100% automated vehicle environments are still far away. Niroumand et al. (2020) designed a model predictive control approach based on a linear vehicle-following model to collaboratively optimize the vehicle trajectory and traffic control signals, and the solution was obtained by dividing vehicle groupings to reduce the problem dimensionality and decomposing the vehicle trajectory and traffic control signal coupling to approximate the solution and improve the solution speed. Jiang et al. (2022) combined traffic signal control with vehicle trajectory to build an integrated control framework that was optimized and micro-controlled for vehicles at signal intersections to reduce fuel consumption and improve sustainability.

4.2 Main line speed guidance

The vehicle speed guidance problem for a single intersection has achieved certain research results, but in the actual operating environment of a vehicle, it will pass through several intersections continuously; therefore, research on multiple arterial intersections can further fit the real operating environment. Compared with the vehicle speed guidance problem of a single intersection, the arterial vehicle speed guidance problem is much more complicated, and it is an organic combination of multiple intersections, as shown in Fig. 4. For the speed guidance problem of multiple arterial intersections, the green wave control strategy is widely used, and the goal of this strategy is to maximize the green wave bandwidth (Zheng and Xu, 2011). However, there are many restrictions for applying this strategy; for example, the spacing of adjacent intersections should be approximately equal, the speeds of vehicles traveling in both directions should be close or proportional, and the signal cycle lengths of all signalized intersections must be equal. These requirements make it difficult to apply green wave control strategies on a large scale in practical traffic organization (Ye et al., 2014). With the continuous development of vehicle networking technologies, a more convenient and effective traffic control method is for vehicles to make timely speed adjustments based on this information to cross intersections during green lights.

Yang et al. (2010) used a suburban arterial road as a research object and constructed a vehicle speed guidance strategy by considering the vehicle position, signal control state, vehicle acceleration and deceleration time, and driver acceptance. Unlike suburban roads, urban roads tend to have more complex traffic organization and higher traffic volumes. Chen et al. (2011) guided the speed through a roadside variable information board. The signal control method was combined with dynamic vehicle speed guidance and dynamic signal control, which were used for coordinated control between the multi-cross ports of the trunk. The results showed that there is an obvious improvement in parking time. Based on the signal phase information of the

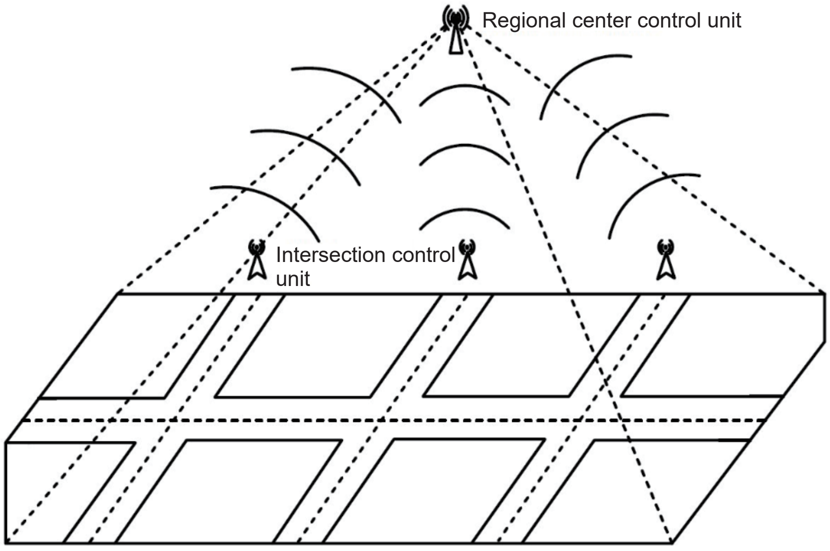

Fig. 4 Schematic of speed adjustment structure of trunk road.

downstream cross-intersection, Xia et al. (2013) considered energy consumption and emissions, designed a speed planning algorithm for the cross-section of the signal, and ensured driving comfort by selecting an appropriate speed and acceleration set. The speed-guided problem of vehicles is difficult to solve, and for this reason, Yang et al. (2021) developed a system that can calculate the optimal ecological speed of a vehicle to reduce the increase of vehicle fuel consumption level caused by frequent stopping at signalized intersections of urban arteries system with low computational complexity. Wang et al. (2022) designed a two-stage model to optimize vehicle trajectories based on traffic signal plans at downstream intersections and the trajectory information of surrounding vehicles to minimize vehicle delays and lane-change costs in an environment where self-driving vehicles coexist with non-autonomous vehicles.

5 Significance of speed guidance

Speed guidance for vehicles is of great practical importance, which is why many researchers have conducted studies on this topic. The negative effects of intersections in the urban road environment can be effectively avoided by guiding the vehicle speed, which has been well documented in existing studies. Therefore, this section presents a literature review of the existing research in terms of the significance of vehicle speed guidance in eco-driving, reducing delays, and ensuring driving safety.

5.1 Eco-driving

As a strategic resource, oil plays a significant role in human industrial growth and is rapidly being depleted as human oil consumption continues to grow. Meanwhile, motor vehicles are an essential source of pollutant emissions, and in recent years, motor vehicle ownership has been increasing every year worldwide, and its pollutants cause significant harm to the environment and the human body (Sciarretta et al., 2015). Significant research has been conducted on how to reduce the pollution emissions from vehicles.

Sivak and Schoettle (2012) defined eco-driving as the choices that drivers can make that affect vehicle fuel consumption based on both the choice of vehicle and post-purchase driving behavior. By analyzing the existing literature, the factors influencing eco-driving can be classified as follows:

1) Driving speed

Chang and Morlok (2005) and Lee and Son (2011) concluded that driving a vehicle at a constant speed under various road conditions ensures maximum ecological driving and reduces energy consumption. Accordingly, many subsequent studies have verified the optimal eco-driving speed under various road conditions, as summarized in Table 1.

2) Vehicle acceleration and deceleration

In reality, it is difficult to ensure that vehicles run at a constant speed, and a constant change in the traffic environment leads to the continuous start and stop of vehicles. Some research has been conducted to study the influence of vehicle start-stop on eco-driving.

Ericsson (2001) analyzed the effects of 16 driving factors on fuel consumption and found that nine factors played a significant role, four of which were related to acceleration, three to gear changes, and two to driving speed. Similarly, Wang et al. (2011) showed that frequent vehicle acceleration, especially sharp acceleration, increases bus emissions. To reduce the impact of acceleration and deceleration on eco-driving, Sun and Liu (2015) proposed a speed-smoothing method for eco-driving to avoid temporary stops and unnecessary acceleration and deceleration at intersections.

3) Other factors

In addition to the significant impacts of driving speed and frequent acceleration and deceleration on ecological driving, factors such as vehicle idle speed (Ashrafur, 2013) and path selection (Ahn and Rakha, 2013) also exist. Because this review focuses on vehicle speed control strategies, other factors will not be explained in detail.

To reduce the pollution emission of vehicles and to achieve as ecological driving as possible, reducing the frequent start-stop of vehicles is a hot research topic. Because intersections, as road nodes, lead to frequent acceleration, deceleration, and start-stop of vehicles, the problem of vehicle speed guidance at intersections has practical application value.

Servin et al. (2006) found that the application of a vehicle speed guidance system reduced fuel consumption by approximately 35%, while the average increase in travel time was approximately 7.7%. Subsequently, scholars have studied speed guidance in terms of fuel economy. Kamal et al. (2013) proposed that coasting deceleration could save fuel and verified the results through simulation tests. Subsequent research has also been extended to the intelligent decision-making layer of self-driving vehicles. Ahn et al. (2013) combined the Eco-Cruise Control (ECC) algorithm with a follow-the-leader model, which showed a 27% reduction in fuel consumption. Jiménez and Cabrera-Montiel (2014) developed a set of speed prompt systems, analyzed actual traffic conditions, obtained the best driving speed curve, and provided speed recommendations for drivers to achieve fuel savings.

Most of the aforementioned vehicle speed control models have been studied in the context of 100% networked autonomous vehicles; however, this is impractical. Wang et al. (2014) proposed a model to achieve precise vehicle control to optimize the speed trajectory, thereby achieving energy conservation and emission reduction. Kamal et al. (2015) proposed that driving a vehicle and a combination of autonomous vehicles would become an important transitional stage. They proposed an ecological driving vehicle control system for this transportation environment. The system measures the front of the car and cross-port information ahead of the vehicle sensor, determines the optimal speed according to traffic light information, predicts the behavior of the vehicle in front, and dynamically adjusts the speed under the

Table 1 Studies on suggested speed of ecological driving

Ref.	Conclusion
El-Shawarby et al. (2005)	The best fuel economy speed per unit is 60–90 km/h.
Wang et al. (2008)	The best fuel economy speed per unit is 50–70 km/h.
EEA (2011)	Reducing the highway speed limit from 120 to 110 km/h would lead to a significant reduction in fuel consumption of 12% for diesel vehicles and 18% for gasoline vehicles.
Wang and Rakha (2016)	The best speed for diesel buses is 40–50 km/h, and 60–80 km/h for light gasoline vehicles.
USDoE (2018)	When the speed exceeds 80 km/h, the fuel quantity increases rapidly.

constraints of the front vehicle and red light signals. The experimental results show that the eco-driving system has obviously improved fuel economy and traffic efficiency, and the existence of eco-driving vehicles has also improved the performance of human-driven vehicles. Bakibillah et al. (2020) used the driving data of a vehicle with a Gaussian regression model to achieve the effect of saving fuel. However, the solution to this model is complex. Therefore, Yang et al. (2021) proposed an eco-driving system that calculates the best energy-consuming vehicle trajectory when crossing multiple signal cross-sections and does not increase the complexity of the calculation.

5.2 Reduced delay

Over the past few decades, rapid population growth and increased vehicle ownership have led to traffic congestion. By 2030, traffic congestion is expected to increase by 60% (Rafter et al., 2017). Since the 1950s, relieving traffic congestion and reducing traffic delays have always been a topic that researchers have paid attention to. Currently, car–road collaboration systems have become a research hotspot for intelligent transportation. By facilitating information interaction and sharing between cars, we can achieve intelligent collaboration and cooperation between vehicles and road infrastructure. This collaboration aims to optimize and utilize system resources in order to improve road traffic safety and alleviate traffic congestion.

Studies have shown that intersections play a key role in delays (Bashiri and Fleming, 2017); therefore, reducing vehicle delays at intersections has become an important research topic, where the speed guidance of vehicles is a key direction.

Chen and Abu-Lebdeh (2006) developed a vehicle speed dynamic control system in a vehicle-road cooperative environment, which is capable of obtaining near-optimal speeds based on real-time data through an optimization algorithm of vehicle space–time relationships and signal timing, subsequently guiding drivers to make the best speed choice. This study significantly reduced the number of delays and stops, speed disturbances, and accident rate. Subsequently, Chen et al. (2011) designed an intersection management strategy using a combination of dynamic vehicle speed induction and signal timing. Based on a suitable speed derived from the relationship between the spatiotemporal and signal timing of vehicle trajectories, this strategy optimizes the green light duration and reduces vehicle delays through signal compensation based on the arrival time of vehicles. Although the signal timing is optimized, the speed obtained is not an optimal solution and thus cannot provide drivers with the optimal driving speed.

In addition to considering the reduction of intersection delays, other metrics were considered for optimization while reducing delays. Müller et al. (2016) proposed a centralized mixed-integer programming model, an algorithm that decomposes the intersection control problem into two parts: vehicle arrival sequence and vehicle trajectory optimization. The control objective of the first part is delay minimization and that of the second part is tailpipe emission and energy consumption minimization. The constraints of the method are first-come-first-served and minimum headway time distance. Feng et al. (2018) developed a spatiotemporal optimal traffic control model that optimizes signal and vehicle trajectories using dynamic and nonlinear programming modeling with the objectives of minimum delay, fuel consumption, and exhaust emissions at 100% permeability. Liu et al. (2022) designed an intersection controller that can send reference trajectories to vehicles in real time to minimize traffic delays and improve intersection capacity.

5.3 Ensured driving safety

Vehicle speed guidance can effectively reduce pollutant emissions and vehicle delays. In addition, safety, an essential consideration when driving a vehicle, is one of the most important concerns for every driver. Failure to drive a vehicle at a reasonable speed is an important factor in traffic accidents, and studies have shown that speed is a cause of fatal traffic accidents in almost all countries. Therefore, to minimize traffic accidents caused by improper vehicle speed, researchers in the field of transportation have conducted significant research on reducing traffic accidents and ensuring traffic safety by coordinating vehicle speed, and the research has achieved certain results.

Gallen et al. (2013) proposed a safe speed profile calculation method for an intelligent speed adaptation system that first uses the 85-th percentile of observed speed as a reference speed under ideal conditions, followed by further adjustment of the speed under adverse weather conditions, thus reducing the risk of traffic accidents. With the increasing computational communication and sensing capabilities of modern vehicles, a basis for more sophisticated speed guidance has become available. Galanis et al. (2019) proposed a framework through their study that combines on-board sensors and data to predict real-time vehicle status. V2X communication is used to collect weather data, route structure information, and onboard diagnostic data to better understand the surrounding environment to which the vehicle should adapt, estimate the weather conditions for a specific route through a trained classification tree, and perform road index calculations based on the road state to prevent rollover owing to improper vehicle speed. This is because of the importance of safety and the influence of environmental factors on the driver’s choice of appropriate speed. De Mello and Chiodi (2018) proposed a fuzzy logic model for road speed limit recommendations. In this study, the main safety factors were investigated using the Delphi method and further classified using soft decision trees. Their results showed that the proposed model can reduce the possibility of vehicle rollover. However, the Delphi method was used to analyze the main factors, lacking objectivity. Park and Oh (2019) proposed a speed control strategy to minimize the risk of vehicle collisions in an autonomous driving environment. The algorithm was simulated using VISSIM, which proved the effectiveness of the algorithm in ensuring vehicle safety. However, currently, the study of vehicle safety in a combination of autonomous and nonautonomous driving environments is more practical.

5.4 Others

Most of the current problems of guiding vehicle speed in urban road environments are aimed at energy saving, reducing delays, and ensuring safe vehicle operation; however, a small amount of research has also been conducted in other areas, such as guiding vehicle speed, thus improving passenger comfort (Olivares-Mendez et al., 2016).

6 Methods of speed guidance research

The vehicle speed guidance problem is a complex mathematical application problem based on the complexity of traffic networks, vehicle kinematics principles, vehicle engineering, and related knowledge from other disciplines. It considers the integration of vehicles with the traffic environment, uses technical means to obtain basic data with the goal of ecological driving, improves the efficiency of vehicle operation, and ensures driving safety, among others, to guide the driving speed of a wide variety of vehicles. By analyzing existing research, research methods for vehicle speed guidance problems can be roughly divided into two categories: traditional and machine learning-based.

6.1 Traditional methods

In the era when communication technology was not yet developed, the speed guidance problem for vehicles was mainly based on mathematical models to divide complex scenarios into simple ones due to inaccessibility of data. Barth et al. (2011) established a vehicle speed planning method with trigonometric functions, which was verified by simulations and proved to be effective in improving fuel efficiency and reducing tailpipe emissions. However, this method considers a simple environment, only a single vehicle, and not a complex vehicle-operating environment. Based on this, Ahn et al. (2013) combined the ecological cruise control algorithm with a corresponding model, and the final validation showed that the algorithm can reduce fuel consumption by 27%, and the vehicle speed control strategy considering the influence of front and rear vehicles has better practical application value than the previous simple model.

With the development of communication technology, vehicle technology, etc., vehicles in an intelligent networked environment can obtain real-time information, such as intersection signals and the operation status of surrounding vehicles, which brings new opportunities for the study of vehicle speed guidance problems. Rakha and Kamalanathsharma (2011) developed a speed guidance system that uses V2I technology to obtain real-time traffic information, based on which a linear computational approach was combined with an energy consumption evaluation to provide drivers with speed recommendations. Yao and Li (2020) also considered vehicle delays, fuel consumption, and safety risks; developed a discrete bounded nonlinear model to plan CAV trajectories; and approximated the solution using a split-rectangle approach. However, vehicle speed guidance based on a net-linked environment defaults the penetration of self-driving vehicles to 100%. In the next few years, there will still be a mix of self-driving and non-self-driving vehicles; therefore, defaulting the penetration of self-driving vehicles to 100% does not have practical application value.

6.2 Machine learning methods

The application of machine learning in the field of transportation has become popular as artificial intelligence technologies continue to mature (Li and Ma, 2023). There are also relevant applications in vehicle speed guidance. Asadi and Vahidi (2011) used traffic signal information to predict the speed trajectory of a vehicle, which enabled the vehicle to reach the intersection at the green light time period to avoid slowing down as much as possible while maintaining a safe distance between vehicles to cruise at the predicted speed range. Bakibillah et al. (2020) developed an eco-driving learning scheme that does not require the use of communication technologies, such as V2I and V2V, and developed a Gaussian process regression model that predicts the time and probability of crossing an intersection from the vehicle's driving data. They then calculated the optimal speed profile through a fuel optimization algorithm, which improved the fuel economy.

All the above vehicle speed guidance problems use machine learning algorithms to predict the state of a factor in the traffic environment, and such prediction results are difficult to apply in practice because of the stochastic nature of traffic state and susceptibility to environmental influences. Machine learning plays an important role in other aspects in addition to predicting traffic states, with the goal of improving mixed traffic flow intersection capacity and reducing vehicle delays. Guo and Ma (2021) proposed a two-stage learning and control framework for intersection signal timing and CAV trajectories that integrates sensing, prediction, planning, and optimization modules. The framework applies a long short-term memory network to implicitly learn traffic patterns and driver behaviors to predict microscopic traffic conditions. Using the number of arriving vehicles, vehicle speed, and vehicle type as inputs, deep reinforcement learning was used to optimize the phased green light duration. Finally, based on the signal timing results, the optimal CAV speed profile was solved using the TP3 algorithm to maximize the utilization of green light time. The model solving time was approximately 0.04 s, with real-time control potential.

There are also in-depth applications of machine learning algorithms for solving speed guidance models. Wang et al. (2023) used reinforcement learning to develop a general optimal control problem solver for autonomous driving and industrial control applications that can handle complex vehicle speed guidance problems well.

7 Conclusions

With the continuous expansion of urbanization, the urban population is increasing, and with it, traffic demand is growing rapidly; however, it is still difficult to meet the increase in demand through the development of road resources. Consequently, a series of traffic problems, such as traffic congestion and pollution, have emerged in cities. It is difficult to solve the above problems using a pure traffic supply; therefore, another approach is technical management, among which, the speed guidance of vehicles is a means to alleviate urban traffic problems that are maturing in the development of emerging technologies. There have been some studies on the guidance of vehicle speed in urban road environments, but the shortcoming is that there are few literature reviews of existing studies, and the existing reviews are one-sided and poorly guided for future research. Therefore, this paper summarized the overall research on the vehicle speed guidance problem and provides suggestions for future in-depth research.

7.1 Shortcomings of existing research

A search and generalized analysis of existing research on the vehicle speed guidance problem led to the following conclusions:

1) The existing research on vehicle speed guidance is dominated by small cars, and the research on other vehicles is insufficient. Small cars cannot represent other models, and the research for small cars is not applicable to other models. For example, for buses, as the main force of the urban road passenger transportation system, due to the existence of bus stops, they must constantly start and stop, and the level of passenger flow at bus stops has also become an important factor limiting the bus scheduling program and planning of the operating trajectory. Moreover, the location of bus stops will also have an impact on the speed guidance strategy of the vehicle. For buses at an intersection before no bus stops, the object of study can be analogous to a small car, but when there is a bus stop, it is no longer applicable. In today's vigorous promotion of bus priority, research on buses needs to be further enhanced to improve the quality of bus services. With the continuous development of the

urban logistics industry, the number of heavy trucks in cities has increased gradually. The pollutants released by heavy trucks during start-stop are much larger than those of small cars, the braking distance of heavy trucks is longer, and the delineation of speed coordination areas will also create new problems. However, current speed guidance for heavy trucks in urban road environments is lacking. In addition, there is insufficient research on speed guidance strategies for mixed traffic of different vehicles.

2) Most existing speed guidance for vehicles uses a single intersection as the research scenario and performs a more ideal environment treatment, lacking the consideration of multi-lane and multi-flow traffic flow, such as left-turning vehicles, right-turning vehicles, and the number of vehicles in line before arriving at the intersection will have a practical impact on the vehicle speed guidance problem at an intersection. Moreover, there is a lack of analysis of the oscillation caused by forced speed changes, which is indispensable in the speed guidance problem at intersections and requires further improvement. With the continuous development of IoT, vehicle-road cooperation, and other technologies, the collaborative optimization of vehicle speed guidance and intersection signal timing has become possible; however, most existing studies have focused on the collaborative optimization of individual directions. Research on vehicle speed guidance of trunk lines is insufficient, and existing research considers the ideal environment, regardless of whether vehicles change lanes or the interactions between vehicles. In addition, the current collaborative control algorithms for vehicle speed and traffic signals are all collaborative control models that consider independent intersections, which are difficult to extend to regional traffic environments, such as main roads and adjacent intersections.

3) Current vehicle speed control strategies are most often targeted at energy saving and emission reduction, followed by the consideration of vehicle delays at intersections and the safety of vehicle operation, in addition to a small number of studies targeting passenger comfort. A few studies have focused on both eco-driving and intersection delay minimization; however, most of the literature still focuses on one goal. The existing consideration of eco-driving focuses on traditional non-renewable resources and lags behind the current era of rapid development of new energy vehicles. The speed guidance model for studying vehicle delays is still essentially based on multiple intersections and signals in a single or arterial route. In a complex road traffic network, it is difficult to change the operating conditions of a large-scale traffic system by changing only a few nodes and vehicles; for example, the effect of reducing vehicle delays is minimal when viewed in the system.

4) Machine and reinforcement learning are widely used in the field of transportation; however, their applications in vehicle speed guidance are unsatisfactory. For example, machine learning is often used in one aspect of vehicle speed guidance, such as the number of vehicles in the queue ahead, size of the passenger flow at bus stops, and other key factors affecting vehicle running time; however, applications in other aspects are relatively lacking. Reinforcement learning has also been well researched in areas such as area signal coordination control; however, its application to vehicle speed guidance problems is rare and requires further study.

7.2 Future research directions

As a technical means that accompanies the continuous development of frontier technology, research on vehicle speed guidance is also in-depth; however, there are still shortcomings. Based on the previous brief analysis, the following suggestions are provided for research on vehicle speed guidance:

1) Current vehicle speed guidance research on small cars, or all vehicles on the road as small cars, is a simplistic treatment of the research object and is extremely unreasonable. The interaction between different types of vehicles, as well as the characteristics of the vehicle itself, will be ignored, which means the theoretical research basis is difficult to apply in actual environments. Based on this, vehicle speed control strategy research in the case of mixed traffic with multiple vehicles should be considered, and targeted research should be conducted for special vehicles. For example, vehicle speed guidance when there is and is not a bus lane have very different research environments; for example, the number of large trucks in the traffic flow will also have an impact on the speed guidance problem.

2) In an urban road environment, speed guidance for vehicles is mainly focused on a single intersection, and the considered environment is more idealized, which should be further integrated with the actual complex environment in future research. For example, the speed coordination between different flow directions of each inlet lane of the intersection requires avoiding vehicle collisions at the conflict point, and the original problem will increase in terms of research objectives and constraints, which greatly increases the complexity of modeling. In addition, current technology should be fully utilized to collaboratively control vehicle speed with intersection signals to further improve intersection capacity. The speed guidance problem for urban arterial vehicles should consider the influence of each intersection on speed guidance and also the influence of the front and rear vehicles, integrating the following behavior of vehicles in the arterial speed guidance.

3) The rapid development of vehicle communication technology and control technology has made vehicles more intelligent; therefore, with the convenience of information access and continuous improvement of information processing technology, in the speed guidance of vehicles, the goal should be further expanded, rather than sticking to ecological driving, reducing delays, ensuring safe driving, etc. Multi-objective research is the future development trend, as far as possible in terms of energy saving and emission reduction at the same time to achieve the reduction of vehicle delay and fully ensure the safety of vehicle driving, followed by the best consideration of passenger travel experience and improvement of passenger comfort. On urban roads, vehicle speed guidance can also be applied to vehicle coordination at unlit intersections.

4) In addition, through a summary of the existing literature, it is easy to see that most of the existing research establishes a mathematical model for a certain situation, designs the corresponding solution algorithm to solve it, and obtains a speed to guide the vehicle operation, some of which use common simulation software for simulation; however, the evaluation of the research results is insufficient to fully illustrate the actual operation effect of the model. Therefore, the evaluation system of the vehicle speed guidance model should be further established and improved so that the speed guidance strategy can be evaluated to fully prove the effectiveness of the model.

5) Machine learning, reinforcement learning, etc. in vehicle speed guidance are rarely applied, and their depth is not sufficient. In addition, in the simple prediction, with the continuous penetration of the networked automatic driving environment, the research direction should be close to reinforcement learning for traffic signal area coordination control, based on the consideration

of the vehicle operation state, from the perspectives of intersection, arterial, regional coordination control vehicle operation speed, and optimization of the transportation system.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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