Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/128/2025.20224

Intelligent Traffic Light Control System and Application

Haoyi Xu[1,a,*]

[1]*Faculty of Engineering, The University of Hong Kong, Hongkong, 999077, China*
a. u3610158@connect.hku.hk
**corresponding author*

Abstract: In recent years, with the surge in the number of vehicles, traffic congestion has become an increasingly severe global issue. So Intelligent Traffic Signal Control Systems have emerged as a critical component of transport systems to address this challenge by optimizing traffic flow, reducing delays, and enhancing road safety. The intelligent system depends on several advanced technologies, such as IoT devices, big data analytics, and artificial intelligence algorithms. Also, the system can dynamically adjust traffic signals based on real-time road conditions via technologies such as Vehicle-to-Infrastructure (V2I), Vehicle-to-Vehicle (V2V), and Vehicle-to-Everything (V2X) communication, which successfully improves traffic flow during peak hours, and minimizes congestion. The review will also mention successful case studies in cities such as Beijing, where smart systems have significantly improved traffic efficiency. The last part of review will focus on future developments about scalability, cost-effectiveness, and data security to ensure the continued success of these systems in modern urban environments.

Keywords: Transport system, Intelligent Traffic Signal Control, Advanced technology.

1. Introduction

With the rapid urbanization and the acceleration of intelligent city construction in 21st century, the number of vehicles has considerably increased. However, because of the limited availability of existing road, traffic congestion has become a growing issue worldwide. Meanwhile, factors such as the frequent occurrence of urban traffic accidents, the low intelligence level of public transportation systems, unclear traffic signs, and suboptimal traffic signal control also impact the fluency and safety of traffic [1]. To address these challenges, Intelligent Traffic Signal Control Systems have become an integral part of Intelligent Transportation Systems (ITS), aiming to optimize traffic flow and enhance urban mobility.

The significance of implementing the Intelligent Traffic Signal Control Systems is that it can enhance urban mobility, improve road safety, reduce delays, and minimize environmental impacts. Unlike traditional systems, intelligent traffic signal control systems use a combination of IoT devices, big data analytics, and AI algorithms to process real-time traffic data. This enables dynamic adjustments to traffic signals based on current road conditions, such as vehicle speed, density, and pedestrian movements. Consequently, this smart system can improve traffic flow efficiency, reduce congestion during peak times, and enhance the overall travel experience for drivers and pedestrians.

Therefore, the following content of this review focuses on exploring how intelligent traffic signal control systems are implemented and their practical applications in real-world scenarios. It first

DOI: 10.54254/2755-2721/128/2025.20224

indicates the fundamental principles of the intelligent control system, highlighting how technologies such as Vehicle-to-Infrastructure (V2I), Vehicle-to-Vehicle (V2V), and Vehicle-to-Everything (V2X) communication enable real-time data exchange between vehicles and traffic infrastructure. These technologies form the backbone of smart system, allowing for the adaptive control of traffic lights based on real-time traffic conditions. This review will also discuss the integration of advanced sensors, smart cameras, and LiDAR to collect detailed road and vehicle information, which aids in optimizing signal timings and improving decision-making.

2. The Fundamental Analysis of Intelligent Traffic Light Control System

2.1. Basic Principles of Intelligent Traffic Control Systems

In this paper, the core principles of intelligent traffic control systems are adaptive control system and the combination of real-time data processing. The intelligent system can utilize real- time data collected from vehicles and infrastructure to adjust signals, which is considerably different from traditional traffic signal systems, that operate according to fixed schedules.

Vehicle-to-Infrastructure (V2I) communication plays the key role of intelligent light control. It is a kind of technology that enables system to adjust dynamically based on current traffic conditions since it create the exchange of information between vehicles and traffic signals. Data such as vehicle speed, density, and lane occupancy are collected from sensors in the road or inside vehicles. These data are transmitted to traffic control centers, where they are processed by algorithms that decide how long to extend or shorten signal durations [1, 2].

Except for V2I, Vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) technologies further enhance the traffic control by facilitating communication between vehicles and other infrastructural elements, such as roadside cameras and sensors. By V2V communication, vehicles can share their location, speed, and route data with nearby vehicles and traffic systems. This enables the traffic control system to predict and adjust signal timings prior to the exacerbation of congestion, thereby improving the overall traffic flow [3].

Therefore, these real-time data processing, adaptive control, and communication between vehicles and infrastructure constitute the basic principles of intelligent traffic control systems. And these technologies offer effective solutions for managing complex traffic environments and ensuring safer travel in nowadays modern city. The following Figure 1 indicates how most of cities utilize the intelligent traffic light by using former technology.

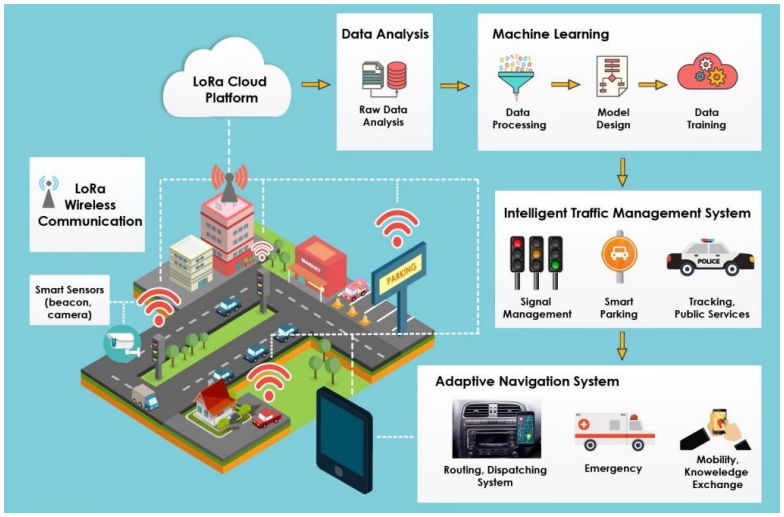

Figure 1: Smart Traffic Management System

DOI: 10.54254/2755-2721/128/2025.20224

2.2. Key Technological Features

2.2.1. Intelligent Cameras

Smart camera is an important element in modern traffic signal control systems, enhancing traffic monitoring and decision-making processes by providing real-time visual data. These cameras have advanced image processing capabilities and are more accurate and efficient than other common cameras when they are work with other sensors such as LiDAR. Intelligent cameras are able to detect vehicles, pedestrians or any other cross users via capturing detailed visual information, making the traffic system to adjust signal times and prioritize different traffic flows dynamically.

One advantage of intelligent cameras is that they can keep an eye on several traffic parameters simultaneously. They can detect how fast vehicles are going, how crowded the roads are, and traffic rule-breaking like running red lights or blocking intersections. This real-time watching helps traffic control centers gather important data. That data is processed through algorithms to make the traffic flow better. For instance, cameras at intersections can detect the number of vehicles waiting on each lane and change the lasts time for green light based on actual demand. That reduces congestion during peak hours.

Another noticeable feature of smart cameras is their ability to integrate with vehicle detection algorithms. One popular algorithm used in conjunction with camera data is YOLOv5 (You Only Look Once version 5), a deep learning model for real-time target detection [4]. YOLOv5 is highly effective in identifying vehicles and pedestrians in traffic environments, even under challenging conditions such as occlusion or low light. This ability enables intelligent traffic systems to maintain high levels of accuracy and responsiveness in various situations. Additionally, recent advancements in multi-scale feature extraction and attention mechanisms have improved the detection accuracy of smart cameras, especially when dealing with occlusion or overlapping objects [4].

In many cases, smart cameras are used in conjunction with LiDAR sensors to enhance the overall detection capabilities of the traffic system. The fusion of visual data from cameras with LiDAR lets more effective vehicle detection, and by combining the high-precision spatial data provided by LiDAR with the visual details provided by cameras, it improves the system's ability to handle complex traffic situations, such as those that traditional systems may struggle to handle in congested or adverse weather conditions [5].

2.2.2. Big Data and IoT in Traffic Control

Big data can be used everywhere in traffic control. Without big data, most of the decision are not able be determined. The reason is that big data analysis can collect, store, and analyze large data sets, providing real-time information on vehicle movement, traffic bottlenecks, and congestion points to traffic managers [6].

Big data are utilized to predictive analysis. By analyzing historical traffic data, predictive models can predict traffic conditions based on time, weather, and road events. This allows the traffic system to proactively adjust signal times and prevent congestion before it occurs [2]. For example, in cities like Xi'an, big data collected from taxi trajectory systems is used to visualize congestion hotspots and optimize traffic signal settings to improve peak-hour traffic flow [7].

IoT is another key technology that is similar to big data, and that is the reason why they are put together, since both of them are useful for decision making in intelligent control systems. IoT involves connecting various devices and sensors through the internet, allowing them to communicate with each other and share data. In the context of traffic control, IoT sensors deployed on the road network can collect real-time traffic conditions, vehicle speeds, and pedestrian movement data [8].

DOI: 10.54254/2755-2721/128/2025.20224

IoT devices such as intelligent cameras, radar, and lidar systems provide detailed information about the road environment. For example, laser radar technology is often used for precise vehicle detection, allowing the system to track the exact number of vehicles at an intersection or determine whether there are pedestrians crossing the street [9]. This data is transmitted to the traffic control center, where it is analyzed to make instant decisions on signal timing and lane priorities.

In addition to traditional road sensors, connected vehicles are also a growing source of valuable traffic data. These vehicles are equipped with IoT devices that can communicate with the traffic control system through vehicle-to-infrastructure (V2I) technology. Connected vehicles share data about their speed, direction, and location, helping the traffic system optimize signal timing to reduce delays and ensure smoother traffic flow [1].

2.2.3. Interconnected Control Devices

For interconnected control devices, interconnected control devices are key components in achieving real-time coordination between traffic signals and sensors at intersections across a network. These devices ensure that traffic signals do not operate in isolation but communicate and respond dynamically to the entire traffic system.

The primary function of interconnected control devices is to coordinate the timing of traffic signals at adjacent intersections. Traditional systems often isolate signal control, which may result in inefficient traffic flows, such as vehicles unnecessarily stopping at multiple consecutive red lights. In interconnected systems, traffic signals communicate with each other and share information about traffic density, vehicle speed, and signal status. This approach allows the system to adjust green light phases in a way that maximizes the number of vehicles passing through multiple intersections without causing unnecessary stops [2].

The next application is centralized traffic management systems. These systems collect data from road sensors, cameras, and connected vehicles and transmit it to a central control center. From there, the system can analyze the traffic conditions across the entire network and adjust traffic signal timing in real-time. For example, if an intersection experiences an accident, the system can quickly reroute traffic and adjust nearby intersection signals to reduce delays [7].

Adaptive signal control technology (ASCT) is also a type of utilization of interconnected control devices. By connecting multiple traffic signals, ASCT can reduce travel time, reduce congestion, and improve fuel efficiency. This technology is particularly suitable for urban areas with high traffic volumes, where optimizing signal coordination can significantly reduce delays [10].

3. Practical application and optimization analysis

3.1. Application in daily life

Intelligent traffic light control systems have been implemented in many cities around the world, demonstrating their ability to significantly reduce congestion, improve traffic flow, and increase road safety. Three news are shown in the following article will indicate how well people utilize the system. One of the most successful real-world applications of intelligent traffic management is in Pittsburgh, where the Surtrac system has been in use for several years. The AI-based system uses real-time data from cameras and sensors to dynamically adjust signal timing at multiple intersections. As the BBC article points out, Surtrac successfully the vehicles will be rushing hour waiting time decreased by 40%, by reducing the stop-and-go traffic, improved the traffic flow, reduce the emissions. The system has proven that AI can be a powerful tool for optimizing urban traffic and reducing congestion in cities with complex road networks [11].

Also in China, Zhejiang is how the AI and big data is applied to a leading example of large-scale traffic management. According to a recent article in Baidu, intelligent transportation systems in China,

DOI: 10.54254/2755-2721/128/2025.20224

big data and integrated with AI technology, traffic signal control based on real-time information. The system cuts travel time by about 20-25 percent and significantly reduces traffic congestion during peak hours. Zhejiang's approach combines predictive traffic modeling with real-time adjustments, enabling the city to better manage the growing population and increasing number of vehicles [12].

Beijing has also been walking in the forefront of intelligent traffic management, with a use of big data and the AI system to predict and control the traffic. According to the Baidu article, Beijing's system collects data from a variety of sources, including GPS signals from vehicles, road cameras and sensors. The data is processed in real time to adjust traffic lights and improve the overall flow of vehicles across the city. As a result, Beijing has seen less congestion during peak traffic hours and overall air quality has improved due to reduced emissions [13].

3.2. Challenges on systems

One of the most important challenges is the cost of deploying intelligent transportation systems. Installing cameras, sensors, and V2X communication equipment throughout a city requires significant investment. So small cities or cities in developing countries often struggle to find the resources needed to install such advanced technology on a large scale.

Also, intelligent transportation systems heavily rely on collecting real-time data from vehicles, pedestrians, and infrastructure, data security is a critical issue. Unauthorized access to these systems can disrupt traffic management and even create dangerous traffic conditions. Ensuring the privacy and security of such data is essential to maintaining the reliability and safety of intelligent transportation systems.

Integrating intelligent transportation systems into cities that already have traditional infrastructure is another challenge. Many cities, especially in the developing world, still rely on outdated traffic signal systems that are not compatible with modern AI and V2X technologies.

3.3. Optimization

Although intelligent systems mostly fix what people need, it still has several types of aspects that can be approved. The following paper have three kinds of views about the development and enhancement of intelligent systems.

The first one is a multi-intersection coordination model that synchronizes traffic signals in a wide-area network to minimize vehicle queue lengths and delays. By using predictive control algorithms, this approach anticipates traffic flow changes and adjusts signal timings dynamically. The study also emphasizes the importance of real-time data in achieving effective signal coordination. Sensors and cameras installed across intersections provide live traffic updates, which feed into the optimization algorithms to ensure continuous and efficient operation of traffic signals [14].

Then, there is an auction-based negotiation mechanism where different traffic streams bid for green time based on their current demand and predicted delay. The goal of this mechanism is to minimize overall person-delay at intersections by prioritizing vehicles with higher passenger occupancy [15]. The research breaks from traditional fixed-phase traffic control systems, instead allowing for dynamic adjustments in the sequence and duration of traffic light phases. The system uses real-time traffic data and applies a multi-agent system (MAS) to negotiate the allocation of green light periods among competing traffic flows. The auction mechanism ensures that the green light is assigned to the traffic stream that would benefit the most in terms of reducing person-delay [15].

Finally, one research enhances the machine learning algorithms in enhancing the generalization capability of traffic control systems. By training models on diverse traffic datasets, the system can learn patterns and apply these insights to new, unseen traffic scenarios. This adaptability is crucial

DOI: 10.54254/2755-2721/128/2025.20224

for cities with fluctuating traffic conditions, as the system can adjust signal timings based on real-time data and historical patterns without requiring manual reconfiguration [16].

4. Conclusion

In summary, the Intelligent Traffic Signal Control Systems can significantly reduce the rate of traffic congestion, also shows great potential in enhancing urban traffic management by dynamically adapting to real-time traffic conditions. Moreover, it can contribute to reducing environmental pollution and enhancing road safety. However, it still has some challenges at present. For instance, high implementation costs, especially in developing countries, can limit their deployment. The data security and privacy are another critical issue, as these systems rely heavily on real-time data collection from vehicles, pedestrians, and infrastructure. Additionally, not all cities have enough technology and infrastructure to build such systems, which is a quite tricky question that needs to be addressed.

But the smart system is still promising. With the improvement of AI, machine learning, and edge computing technologies, the Intelligent Traffic Signal Control Systems will probably allow for more precise traffic prediction, faster response times, and improved adaptability to fluctuating traffic patterns. Moreover, as autonomous vehicles become more prevalent, the collaboration between these vehicles and intelligent traffic systems will further enhance traffic efficiency and safety. Developing scalable and cost-effective solutions while ensuring data security will be key to the continued success and growth of this smart system.

References

[1] *Jianchun L, Chongjin T. Optimization control strategy for intelligent traffic lights based on vehicle-road collaboration. Scientific and Technological Innovation and Application, 2023, 13(30): 144-147.*

[2] *Han Z. Research and application of electronic information technology in intelligent traffic signal control systems. Shihezi Science and Technology, 2022(03): 12-13.*

[3] *Harding J, Powell G, Yoon R, et al. Vehicle-to-vehicle communications: readiness of V2V technology for application. United States. National Highway Traffic Safety Administration, 2014.*

[4] *Wang J, Chen Y, Dong Z, et al. Improved YOLOv5 network for real-time multi-scale traffic sign detection. Neural Computing and Applications, 2023, 35(10): 7853-7865.*

[5] *Haokai M. Research on intelligent vehicle target detection algorithms based on LiDAR and cameras. Jilin University, 2024.*

[6] *Lv Y, Duan Y, Kang W, et al. Traffic flow prediction with big data: A deep learning approach. IEEE Transactions on Intelligent Transportation Systems, 2014, 16(2): 865-873.*

[7] *Li Z. Research on traffic trend visualization methods based on trajectory big data. Shenyang University of Technology, 2023.*

[8] *Guanglei L, Lei Z, Qianli D. Research on the architecture of intelligent traffic signal control system based on big data. Engineering Technology Research, 2020, 5(18): 251-252.*

[9] *Felguera-Martín D, González-Partida J T, Almorox-González P, et al. Vehicular traffic surveillance and road lane detection using radar interferometry. IEEE Transactions on Vehicular Technology, 2012, 61(3): 959-970.*

[10] *Khattak Z H, Magalotti M J, Fontaine M D. Estimating safety effects of adaptive signal control technology using the Empirical Bayes method. Journal of Safety Research, 2018, 64: 121-128.*

[11] *BBC Future. Can artificial intelligence end traffic jams?. 2018. https://www.bbc.com/future/article/20181212-can-artificial-intelligence-end-traffic-jams.*

[12] *Baidu Baijiahao. "From car watching lights to lights watching cars, " AI traffic light systems help solve urban congestion. 2024. https://baijiahao.baidu.com/s?id=1795280356524605253&wfr=spider&for=pc.*

[13] *Sina Finance. "Green light freedom" achieved as lights move with vehicles. 2024. https://finance.sina.com.cn/jjxw/2024-09-11/doc-incnunpn8515867.shtml.*

[14] *Rensi C. Research on the theory of regional coordination optimization and control of urban road network traffic signals. Southeast University, 2018.*

[15] *Vilarinho C, Tavares J P, Rossetti R J F. Intelligent traffic lights: Green time period negotiation. Transportation Research Procedia, 2017, 22: 325-334.*

DOI: 10.54254/2755-2721/128/2025.20224

[16] Yanyu R. Research and implementation of an intelligent traffic signal control system with strong generalization capability. University of Electronic Science and Technology of China, 2023.