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Research on Route Optimization for Electric Vehicles Leveraging 5G-Enabled Vehicular Networks

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Abstract. With the deep deployment of 5G in intelligent transportation, 5G Internet of Vehicles (IoV) has become an important carrier for vehicle-road collaboration, smart mobility and intelligent transportation development. Taking into account the differentiated travel behaviors of electric vehicles, the incomplete spatiotemporal traffic parameters and the limited collaborative perception and decision-making, this paper presents a systematic 5G-IoV traffic model for complex urban scenarios. Electric vehicles are classified as taxis, commuter private cars, and other functional vehicles based on global traffic statistics and industry norms, excluding pure electric busses with fixed charging patterns. In this study, the parameters of vehicle state and multi-type travel chains are defined by mathematical models, including normal distributions to describe the patterns of vehicle departure and return for different travel chains. The 5G-IoV model integrates 5G-V2X vehicle-road collaboration, smart mobility, and digital automotive supply chain management, and integrates with vehicle-road-cloud to support comprehensive modeling of vehicle perception, information interaction, traffic scheduling, and operation and maintenance. The results show that the model can effectively reflect the differentiated spatiotemporal travel characteristics, and is helpful for traffic simulation and collaborative scheduling. Major challenges include security and privacy risks, technical incompatibility, lack of infrastructure and immature business models.

Keywords: Electric Vehicles, Internet of Vehicles, Travel-chain Structure, 5G

1. Introduction

With the rapid development of 5G communication and artificial intelligence, the Internet of Vehicles (IoV) is evolving from single-vehicle intelligence to intelligent, connected and cooperative systems. The deep integration of 5G-V2X, edge computing and AIoT technologies has become an important driving force in the transformation of the automotive and transportation industries [1]. Smart sensing and high-precision positioning are the foundation for connected autonomous vehicles, while vehicle-to-everything (V2X) communication allows vehicles to exchange information in real-time with the infrastructure, other vehicles, pedestrians, and networks, which can greatly improve the safety and efficiency of traffic [2, 3]. Moreover, the "vehicle-road-cloud integration" framework supports novel applications such as intelligent transportation and supply chain management. However, there are still critical challenges in security and privacy, technology standardization and infrastructure

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construction for large-scale deployment. This paper reviews the key technologies, applications and challenges of 5G-enabled IoV, and is expected to provide a useful reference for future research and industrial development.The CAV penetration rate is the percentage of vehicles on the road that have both connectivity and autonomous driving capabilities and can therefore participate in vehicle-road-cloud cooperative control (e.g., receiving signal phase and timing information, adjusting speed in an optimal manner, and coordinating movements at intersections).

2. 5G- IoV Situation

2.1. Electric vehicle classification

Based on the application status of electric vehicles in China, this paper classifies electric vehicles into three categories according to travel characteristics [4]:

A. Taxis: Generally operated by multiple drivers. They have many short parking durations and urgent charging needs during frequent travel days; travel destinations exhibit high randomness.

B. Commuter private cars: Daily travel between residential and workplace locations. Long-duration parking has sufficient charging time, and destinations for travel are relatively fixed.

C. Other functional vehicles: Non-commuters private cars, business cars and light-duty commercial vehicles. They make multiple trips a day. There are time gaps in between trips. Charging time depends on trip intervals. Travel destinations are unfixed.

2.2. Trip chain structure

The trip chain structure is adopted to reflect the travel time, travel purpose, number of activities, and the order of occurrence of electric vehicle users. The length of the trip chain is the number of trips a user makes in a day, with an average of 2.5. A user may make short stops at some locations during a day's travel, e.g. dropping off children on the way to or from work. These are secondary travel purposes and the likelihood of choosing to charge at such stops is very low. The trips of commuting private cars are classified into three categories: home (trip H), work (trip W), and other (trip E) ignoring the secondary travel purposes and only taking into account the primary travel purposes. Trip E is mainly about shopping, eating out and social leisure. Trip chain structures can be divided into two modes: simple chains (H–W/E–H) and complex chains (H–E–W–H and H–W–E–H).

2.3. Initial trip departure time

For the travel chain from home to work and back to home (denoted as H-W-H, same below), according to 2016 statistics from the UK Department for Transport, the departure and return times on weekdays are fitted with a normal distribution.

$$f_{\text{Gamma}}(x;\alpha;\theta) = \begin{cases} \dfrac{\theta^{-\alpha}}{\Gamma(\alpha)} x^{\alpha-1} \exp\left(-\dfrac{x}{\theta}\right) & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{1}$$

Where μ is the expected value of the departure time t for electric vehicle trips; σ is the standard deviation; the values of μ and σ depend on the trip chain structure and the origin-destination points. Different users have different μ and σ values. In 2016, the UK Department for Transport collected statistics on the mean and standard deviation of departure and return times for H-W-H trip chains. The mean departure time μ_H-W can be fitted using a gamma distribution

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$$f_{\text{Norm}}(x;\sigma) = |\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{x^2}{2\sigma^2}\right)| \tag{2}$$

The average return time value μ W-H can be fitted using the Weibull distribution, as shown in the formula.

$$f_{\text{Weibull}}(x;k;c) = \begin{cases} \left(\frac{k}{c}\right)\left(\frac{x}{k}\right)^{k-1}\exp\left(-\left(\frac{x}{c}\right)^{k}\right) & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{3}$$

Where: k is the shape parameter; c is the scale parameter. The standard deviation σ W-H can be fitted using the normal distribution. For the travel chain H - E - H, based on the 2009 U.S. Department of Transportation statistical data, a three-parameter Weibull distribution is used to fit the starting and return times, as shown in the formula.

$$f_{\text{Weibull}}(t;k;c;\lambda) = \begin{cases} \left(\frac{k}{c}\right)\left(\frac{t-\lambda}{k}\right)^{k-1}\exp\left(-\left(\frac{t-\lambda}{c}\right)^{k}\right) & t \geq 0 \\ 0 & x < 0 \end{cases} \tag{4}$$

In the formula: λ represents the position parameter. For the travel chain H - E - W - H, the starting time of the third segment of the journey W - H is the same as the corresponding part of the simple chain H - W - H. Considering the constancy of the working hours, the distribution pattern of the starting time t E - W for the second segment of the journey E - W is the same as that of the simple chain H - W, while the starting time t H - E of the first segment of the journey H - E is constrained by the second segment of the journey E - W, as shown in the formula.

$$t_{H-E} = a_1 t_{E-W} + b_1 \tag{5}$$

In the formula: a1 and b1 are travel constraint coefficients, both of which are constants. For the travel chain H-W-E-H, the starting time of the first segment of travel H-W is the same as the corresponding part of the simple chain H-W-H. Considering the constancy of the off-duty time, the starting time tW-E of the second segment of travel W-E adopts the same distribution pattern as the simple chain W-H, while the starting time tE-H of the third segment of travel E-H is constrained by the second segment of travel W-E, as shown in the formula.

$$t_{E-H} = t_{W-E} + b_2 \tag{6}$$

In the formula: b2 is a random variable. Considering the randomness of the user's activity time in the commercial area, b2 is uniformly distributed and randomly selected.

3. Factors

3.1. Intelligent perception and high-precision positioning

Intelligent perception and high-precision positioning are the foundation of AIoT-enabled Intelligent Connected Vehicles (ICVs). The Intelligent Road-Side Units (RSUs) and Mobile Edge Computing (MEC) nodes at the critical points, such as the urban roads and highways, are used to build a wide-

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spread roadside perception network. These facilities are equipped with high definition cameras, millimeter wave radar, LiDAR and other sensors to complement onboard sensors. The higher vantage point of roadside equipment can fill in the visual blind spots of sensors on vehicles, enabling early detection of distant traffic participants and possible dangers in bad weather or complicated situations. Besides, the high-speed and low-latency transmission characteristics of 5G and C-V2X networks are used in conjunction with high-precision positioning systems such as BeiDou to achieve centimeter-level vehicle positioning. Typical application scenarios include intersection blind spot warning systems, which can monitor pedestrians crossing and vehicles merging in real time to provide early warning; in ramp merging areas, roadside perception devices acquire main road traffic flow data to provide merging vehicles with optimal gap recommendations, thus improving traffic safety.

3.2. Vehicle-to-Everything (V2X) and collaborative decision-making

The main application of AIoT in this field is Vehicle-to-Everything (V2X). Based on the interconnected network constructed by 5G-V2X, real-time information interaction is realized between Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P) and Vehicle-to-Network (V2N), which promotes the development of monolithic vehicle intelligence to systemic intelligence. In safety warning, it can realize functions such as forward collision warning, intersection collision warning and emergency brake warning. In terms of efficiency improvement, vehicle platooning can reduce wind resistance and save energy, and green wave speed guidance based on traffic signal status can reduce stopping and waiting. In the domain of cooperative control it supports advanced autonomous driving functionalities like Cooperative Adaptive Cruise Control (C-ACC) or cooperative lane change. These applications not only enrich the intelligence of individual vehicles but also improve the operational efficiency and safety of the transportation system by integrating vehicle-road-cloud collaboration.

3.3. Smart mobility and supply chain management

In smart mobility, AIoT supports the creation of Mobility as a Service (MaaS) platforms that combine different transportation modes and utilize intelligent algorithms to efficiently allocate assets and meet demand. These services include RoboTaxi dispatch planning, dynamic pricing and location optimization for car-sharing, and smart parking guidance with integrated payment. These services can increase the utilization rate of vehicles and reduce urban congestion and parking resource waste. For supply chain management, AIoT builds an end-to-end digital system: with onboard sensors and RFID technology to realize real-time monitoring and dispatching of vehicle logistics; with blockchain to build component traceability systems to ensure data immutability and traceability; and with big data analysis to predict the component demand to optimize inventory and delivery routes. This supports innovation in quality control and after-sales service in the automotive field.

4. Circumstances

4.1. Security and privacy challenges

The safety of Intelligent Connected Vehicles is a prerequisite for its large-scale development. Deep application of AIoT technology can not only improve the intelligence level of vehicles, but also greatly expands the attack surface of the system [5]. Specifically, safety hazards are mainly reflected

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in three aspects: Firstly, the IVI system, ECU control units, and mobile applications on the terminal side can be used as the entrance for attacks. If a link is compromised, it might lead to the massive leakage of user privacy data in the mildest case, or in the most severe case, it can cause illegal seizure of vehicle driving control, which can even lead to regional traffic paralysis in the most extreme case. Privacy protection is also facing serious challenges. The sensitive information collected during the continuous operation of the vehicle, such as high-precision trajectory data, driver facial features, driving behavior habits, and in-car voice recordings, if not effectively protected and used in compliance with regulations, will not only violate user privacy but also bring risks to personal and property safety.

4.2. Technical and standardization challenges

The Intelligent Connected Vehicle industry is the deep integration of multiple fields such as automobile manufacturing, communication technology, artificial intelligence and cloud computing, facing multiple obstacles in technical integration and standardization [6]. Data formats and protocols differ widely across these domains, creating barriers to data sharing. China is mainly promoting the C-V2X technology in the communication standards, and has completed a number of large-scale tests, but the physical layer and the protocol stack are not compatible with the DSRC (IEEE 802.11p) standard dominated by Europe and the United States. The incompatibility leads to vehicles with different standards unable to perform V2X information interaction when driving across borders, which directly impedes the realization of the international roaming function. At the same time, it will increase the technical adaptation cost for cross-regional traffic coordination, which will bring challenges to international roaming and cross-regional collaboration. Moreover, AIoT applications produce a huge amount of real-time data, which puts extremely high requirements on the computing power, network bandwidth, and storage resources of edge nodes. The technical breakthroughs focus on the efficient compression, transmission and processing of data, and optimize the collaborative computing architecture of "Cloud-Edge-End".

4.3. Infrastructure construction and business model challenges

The construction and operation of new infrastructure are faced with enormous challenges, and the large-scale deployment of new infrastructure is highly dependent on the development of the "Vehicle-Road-Cloud Integration" system. Infrastructure construction requires nationwide deployment of a large number of RSUs, 5G/5G-V2X base stations, MEC servers, and high-precision map acquisition/update systems, which requires extremely high upfront investment costs [7, 8]. It also includes coordination problems between industries (communication, transportation, automotive, etc.) and departments (Ministries of Industry, Transportation, Public Security, etc.). As far as business models are concerned, a clear and sustainable path to profit has not yet been created: On the other hand, government-led investment models are hard to maintain in the long run, and commercial operations have problems such as low willingness to pay among users and difficulty in quantifying the value of services. In contrast, the profit methods are various (e.g. high-precision map subscription, autonomous driving operation service, data value-added service, insurance innovation), all need to break through the technical bottlenecks, policy restrictions and market education barriers. The current construction speed of smart road infrastructure cannot keep up with the penetration rate of Intelligent Connected Vehicles, which will lead to developmental dissonance such as "vehicles waiting for roads" or "roads waiting for vehicles", thus affecting the overall application effectiveness and return on investment efficiency.

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5. Case study

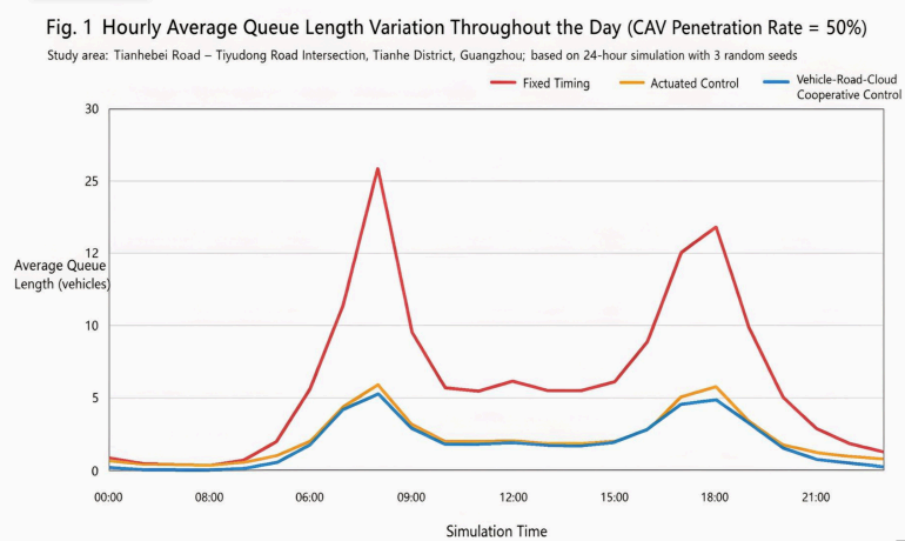


Figure 1. Hourly average queue length variation throughout the day (CAV penetration rate = 50%)

As shown in Figure 1, under the condition of 50% penetration rate, the all-day average queue length has a bimodal peak pattern. The traffic demand is relatively small from 1:30 to 3:00 in the early morning and the queue lengths of all schemes are not large. At about 8:00, the commuter traffic is accumulated and the queue length of fixed-timing scheme grows rapidly and reaches the peak of the whole day. The evening peak is around 18:00 but the peak value is lower than the morning peak. The queue curves of the actuated control and the vehicle-road-cloud cooperative control have similar trend in general and both of them can effectively suppress the growth of queues in peak hours. Among them, the vehicle-road-cloud cooperative control has a slightly smaller number of queued vehicles, and thus has a better congestion relief effect.

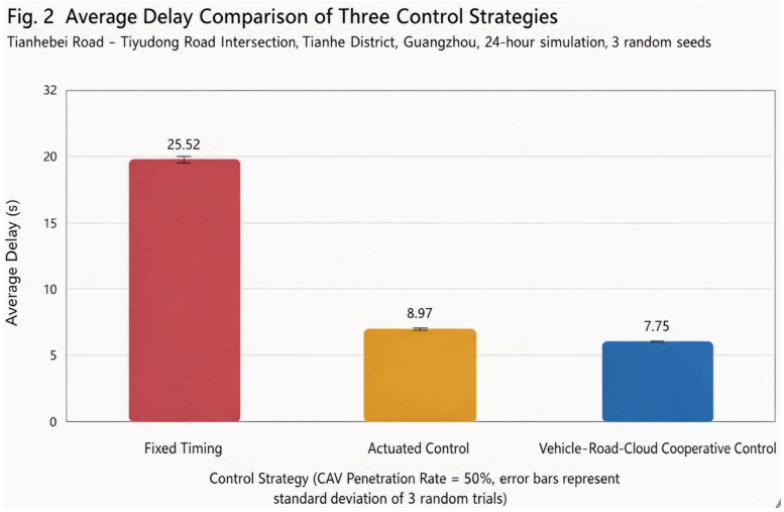


Figure 2. Average delay comparison of three control strategies

Figure 2 shows the average delay of the three control strategies at 50 % penetration rate. The average delays for fixed timing, actuated control, and vehicle-road-cloud cooperative control are 25.52, 8.97, and 7.75 s, respectively. Compared with fixed timing, actuated control and vehicle-

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road-cloud cooperative control reduce the delay by 64.85% and 69.63% respectively, showing a significant reduction of delay. Compared with actuated control, vehicle-road-cloud cooperative control reduces the delay by 13.60%, which shows more effective traffic efficiency in the current simulation scenario. Moreover, the error bars of the three strategies are relatively short, i.e., little fluctuations over the three random trials.

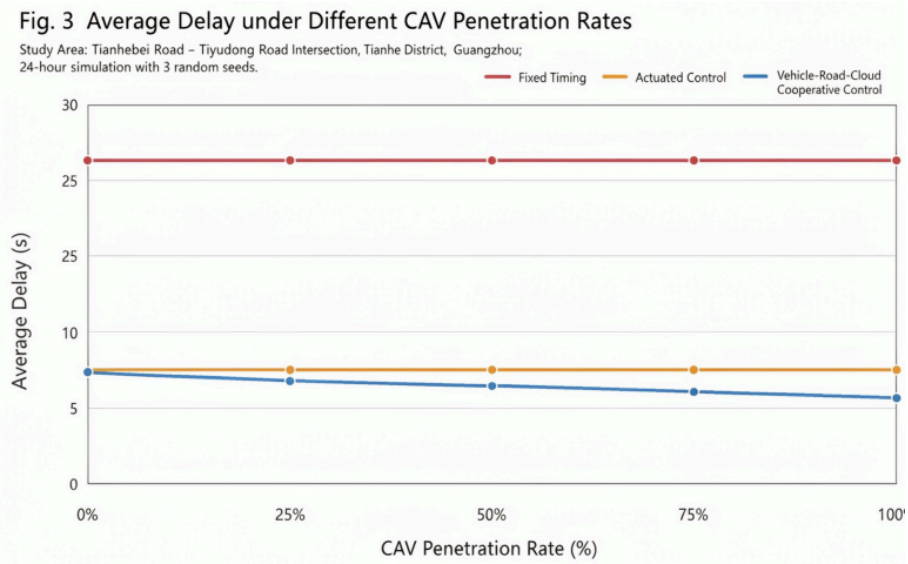


Figure 3. Average delay under different CAV penetration rates

Figure 3 shows the different impact of the CAV penetration rate on the average delay of different control strategies. With the penetration rate increasing from 0% to 100%, average delay of fixed timing and actuated control are relatively stable at about 25.5s and 9.0s respectively, while average delay of vehicle-road-cloud cooperative control keeps reducing. For the low penetration rates, the cooperative control is similar to the actuated control. With the increase of penetration rate, the delay gap between two methods gradually expands and the advantage of cooperative control becomes more obvious.

6. Conclusion

The travel of electric vehicles and the vehicle-road cooperative control in complicated urban traffic scenarios are studied in this paper based on 5G-IoV (5G Internet of Vehicles). First, the electric vehicle is classified into three types of taxis, commuting private vehicles, and other purposes according to the travel frequency, parking duration and destination features. Together with the structure of travel chains, the travel behavior of different vehicle types is characterized, thus providing a basis for modeling traffic scenarios. Secondly, historical traffic statistics are used to fit the probability distributions of departure and return times of different trip chains, which enhances the validity of traffic demand temporal modeling. On this basis, the paper further analyzes the application of AIoT technology in intelligent perception, high-precision positioning, V2X communication and collaborative decision-making, and discusses practical challenges such as security and privacy, technical standardization, infrastructure development and business models.

The simulation results show that the average delay is only 7.75 s at 50% CAV penetration rate under vehicle-road-cloud cooperative control, which is decreased by 69.63% and 13.60% compared with fixed-timing and actuated control respectively. With the increasing penetration of CAVs, the

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delay under cooperative control is further reduced, which indicates that the 5G-IoV together with vehicle-road-cloud cooperation can effectively improve the traffic operational efficiency and alleviate the peak-hour congestion. In the future, communication, perception and computing infrastructure should be further improved, and the development of cross-platform standards and commercial mechanism should be strengthened to promote the large-scale application of 5G-IoV in complex urban traffic.

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