Development and Application of Digitally Intelligent Traffic Signal Lights in the "Internet+" Era

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Abstract: Traffic signal lights are an important part of the modern urban transportation system and play a vital role in the control and management of urban road traffic. Based on the research background of the "Internet+" era, this paper expounds the combination and spatial application configuration of traffic lights in China, and deeply analyzes the advanced functions of traffic lights after intelligent transformation and upgrading, as well as the convenient and green travel experience provided. By using the example analysis method, through the flow data collection of each entrance road at the intersection of Weiyang Road and Fengcheng 2nd Road in Weiyang District, Xi'an City, with the help of Synchro software, the difference in control efficiency between the use of traditional timing signal lights and the use of intelligent induction collaborative signals is compared, and the necessity of the advancement and development of digital intelligent signal lights is further demonstrated.

Keywords: Traffic Signal Lights; Digital Intelligence; Induction and Coordinated Control; Traffic Congestion; Simulation Optimization

1. Introduction

Traffic is the lifeline of a city, ensuring mobility, serving as a window to civilization, and forming the foundation for people to enjoy a better life. Currently, as China is building up its strength in transport, traffic signal lights, an indispensable part of the transportation management system, are subject to requirements for digitization in various official documents, including the "Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and Vision 2035 of the People's Republic of China" "Development Plan for Public Security Traffic Management Technology (2021-2023)," and "Guiding Opinions on Further Strengthening the Application of Urban Road Traffic Signal Control"[1]. In the era of "Internet+," technological empowerment has enabled the construction of a safer, more orderly, efficient, and harmonious traffic management environment through traffic signal lights.

The article is divided into five parts. After the introduction, the second part explores the historical origins of the red, yellow, and green traffic signals. The third part elaborates on the varied forms and spatial application configurations of universally adopted traffic signal lights in China. The fourth part analyzes the advanced features of traffic signal lights after their intelligent transformation and upgrade. The fifth part presents exemplification analysis of the application of digitized traffic signal lights. Through a traffic flow investigation at the intersection of Weiyang Road and Fengcheng Second Road in the Weiyang District of Xi'an, and by using Synchro software to compare the control efficiency of fixed-time signals with sensor-coordinated signals, the article demonstrates the advanced nature and necessity of the development of digitized signal lights.

2. Origins of Traffic Signal Lights

The world's first traffic signal lights were born in London, United Kingdom. Inspired by the tradition where women wearing red attire indicated marriage and green attire represented single status, mechanic John Knight invented a signal light with red and green colors, where red meant prohibition and green signified smooth passage. In 1868, the world's first traffic signal light was officially put into operation at the intersection in front of the British Parliament building. However, its promotion and use were hindered as it exploded during operation, raising safety concerns. It wasn't until 1914, with improvements in electrical technology, that the first truly meaningful electric switch signal light system was pioneered in Cleveland, USA, playing a significant role in traffic control. In 1918, Chinese electrical and automation expert

Hu Ruding, inspired by a near-accident, proposed the idea of adding a yellow signal light between the red and green lights to warn drivers and pedestrians. This design quickly gained approval and adoption by relevant authorities. Since then, the classic combination of red, yellow, and green signal lights has officially become a staple in the world's traffic systems.

3. Application and Configuration of Traffic Signal Lights in China

The application and configuration of traffic signal lights across the country adhere to the specifications outlined in the national standard GB14886-2016, titled "Specifications for road traffic signal settings and installation." This standard provides clear construction guidelines for the styles, displays, sequence transitions, combination methods, installation positions, and other aspects of traffic signal lights throughout various regions in China. Particularly, it emphasizes scientific, rigorous, and standardized requirements for the visibility and adjustability of signal lights. These measures aim to enhance the functionality of traffic signal lights and underscore their significance.

3.1 Combination Application Settings

3.1.1 Three-color Combination

Traffic signal lights are composed of three colors: red, yellow, and green. The red signal light indicates prohibition, requiring vehicles and pedestrians to come to a halt when illuminated. The yellow signal light serves as a warning, signaling drivers and pedestrians to be cautious, slow down, and prepare to stop. The green light indicates permission to proceed, allowing vehicles and pedestrians to move freely.

The selection of this classic three-color signal light combination is not random. It is rooted in the trichromatic theory of German physicist and physiologist Hermann von Helmholtz, which states that the human retina has three basic visual nerve fibers for perceiving red, green, and blue. When the "red" nerve fibers are stimulated by red light, individuals experience an expansive, exciting, tense perception of the color red [2]. On the other hand, stimulation of the "green" or "blue" nerve fibers by green or blue light induces calm, soothing, and cool physiological sensations. This physiological projection effect generated by color allows drivers to instinctively react to the alternating changes in signal lights.

3.1.2 Phase Sequence and Timing Transformation Combination

Traffic signal lights achieve optimized road traffic management through the transformation of light color phases and timing coordination. The red, yellow, and green traffic signal lights alternate between lit, flashing, and extinguished states in a sequence facilitated by luminous units. Typically, the phase sequence, starting with the red light, is as follows: simultaneous illumination of red lights for straight and left turns → green light for straight movements, flashing, extinguished → yellow light for straight movements, extinguished → red light for straight and left turns → green light for left turns, flashing, extinguished → yellow light for left turns, extinguished → red light for left turns. Precise control and design by the signal light management system are required for the timing of phase sequence transitions. Currently, the application of "Dynamic Green Wave Control" technology allows significant adjustments to parameters such as signal light timing cycles, phase sequences, and green-light-to-red-light ratios based on real-time traffic flow. This greatly enhances urban road capacity and improves the travel experience for citizens [3].

3.1.3 Arrangement Sequence Combination

The three colors, red, green, and yellow, can be arranged horizontally or vertically in traffic signal lights. For horizontally arranged traffic signal lights, in countries and regions where driving is on the right side, facing the signal lights along the direction of travel, the sequence is from left to right: red on the left, yellow in the middle, and green on the right. In countries and regions where driving is on the left side, the sequence is reversed. For vertically arranged traffic signal lights, whether driving on the left or right side, the sequence is designed from top to bottom: red at the top, yellow in the middle, and green at the bottom.

3.2 Spatial Application Settings

The spatial element design of traffic signal lights is primarily reflected in the orientation of signal lights at intersections. Urban road intersection types can generally be categorized as flat intersections and elevated intersections. Tailored to the requirements of road structures, traffic flow, and travel needs for different types of intersections, traffic signal lights have unique spatial designs [4]. These designs aim to enhance the safety, efficiency, and comfort of traffic flow.

3.2.1 Flat Intersections

Flat intersections include traditional four-way intersections, T-shaped intersections, and complex intersections. In the design of traditional four-way intersections, a signal light is typically installed at each entrance, positioned above the intersection to ensure clear visibility for all participants. In T-shaped intersections, the traffic flow on the main road often exceeds that on the side roads. By installing signal lights on the main road specifically to control traffic on the side roads, the goal is to facilitate smooth flow on the main road and rapid merging of traffic from side roads[5]. Complex intersections comprise multi-lane intersections and roundabouts. Due to the increase in the number of lanes and the intricate road conditions, spatial design for signal lights requires meticulous planning. By considering factors such as traffic flow, vehicle speed, and conflicts at different lanes, the goal is to ensure both safety and efficiency of traffic.

3.2.2 Elevated Intersections

Elevated intersections mainly refer to separated elevated intersections, typically achieved through overpasses or underground tunnels, providing separation of roadways in horizontal and vertical directions. Due to the absence of direct intersections in horizontal or vertical directions, the placement of signal lights is fundamentally different from traditional flat intersections. In separated elevated intersections, signal lights are usually positioned at a certain distance from the intersection, before vehicles enter the elevated structure. Signal light intervals are regulated based on real-time peak traffic volumes at the elevated intersection. Additionally, the spatial design of signal lights in separated elevated intersections needs to consider cross-driving demands, lane numbers, lane widths, and turn radii, maximizing the advantages of signal light placement.

4. Smart Development Trends of Traffic Signal Lights in China

4.1 Flexible Regulation Modes

As a hub for traffic flow management, traffic signal lights must be adjustable to flexibly adapt to rapidly changing traffic conditions. In cases of abnormal traffic flow or road construction, it is necessary to dynamically regulate traffic signal signals based on different road traffic and pedestrian flow conditions, as well as intersection characteristics. This can be achieved through counterclockwise release, clockwise release, and simultaneous release. By dynamically adjusting signal lights, the goal is to facilitate the rapid evacuation of both vehicular and pedestrian traffic, enhance intersection vehicle throughput, and ensure smooth road traffic. Additionally, for road segments with significantly reduced nighttime traffic flow, a "night mode" for signal lights from 8 p.m. to 6 a.m. can be implemented. This mode involves closing left-turn signal lights, transforming the intersection's three-phase release into a two-phase mixed release. This reduces idle time for traffic signal lights, thereby increasing road capacity.

4.2 Humanized Travel Management

To meet the travel needs of special populations and provide a convenient and comfortable traffic experience, modern traffic signal lights incorporate more humanized designs.

4.2.1 Color-blind Friendly Design

For individuals with color blindness or color weakness, accurately discerning the colors of traditional traffic signal lights poses a potential risk during travel. Therefore, designs that utilize other visual elements such as position, shape, pattern, brightness, and contrast have emerged to facilitate signal light recognition [6]. For example, adding different shapes or symbols to red and green lights, or arranging the three signal lights in specific positions and brightness sequences, allows individuals with color blindness or color weakness to obtain accurate travel information.

4.2.2 Audio Cues and Vibration Feedback

To meet the needs of visually impaired individuals, such as blind or severely visually impaired individuals, audio cues and vibration feedback features have been added to traffic signal lights. This creates perceptual experiences in terms of hearing and touch, aiding them in determining the displayed status of the signal lights and safely navigating the intersection.

4.2.3 Touch Interaction Settings

With the development of smart transportation technology, "touch-controlled traffic lights" have become a "safe haven" for individuals with limited mobility or slow mobility. By embedding special touch buttons or touch screens into the traffic light poles at both ends of a crosswalk, a touch-controlled interface for traffic lights is implemented. Pedestrians can use a dedicated protocol card to swipe and touch, autonomously controlling the changes in signal lights and indicating the direction of travel. This system provides security for safely crossing the crosswalk.

4.3 Digitization of Operating Systems

4.3.1 Smart Connectivity of the Internet of Vehicles (IoV)

The Internet of Vehicles (IoV) is one of the important application scenarios of 5G and 6G. It perceives vehicle-side information, utilizes the latest sensing and mobile communication technologies, and integrates in-vehicle networks, vehicle-mounted mobile internet, and inter-vehicle networks through a three-layer system architecture—sensing layer, network layer, and application layer. This creates intelligent connections between vehicles, people, roads, and network service platforms, enabling real-time information collection and processing [7]. This ensures that traffic elements such as people, vehicles, and roads are "visible, clear, and accurate" in real-time and space, making vehicle travel services more intelligent. Moreover, IoV improves the efficiency and service level of the traffic system, shifting the traffic signal control mode from "post-response management" to "pre-service guidance." For vehicles with special traffic tasks, traffic signal lights can be adjusted in advance as the vehicle approaches. For congested road segments during specific periods, traffic signal lights can dynamically adjust red-green signals based on vehicle information, achieving efficient configuration of traffic control elements such as people, vehicles, and roads [8].

4.3.2 Efficient and Accurate Cloud Computing

Faced with the generation of massive traffic information in the process of modernizing traffic, the capacity and speed of traditional information processing systems are unable to meet the simultaneous processing, storage, and transmission requirements of millions or even tens of millions of basic traffic elements. By employing cloud computing methods, efficient collection, processing, mining, and analysis of massive traffic information have been achieved [9]. All information collection and analysis results are transmitted back to the traffic control system as integrated units. This not only meets the real-time traffic information control needs of traffic management departments but also allows traffic flow analysis based on data. Through traffic signal facilities, the existing travel demand is guided, and road network traffic is balanced, leading to the formulation of regional traffic timing plans. Additionally, the cloud computing method can dynamically invoke different numbers of computing units for efficient calculations based on computing needs, meeting the differences in computing demand at different times. This becomes an effective approach for implementing dynamic traffic predictions.

4.4 Green Energy Supply

Green energy, referring to clean and renewable energy, is energy that does not emit pollutants and can be directly used for production and daily life. Solar energy, one component of green energy, is widely used as a source of energy for traffic signals. An example is the ultra-low-carbon solar signal lights implemented in Beijing. Their appearance and functions are identical to traditional signal lights, with the only difference being that they are powered by solar panels instead of the traditional 220V AC power grid. Compared to ordinary signal lights, solar-powered traffic signal lights are more environmentally friendly, energy-efficient, and equipped with energy storage capabilities. During installation, there is no need to lay signal cables, effectively avoiding power outages caused by construction, making them increasingly prevalent [10]. Currently, solar-powered traffic signal lights represent an inevitable trend in the modern development of traffic signal control. Utilizing high-brightness LEDs as light sources, they emit monochromatic light, eliminating the need for color filters to directly display red, yellow, and green signal colors.

5. Application of Intelligent Traffic Signal Lights

5.1 Experimental Design

By modeling the actual intersection layout of Wenyang Road and Fengcheng Second Road in the Synchro software and combining the traffic flow data obtained from on-site surveys, a simulation was conducted to compare the impact of sensor-coordinated control signal lights and timed control signal lights on the operational efficiency of the road. The aerial photograph below illustrates the basic intersection layout of Wenyang Road and Fengcheng 2nd Road (Figure 1. Basic type of the intersection of Weiyang Road and Fengcheng 2nd Road).

In the Synchro Network traffic network parameter settings, input the corresponding survey values as follows (Table 1. Survey values of traffic network parameters):

Figure 1. Basic Type of the Intersection of Weiyang Road and Fengcheng 2nd Road

Table 1. Survey Values of Traffic Network Parameters

Parameter Attribute	Parameter Name	Value
Lands	Lands Width(m)	3.5
	Flow Rate(vphpl)	1650
	Travel Speed (km/s)	40
	PHF	0.92
Volumns	Heavy Vehicles(%)	0
	Walking Speed(m/s)	1.35
Timings	Yellow Times(s)	3.0
	All Red Times(s)	2.0

Through on-site investigations, the physical channelization information (Table 2. Physical channelization information for intersection inlet approaches) and the balanced traffic volumes for each inlet approach of the intersection (Table 3. Traffic volume balancing results for Wenyang Road and Fengcheng 2nd Road intersection) are as follows:

Table 2. Physical Channelization Information for Intersection Inlet Approaches

Inlet Direction	Exclusive Left	Shared Left	Through	Right Turn
East	1	0	1	1
West	1	0	1	1
South	1	0	2	1
North	1	0	2	1

Table 3. Traffic Volume Balancing Results for Wenyang Road and Fengcheng 2nd Road Intersection

Inlet Direction	Left Turn	Through	Right Turn	Total Volume
North Inlet	290	1049	245	1754
South Inlet	310	1123	321	1660
West Inlet	300	421	111	852
East Inlet	312	510	240	1062

5.2 Experimental Process

Modeling is carried out according to the relevant data collected above, and the following figure is obtained (Figure 2. Intersection Modeling):

Figure 2. Intersection Modeling

In the Timing setting, a left-turn protection phase (Prot) was established based on the actual phase. Subsequently, simulations were conducted separately under Inductive Coordinated Signal Control and Fixed-Timing Signal Control. Reports were generated, and the simulation results were compiled and summarized into a table.

5.3 Data Analysis and Conclusion

From the above experimental results, the following table can be drawn (Table 4. Comparison under Different Traffic Demands):

Table 4. Comparison under Different Traffic Demands

Control Mode	Total Stops	Average Delay	Service Level	Queue Length
Fixed-Timing Signal Control	3700	122.7	F	56.4
Inductive Coordinated Signal Control	3586	115.4	D	49.3

The data in the table above indicates that, compared to the current fixed-timing signal control at the intersection, inductive coordinated signal control reduces the total number of stops, average delay, and queue length for vehicles. Moreover, under higher traffic demands, inductive coordinated signal control achieves a higher service level. This suggests that inductive coordinated signal control effectively improves the traffic operation at the intersection of Wenyang Road and Fengcheng Second Road, alleviating road congestion. The reduction in stops also implies a decrease in the number of times vehicles start and stop, thereby reducing fuel consumption and carbon emissions, indirectly promoting the greening of transportation.

6. Conclusions

As the Internet advances at an unprecedented pace, the integration of information technology with the transportation industry is propelling the rapid development of smart transportation. The traffic signal system, a crucial component of smart transportation, serves not only as intelligent, agile, and safety-controlled infrastructure but also as a catalyst for promoting intelligent travel, global traffic control, and real-time traffic services. In the era of "managing urban traffic and regulating traffic signals," the modern "traffic signal" resembles anchor points within the extensive network of the "traffic neural system." Continuous exploration and innovation are essential. These efforts, acting as focal points, provide robust support for the development of intelligent automobiles, autonomous driving, smart travel, and intelligent cities. This constant progress contributes to the continuous advancement of intelligent traffic, marking the splendid chapters in the journey toward a strong and efficient transportation network.

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