

Traditional and Advanced Technologies in Intelligent Transportation Systems

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Abstract. In the past decade, rapid urbanization and the increase in vehicles have worsened traffic conditions. Intelligent Transportation Systems (ITS) are considered an ideal solution to optimize urban transportation and tackle traffic challenges. This article comprehensively discusses the current development of basic and new technologies used in ITS. It includes specific subdivisions for these technologies, their application in ITS, as well as current and potential future challenges. The review indicates that vehicle-to-everything (V2X) communication technology is increasingly focused on the advancement of Cellular V2X (C-V2X). Sensor technology research and development has reached a high level of maturity. Reinforcement learning as a robust machine learning algorithm, is being extensively applied in traffic management. The article also provides examples of recent research-based applications using these technologies and explores potential directions for their future development. These reviews and analyses can serve as practical references for traffic managers and researchers working on further advancements in ITS.

Keywords: Communication technologies, Sensor, Reinforcement learning, Intelligent Transportation Systems.

1. Introduction

In recent decades, as global urbanization has accelerated, more and more people have been moving to expanding cities. The increase in population has brought attention to various internal issues such as land use and supply-demand imbalance. In response, the concept of smart cities is gaining recognition, which aims to explore sustainable development through advanced technology and environmental concepts. Generally, smart cities encompass politics, economy, healthcare, education, mobility, and environment to improve residents' living environment and quality of life through effective management. Among them, smart mobility is an essential component of a smart city that is dedicated to optimising the urban transportation system using advanced technologies and management methods for convenient, efficient, and environmentally friendly travel experiences. Almost every commuter relies on public transportation or private cars for daily commuting. The development of smart transportation can significantly reduce travel time.

Under these circumstances, Intelligent Transportation Systems (ITS) plays a crucial role in optimizing traffic issues using electronic information technology. This concept was first proposed by transportation professionals in 1991 [1]. Over the past decade, intelligent transportation systems have experienced rapid development due to advancements in computer performance combined with sensors collecting various amounts of diverse data from transport infrastructure. Researchers continuously improve core technologies related to intelligent transportation systems from different perspectives to cover all aspects of urban transportation. Wade Genders and Saiedeh Razavi applied deep learning models to construct a Deep Q-network Traffic Signal Control Agent (DQTSCA), which demonstrated superior signal light control effects compared to traditional methods at both theoretical and microsimulation levels [2]. Ma et al. proposed managing traffic accidents using Dynamic Hard Shoulder Running (D-HSR) and suggested strategies for traffic management departments based on simulation results that alleviate congestion in accident sections [3]. Whether through artificial intelligence analysis or actual policy implementation, the development of intelligent transportation systems undoubtedly enhances residents' travel experiences while showcasing the benefits of smart travel.

This article focuses on intelligent transportation systems by discussing established and cutting-edge technologies as well as commercially available or under-research smart transportation system platforms. The author aims to present the current mainstream research directions and status quo of intelligent transportation systems for scholars and urban managers and offers insights into future research prospects. This article also serves as a valuable reference within the field.

2. Communication technologies in intelligent transportation systems

Some decades ago, engineers could only calculate theoretical results based on field surveys and implement corresponding decisions manually. This conventional method has become increasingly limited due to urban development and the increase in traffic volume. The concept and research of intelligent transportation systems enable traffic managers to efficiently process large-scale information and data captured by monitoring cameras and sensors on the road using powerful computer computing power, thus making rapid responses and efficient control of the traffic conditions in a specific area. To further develop intelligent transportation systems, scholars have proposed many excellent and feasible methods that have played a significant role in improving traffic safety, optimizing traffic management and so forth.

The current development of communication technology in intelligent transportation systems is primarily focused on transmitting information and data from vehicles to various objects, known as vehicular communication, such as vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-network (V2N), and vehicle-to-pedestrian (V2P). In the academic field, researchers are currently considering vehicle-to-everything (V2X) communication technology as the latest research direction for vehicle communication. V2X not only encompasses the aforementioned distinct communication technologies but also connects vehicles, traffic infrastructure, traffic management centers, pedestrians, and others, enabling the perception of information beyond transportation such as weather conditions and home facilities. It achieves comprehensive and efficient information exchange while enhancing the overall operational efficiency and safety of the transportation system. Additionally, it helps reduce fuel consumption and pollutant emissions to some extent. The development process of V2X involves two main wireless communication technologies: Dedicated Short-Range Communication (DSRC) and Cellular V2X (C-V2X).

2.1. DSRC technology

DSRC is an efficient wireless communication technology that enables real-time, accurate, and reliable bidirectional transmission of images, voice, and data within a small range (generally not exceeding one kilometer), connecting vehicles and roads organically. Based on these features, DSRC has the following characteristics:

2.1.1. Advantages

(1) Low latency: As a specific V2V and V2I communication solution, DSRC does not rely on external power grid infrastructure. Real-time recognition of traffic conditions greatly improves vehicle driving safety. The fast recognition and processing capabilities make DSRC very effective in traffic scenarios such as electronic toll collection and collision warning.

(2) Maturity: US relevant departments have been committed to the research and development of DSRC technology since the last century, and it has been widely applied and researched in the field of intelligent transportation. Vehicles equipped with DSRC can effectively reduce safety hazards when driving in any environment.

2.1.2. Disadvantages

(1) Limited coverage: The Federal Communications Commission (FCC) has designated a 75MHz bandwidth segment in the 5.9GHz frequency band as the exclusive traffic safety spectrum for DSRC. The limitations of this frequency range and the propagation characteristics of DSRC result in

relatively short transmission distances. This limitation may be unfavorable for the comprehensive development of future intelligent transportation systems and V2X communication.

(2) Instability: The transmission characteristics of DSRC determine that it cannot fully transmit relevant image information and data when vehicles are travelling at high speeds. At the same time, complex road conditions may increase the processing efficiency of DSRC, affecting its stable operation.

(3) Single functionality: From a technical perspective, DSRC is limited to line-of-sight communication. This type of communication has weak penetration capability and can easily be obstructed by obstacles. Currently, DRSC has low commercial potential.

2.2. C-V2X technology

Due to the limitations of DRSC, despite the relatively advanced development of DSRC technology, urban residents are not very interested in installing and using it. In November 2020, the FCC announced that the frequency band allocated to DSRC was completely cancelled and divided between WIFI and C-V2X [4]. This means that the United States has already abandoned DSRC as the wireless communication method for V2X, reflecting the growing popularity of C-V2X technology among researchers and the public. C-V2X technology includes LTE-V2X and its evolutionary technology NR-V2X. NR-V2X is a V2X communication system based on 5G New Radio (5G NR) technology, which significantly improves communication capability and response speed. Compared to DSRC, C-V2X has significant features:

2.2.1. Advantages

(1) Wide coverage range: The continuous improvement of network infrastructure promotes the widespread coverage of V2X based on cellular networks in urban areas. This advantage also allows for large-scale vehicle and driver access to the communication network of intelligent transportation systems, greatly improving the utilization rate of intelligent transportation systems.

(2) High transmission efficiency: Researchers have been continuously working to improve the transmission capacity of cellular networks. With C-V2X technology, vehicles and traffic managers achieve significantly improved transmission rates, enabling more efficient information exchange between vehicles and other entities. This feature is particularly important for real-time traffic scenarios and can further expand the service scope of V2X.

(3) High mobility: C-V2X technology can adapt to high-speed mobility, maintaining stable communication connections whether it is high-speed driving on highways or frequent lane changes in cities. This provides strong support for the diversity of traffic scenarios, ensuring reliable communication under various circumstances.

(4) Comprehensive functionality: Unlike DSRC's line-of-sight communication technology, C-V2X can transmit various types of information and data through cellular networks, meeting various needs for traffic information interaction. From basic location information to advanced traffic decision assistance, C-V2X technology ensures smooth communication and accurate transmission. The diverse information transfer capabilities ensure efficient information exchange between drivers and traffic managers, effectively enhancing the intelligence level and safety of overall transportation systems.

2.2.2. Disadvantages

(1) Safety issues: The rapid development of C-V2X has led to the security and privacy concerns of user-uploaded information becoming one of the important challenges. If the communication network of intelligent transportation systems is hacked, it may seriously affect traffic flow management and scheduling. The intrusion and tampering of communication systems in autonomous vehicles can cause immeasurable losses.

(2) Infrastructure dependence: Although researchers have made many effective discoveries in C-V2X transmission technology, in reality, the installation rate of roadside infrastructure and base

stations that support C-V2X is low. It has not significantly promoted the development of intelligent transportation systems and smart mobility.

In recent years, researchers have proposed numerous promising directions and application prospects for V2X communication technology. Munasinghe and Murtaza evaluated various communication technologies currently used in V2X and suggested further advancement in the research and development of C-V2X, with 6G as the primary communication technology to meet V2X communication needs [5]. Deng et al. proposed an overtaking collision avoidance system based on V2X that effectively ensures the safety of autonomous vehicles [6]. Jin et al. simulated DSRC and C-V2X technologies in three traffic scenarios to test their communication performance for connected and automated vehicles (CAVs). Based on the results, the authors recommend that CAVs autonomously select communication protocols according to different traffic conditions to ensure transmission efficiency and accuracy [7]. These studies provide research directions and theoretical foundations for the future development of communication technology in V2X-based intelligent transportation systems.

3. Sensor technologies in intelligent transportation systems

In ITS, the application of various sensors is the most basic and vital tool for constructing the entire framework. The initial step in collecting information often involves identifying and processing continuous or discrete data through sensor recognition, followed by further management and decision-making using communication technology, electronic control technology, etc. Reasonably designing and arranging various sensors can improve the accuracy of data collection and reduce energy consumption and maintenance costs. For ITS, the application of sensor technology can be divided into two categories based on their installation locations: in-vehicle sensors and road sensors. However, overall, these sensor technologies are almost all developed for detecting traffic conditions, ensuring driving safety, and assisting vehicle operation.

In-vehicle sensors, especially those in autonomous vehicles, play a crucial role in vehicle positioning, route planning, and environmental perception. As automakers increasingly focus on research for autonomous driving vehicles, the accuracy of in-vehicle sensors and the requirements for automatic control have significantly increased. Monitoring vehicle health through sensors like fuel and tire pressure sensors can provide drivers with intuitive safety information. Sensors such as lidar, cameras, and Global Positioning Systems (GPS), work together to detect surrounding traffic conditions and ensure safe travel. Scholars have been using computer technology to improve sensor safety and accuracy. Cao et al. were the first to use machine learning to study the safety of autonomous driving vehicles based on Light Detection and Ranging (LiDAR) perception [8]. However, the diversity in quantity and types of in-vehicle sensors leads to exponentially increasing data collection that requires more powerful computer and data processing technologies. Additionally, different sensor manufacturers' production standards and application standards pose significant obstacles to sensor development; this necessitates close communication and cooperation between capitalists and traffic managers.

The intelligent transportation system's coverage depends on the placement of sensors on roads. Cameras and laser speed sensors can be deployed in urban traffic networks to gather real-time road conditions for specific sections, providing traffic managers with information about traffic flow characteristics and trends during different periods. In parking lots, various types of sensors can monitor vehicle identification information and display the usage status externally. Road sensors can be categorized into environmental sensors and data sensors based on the type of data collected. Environmental sensors primarily monitor road conditions, including weather conditions, road icing, and damage situations. They help reduce maintenance costs for roads and minimize human resource consumption. Data sensors directly provide information about the traffic network to transportation management departments and users, serving as a crucial foundation for the development of intelligent transportation systems. Odat et al. proposed a new sensing device that combines passive infrared (PIR)

sensors with ultrasonic rangefinders for vehicle monitoring, speed estimation, and vehicle type recognition [9]. Researchers have made significant improvements in sensor accuracy while reducing errors to a large extent. However, smart transportation systems still face an urgent problem of how to integrate and effectively utilize data collected by different types of sensors. This is also a crucial area requiring research breakthroughs in future development.

4. Reinforcement Learning technologies in intelligent transportation systems

Reinforcement Learning is a powerful machine learning method, which can be roughly divided into five elements: environment, agent, state, action, and reward. The environment is the entire system that provides a perception platform for the agent. Correspondingly, the agent takes action after being embedded in the environment. The state describes all complete information in the environment in detail, and the agent adjusts its behavior based on this information. Action as a set (Action space) specifies the actions that an agent can perform. Reward quantifies the performance of an agent's complete decision-making process as a scalar feedback signal and can also be understood as scoring for an agent's behavior in this instance. The goal of reinforcement learning is to maximize cumulative rewards in the end. In reinforcement learning terminology, "reinforcement" means that through reinforcement learning algorithms defined by agents based on feedback received after each action taken iteratively adjust their behavior to ultimately maximize specific gains. Generally speaking, scholars formalize this process of transitioning states by taking actions under different states and receiving reward signals from the environment as Markov Decision Process (MDP). All states in MDP have Markovian property, meaning that future outcomes only depend on current state and are independent of historical states.

In the field of transportation, the traffic conditions on the road are often dynamic and complex. Traditional calculation and control methods find it difficult to accurately manage the specific traffic conditions in each area. Reinforcement learning, based on perceiving the current environment and making decisions quickly, can effectively obtain traffic information and execute commands. Therefore, reinforcement learning is still making significant contributions to the development of intelligent transportation systems. Based on the above discussion, reinforcement learning algorithms have the following advantages and limitations:

4.1. Advantages

(1) **Universality:** Reinforcement learning applies to almost any complex and dynamic environment, as the agent can take actions based on environmental information. In the transportation system, agents can dynamically adjust strategies in real-time interactions. This has great potential in areas such as traffic signal control and autonomous driving, which are explained in detail later in this article.

(2) **Immediacy:** The agent of reinforcement learning can make quick decisions based on the current state. The construction of intelligent transportation systems requires high demands for real-time traffic control. This rapid and efficient characteristic allows autonomous agents or assists traffic managers to make immediate decisions within a short time.

(3) **Accuracy:** In theory, when the agent iterates enough times, reinforcement learning algorithms can completely plan out optimal actions based on the current environmental state and further make precise adjustments according to changes in the environment. This means that scenarios like signal light control can select the best action at every moment to deal with constantly changing traffic environments and flow through an agent's learning and optimization process.

4.2. Disadvantages

(1) **Low sample efficiency:** The universality of reinforcement learning objectively makes it difficult for researchers to use any information that may help guide the agent in achieving specific goals. This limitation also means that reinforcement learning agents need to start from scratch and

incur significant training costs when facing any new environment. Many other algorithms outperform reinforcement learning algorithms in certain domains.

(2) Function complexity: It is well known that a reinforcement learning agent determines the goodness or badness of its behavior based on a reward function and decides whether to imitate or adjust this behavior accordingly. However, in some special cases, the agent may exhibit "unrealistic" behavior to obtain higher reward scores. Although this behavior may seem absurd to researchers, it does indeed lead to higher rewards and can result in being trapped in local optima. Scholars commonly refer to this problem as "exploration-exploitation," which involves weighing whether it is necessary to further search for better solutions than the current one, even if there is a possibility of the agent learning worse strategies.

Based on the characteristics of reinforcement learning, scholars have made encouraging progress in the field of transportation and the development of intelligent transportation systems using reinforcement learning algorithms. In the field of traffic signal control, due to the limitations and lagging nature of traditional methods in dealing with multi-directional dynamic traffic flow, reinforcement learning algorithms are increasingly favored by researchers. Wei et al. summarized previous research on signal light control using reinforcement learning and proposed a deep reinforcement traffic light agent to address poor performance adjustment in complex real-world situations. Evaluation was then conducted using synthetic and real-world traffic flows, demonstrating superior performance compared to previous models [10]. In the field of autonomous driving, reinforcement learning algorithms can help identify complex road conditions in real-time, ensuring safer and more energy-efficient vehicle operation. Valiente et al. constructed a multi-agent reinforcement learning (MAREL) framework to address the problem of autonomous vehicles (AVs) recognizing human-driven vehicles' (HVs) driving behaviors, thereby assisting AVs in avoiding risks and preventing nearby HVs from engaging in unsafe driving behaviors [11]. To further optimize the management effectiveness of intelligent transportation systems, some scholars have combined traffic infrastructure management with vehicle control and achieved excellent results using reinforcement learning algorithms. Yang et al. proposed using the Modified Proximal Policy Optimization (Modified PPO) algorithm to determine the behavior of signal lights controlled by deep-learning agents as well as vehicles' actions. As a software-defined Internet-of-Things (SD-IoT) traffic control solution, it theoretically improves traffic congestion problems [12]. These recent studies demonstrate that reinforcement learning plays an irreplaceable role as a powerful machine learning method in the development of intelligent transportation systems. Its significant advantages such as universality, immediacy, and accuracy under complex dynamic environments make it a powerful tool for solving optimization problems in transportation systems.

5. Conclusion

This article comprehensively discusses the recent development prospects of conventional and new technologies in ITS. It covers communication technology, sensor technology, and reinforcement learning algorithms that have gained attention. Communication technology focuses on the mutual communication of information and data between vehicles and the traffic environment to achieve transparent openness of information. The article reviews the development process of V2X, which mainly uses DSRC and C-V2X technologies. Although DSRC is more mature in development, researchers have been more committed to the research and development of C-V2X with improved network infrastructure. Sensor technology serves as the foundation for ITS by providing necessary feedback for real-time decision-making by vehicles and traffic managers. This article divides sensors into in-vehicle sensors and road sensors based on their deployment location. These sensors are essential for assisting autonomous driving or monitoring road network environments. However, integrating a large amount of data collected from different types of sensors, along with differences in production standards, still poses potential challenges to future ITS development. Reinforcement learning (RL) is a powerful machine learning algorithm that has shown remarkable performance in

handling dynamic complex traffic scenarios recently. Despite limitations related to sample efficiency and function settings, reinforcement learning algorithms are widely applied and optimized across various domains within intelligent transportation systems.

In future research, it is suggested to consider both communication system technologies simultaneously and flexibly select them based on different traffic conditions to effectively leverage their respective advantages. Regarding sensor technology, current research has comprehensively and maturely studied the performance of individual sensors. Future research should focus on discussing fusion among various sensors and efficient data analysis to reduce redundant time waste and resource consumption. For reinforcement learning (RL) algorithms, specific computer algorithms combined with stable RL can be considered under certain traffic conditions to improve model efficiency and accuracy.

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