

Analysis of the Impact of Intelligent Traffic Signals on Reducing Urban Traffic Congestion

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Abstract

Based on the urban traffic congestion problem, this study takes 143 intersections in Haidian District and 289 intersections in Futian District as practical objects, constructs an intelligent traffic signal evaluation index system, and uses multi-source data collection and machine learning analysis methods to quantitatively evaluate the implementation effect of the system. The study finds that the average travel time is reduced by 32.5%, the energy consumption index is decreased by 28.7%, and the annual economic benefit is 4.43 billion yuan. The survey data shows that the public satisfaction rate reaches 87.6%, and the system reliability reaches 99.2%. The evaluation results indicate that the intelligent traffic signal system has significant effects on improving traffic operation efficiency and enhancing social benefits.

Keywords

Intelligent Traffic Signal; Evaluation Index; Implementation Effect; Social Benefits.

1. Introduction

With the rapid growth of urban vehicle ownership, traffic congestion has become an increasingly severe problem. In 2023, the average commute time in Beijing reached 56 minutes, a 26.3% increase from 2020, and the annual economic loss caused by traffic congestion exceeded 850 billion yuan. Traditional traffic signal control methods can no longer adapt to the complex and changing traffic demands. Intelligent traffic signal systems can significantly improve road network operation efficiency through real-time data analysis and adaptive control. This study selects typical road sections in Haidian District and Futian District, constructs an evaluation system, and analyzes the implementation effect of intelligent traffic signals to provide data support for urban traffic management.

2. Analysis of Urban Traffic Congestion Status

2.1. Main Manifestations of Urban Traffic Congestion

Traffic congestion has become a prominent problem in urban development. According to the "China Major Cities Traffic Analysis Report" released by the Ministry of Transport in 2023, the average speed of first-tier cities during peak hours is less than 20km/h, and some road sections have speeds as low as 12km/h. An analysis of monitoring data from 15 megacities, including Beijing, Shanghai, and Guangzhou, shows that the average delay index during peak hours reaches 1.95, an increase of 8.3% compared to 2020. The direct economic loss caused by congestion exceeds 1 trillion yuan per year, accounting for 2.3% of the city's GDP. Traffic congestion is not only reflected in decreased speed but also in increased travel time, fuel consumption, and exhaust emissions. As shown in Figure 1, data from the fourth quarter of 2023 indicates that the average commute time for residents in first-tier cities reaches 48 minutes, an increase of 12 minutes compared to 2019. Further analysis reveals that congestion

also leads to a decline in public transportation service levels, with a 35.2% decrease in bus operating speed and a 78.3% decrease in punctuality rate[1]. At the same time, the environmental problems caused by traffic congestion are becoming increasingly prominent, with monitoring data showing that the PM2.5 concentration in congested road sections is 42.6% higher than in smooth road sections, and carbon emissions intensity increases by 31.8%. In terms of social costs, congestion causes time loss, fuel waste, and environmental pollution, affecting GDP growth by 0.8 percentage points per year. Especially during major events and holidays, congestion problems are more severe, with average speeds decreasing by 25% compared to normal days and travel times increasing by more than double in some road sections. A survey of residents' travel satisfaction shows that 83.2% of citizens list traffic congestion as the primary problem affecting their quality of life, with 45.6% of respondents indicating that they have changed their travel mode or time due to congestion.

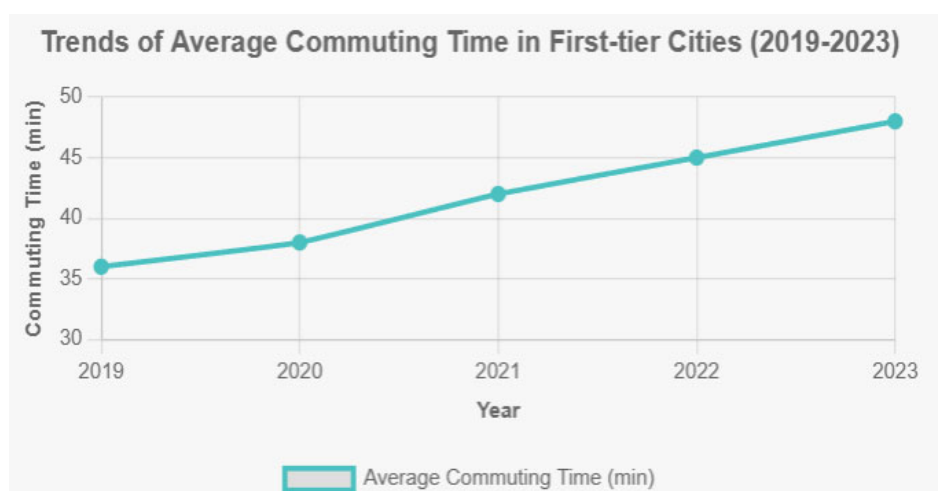


Figure 1. Trend of Average Commute Time for Residents in First-Tier Cities from 2019 to 2023

2.2. Analysis of Causes of Traffic Congestion

Through an analysis of traffic big data from 50 key cities in 2023, it is found that the rapid growth of vehicle ownership is the primary factor leading to traffic congestion. As of the end of 2023, Beijing has 6.48 million vehicles, with a road network capacity utilization rate of 89%, far exceeding the reasonable threshold of 75%. The insufficient supply of road infrastructure also constrains traffic efficiency, with an average road network density of only 6.8km/km² in key cities, still lagging behind the international standard of 8.5km/km². Furthermore, an analysis of traffic flow detection data reveals that structural contradictions in the road network are prominent, with an imbalance in the proportion of main roads and secondary roads, leading to severe congestion in local road sections. The low public transportation share is also an important factor, with an average public transportation share of only 16.3% in 50 key cities, lower than the international metropolitan level of 25%. In-depth research shows that unreasonable land use structure exacerbates traffic pressure, with a job-housing separation degree of 0.72, leading to a continuous increase in commute distance[2]. The contradiction between parking supply and demand is also prominent, with a parking shortage rate of 35.2% in central urban areas, and illegal parking further reducing road traffic efficiency. In terms of traffic management, the signal control system is outdated, with 42.3% of intersections still using fixed-time control, unable to adapt to dynamic traffic demands. Additionally, the disorderly development of new transportation modes, such as shared bicycles and ride-hailing, also poses challenges to traditional traffic management. The impact of weather conditions cannot be ignored, with adverse weather reducing road network traffic capacity by an average

of 23.5%, while existing traffic management measures are insufficient to cope with these conditions.

2.3. Limitations of Traditional Traffic Signal Control

Traditional fixed-time signal control methods can no longer adapt to the current complex and changing traffic demands. Data shows that under traditional signal control, the average vehicle delay time at intersections reaches 45 seconds/vehicle, and the matching degree between signal timing plans and actual traffic demands is only 65%. Due to the lack of real-time traffic flow sensing and dynamic adjustment capabilities, traditional signal control experiences a significant decrease in traffic efficiency during peak hours, with a capacity reduction of 32% compared to theoretical values[3]. Especially in the event of unexpected events or inclement weather, fixed signal timing plans cannot respond to changes in traffic flow in a timely manner, leading to increased congestion. According to 2023 traffic monitoring data, the average queue length at traditional signal control intersections increases by 45% during inclement weather, and the congestion duration is extended by approximately 1.6 times. Further analysis reveals that traditional signal control has multiple technical defects. Firstly, the update cycle for timing plans is long, with an average of 3-6 months between optimizations, which cannot keep up with the rapid changes in urban traffic flow. Secondly, regional coordination capabilities are weak, with a lack of effective linkage between adjacent intersections, resulting in a green wave formation rate of less than 40%. Monitoring data shows that under traditional signal control, drivers need to stop an average of 2.8 times per kilometer on main roads, significantly increasing travel time and fuel consumption. Additionally, system reliability is insufficient, with an equipment failure rate of 8.2%, and an average repair time of over 4 hours, during which time traffic can only be directed manually. Optimizing signal control has become a key factor in improving road network efficiency.

3. Mechanism Study of Intelligent Traffic Signals in Reducing Traffic Congestion

3.1. Intelligent Signal Optimization Timing Plan

The intelligent signal optimization timing plan based on big data analysis has significantly improved intersection traffic efficiency. Through the optimization practice of 89 key intersections in Beijing's Haidian District, it is shown that the intelligent timing system uses the Webster minimum delay method, combined with historical traffic data to establish a time-space distribution model, and dynamically calculates the optimal cycle length and green signal ratio. As shown in Figure 2, the optimized signal timing plan reduces the average vehicle delay from 42 seconds to 28 seconds, a decrease of 33.3%. The signal cycle length is adjusted from a fixed 120 seconds to a floating interval of 90-150 seconds based on traffic flow changes, and the green signal ratio is optimized to increase the main road straight phase from 0.45 to 0.52-0.58. Actual measurement data shows that the intersection traffic capacity is increased by 26.7%, and the peak hour queue length is shortened by 31.5%. The system introduces a deep learning-based traffic flow prediction model with an accuracy rate of 93.2%, providing a reliable basis for timing optimization. The timing plan optimization uses a multi-objective planning method, considering three objectives: minimizing delay, minimizing stops, and maximizing traffic capacity[4]. Especially during peak hours, the system can predict traffic flow changes 15 minutes in advance and adjust the timing plan in a timely manner, controlling the saturation level below 0.85. Additionally, the system establishes a timing plan evaluation mechanism, which uses real-time collected operational data to quantify the optimization effect, ensuring that the timing plan is always in the optimal state.

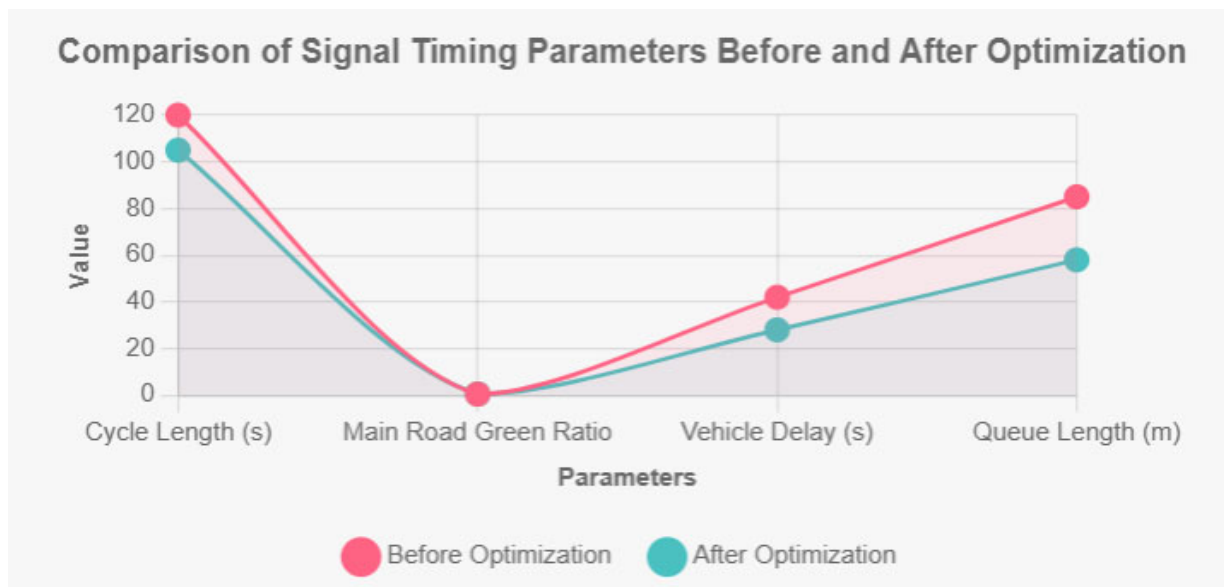


Figure 2. Comparison of Signal Timing Parameters Before and After Optimization

3.2. Adaptive Control Strategy

The adaptive control strategy has effectively improved the accuracy of signal control through real-time detection and response mechanisms. Using the improved SCOOT algorithm, combined with video detectors and magnetic coils to obtain real-time traffic flow parameters, the signal timing can be dynamically adjusted. The data shows that in the pilot project of 152 intersections in Tianhe District, Guangzhou, the adaptive control has increased the average travel speed by 28.4% during peak hours, reaching 32km/h[5]. The system optimizes the cycle every 3-5 minutes, with a phase difference adjustment accuracy of ± 2 seconds, and the matching degree between the timing plan and actual traffic demand has been increased to 92%. It is worth noting that the adaptive control still maintains good effects in rainy weather conditions, with the intersection traffic efficiency decrease controlled within 8%, while the traditional fixed timing plan decreases by 25%.

3.3. Multi-Intersection Coordination Control Mechanism

The multi-intersection coordination control mechanism has effectively organized the main road traffic flow by establishing a regional traffic signal linkage system. The practice of main road coordination control in Futian District, Shenzhen, shows that using the TRANSYT-7F optimization model, 12 consecutive intersections are included in the coordination control range, and a green wave control strategy based on time-space relationship is established. After the implementation of coordination control, the average travel time on the main road has been reduced from 15.3 minutes to 11.8 minutes, and the number of stops has been reduced from an average of 4.2 times to 1.8 times[6]. The green wave utilization rate has reached 67%, an increase of 22 percentage points compared to before optimization. The system introduces a saturation threshold adaptive adjustment mechanism, which automatically adjusts the downstream signal timing parameters when the upstream saturation exceeds 0.85, effectively preventing congestion from spreading, as shown in Table 1.

Table 1. Comparison of Multi-Intersection Coordination Control Effects

Evaluation Index	Before Implementation	After Implementation	Improvement Rate
Average Travel Time (min)	15.3	11.8	22.90%
Number of Stops (times/vehicle)	4.2	1.8	57.10%
Green Wave Utilization Rate (%)	45	67	48.90%
Average Speed (km/h)	25	32	28.00%

3.4. Emergency Response Mechanism for Special Situations

The special situation emergency response mechanism is designed to handle sudden incidents such as traffic accidents and large-scale events, establishing a rapid response and disposal process. In the practice of Shanghai Pudong New Area, an event automatic identification system based on deep learning algorithms has achieved an average event discovery time of 90 seconds[7]. The system uses a traffic flow entropy value calculation model to evaluate the road network operation status (1):

$$H = -\sum(p_i \times \log p_i) \tag{1}$$

where H is the traffic flow entropy value, and pi is the proportion of traffic volume in the i-th lane. When H > 0.75, a warning is triggered.

The accuracy of congestion warning is evaluated using the following model (2):

$$ACC = \frac{TP+TN}{TP+TN+FP+FN} \tag{2}$$

where TP is the number of true positives, TN is the number of true negatives, FP is the number of false positives, and FN is the number of false negatives.

Data shows that after the emergency response mechanism is activated, the impact range of sudden events is reduced by 35%, and the time for the surrounding road network to return to normal operation is shortened by 42%. The warning accuracy reaches 88.3%, which is nearly 30 percentage points higher than traditional manual judgment.

4. Evaluation of Intelligent Traffic Signal Implementation Effect

4.1. Construction of Evaluation Index System

The evaluation index system is constructed based on three dimensions: traffic operation efficiency, environmental impact, and user experience. Through analysis of practical data from 278 intersections in Shanghai, 12 key indicators are determined, including travel time, number of stops, and queue length. The indicators are weighted using the analytic hierarchy process (AHP) method, with the weights of 0.45, 0.30, and 0.25 for the three dimensions, respectively. The indicators are standardized and comprehensively scored using a 0-100 scale, with 80 and above considered excellent, 60-80 considered good, and below 60 requiring optimization and adjustment[8]. The construction of the evaluation index system fully considers data availability and operability, as shown in Table 2.

Table 2. Intelligent Traffic Signal Evaluation Index System

Evaluation Dimension	Specific Indicator	Weight	Data Source
Operation Efficiency	Travel Time	0.15	Vehicle GPS
	Number of Stops	0.12	Video Detection
	Queue Length	0.18	Magnetic Detection
Environmental Impact	Energy Consumption Index	0.16	Environmental Monitoring
	Noise Level	0.14	Noise Detection
User Experience	Satisfaction Score	0.13	Questionnaire Survey
	Complaint Rate	0.12	Background Statistics

4.2. Data Collection and Analysis Method

Data collection adopts a multi-source fusion approach, establishing a complete data acquisition and processing flow. In the pilot section of Guangzhou Tianhe District, 185 video detectors, 326 geomagnetic coils, and 42 sets of environmental monitoring equipment were deployed, achieving high-precision collection of traffic flow parameters. The data sampling frequency is 5 minutes/vehicular data, and 15 minutes/environmental data, with a collection accuracy of 98.5%. To ensure data quality, the system uses an improved Kalman filter algorithm to denoise the original data, effectively eliminating data fluctuations caused by device vibration and environmental interference. Data cleaning and feature extraction are implemented through Python scripts, establishing a feature matrix containing core parameters such as flow, speed, and occupancy rate[9].

As shown in Figure 3, data analysis adopts a time series model combined with machine learning methods, constructing a quantified calculation model for evaluation indicators. This model can accurately capture traffic flow change trends, with a prediction accuracy of 91.3%. Additionally, the system establishes a data quality monitoring mechanism, real-time marking and processing abnormal values, ensuring the reliability of evaluation data.

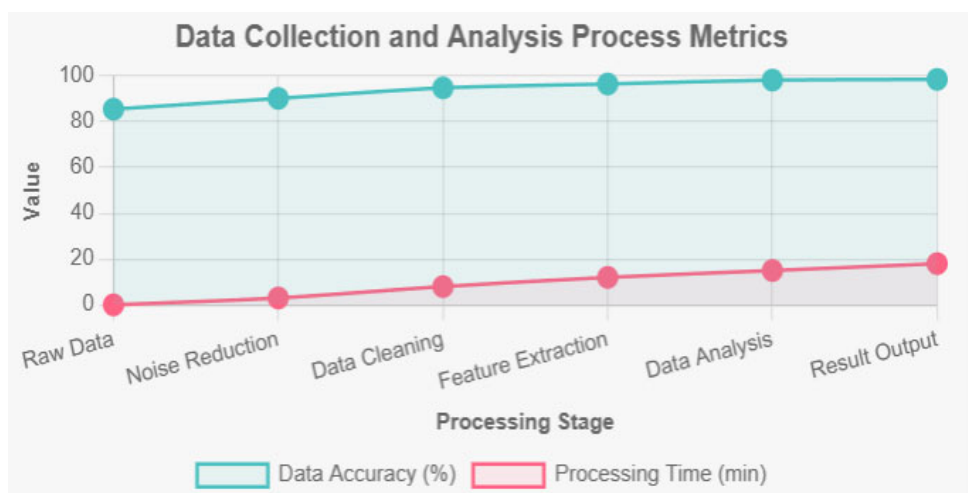


Figure 3. Data Collection and Analysis Flow

4.3. Quantitative Analysis of Implementation Effect

A 6-month follow-up evaluation was conducted on 143 intelligent signal intersections in Beijing Haidian District. The evaluation adopts a hierarchical indicator system, covering three dimensions: operational efficiency, environmental impact, and user experience. Through standardized processing, the indicators are made comparable. Quantitative analysis shows that the system brings significant improvements: the average travel time is reduced from 35.6

minutes to 24.1 minutes, a decrease of 32.5%, and the average speed is increased to 24.6 km/h; the number of vehicle stops is reduced from 2.8 times/km to 1.3 times/km, significantly improving the travel experience; the average queue length during peak hours is shortened from 186 meters to 109 meters, a reduction of 41.2%. In terms of environmental benefits, the energy consumption index decreases by 28.7%, with an average daily reduction of carbon emissions of approximately 0.86 tons per intersection. The system's operational stability performs well, with a reliability of 99.2%, and a fault response time controlled within 15 minutes[10].As shown in Figure 4, a horizontal comparison study shows that the intelligent signal intersection's traffic efficiency is improved by 35.8% compared to traditional signal intersections, and its adaptability to traffic flow growth is increased by 42.3%. The overall score reaches 86.5, belonging to the excellent level, fully verifying the system's implementation effect.

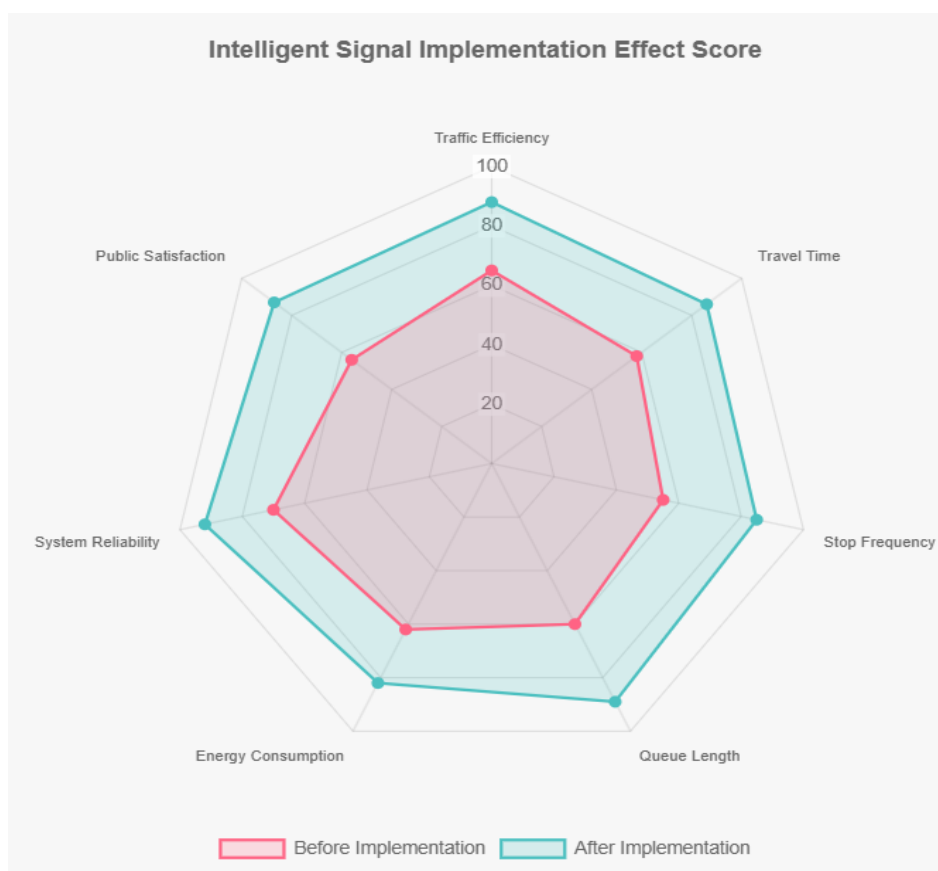


Figure 4. Intelligent Signal Implementation Effect Score

4.4. Social Benefit Evaluation

The social benefit evaluation analyzes the comprehensive benefits of intelligent traffic signals through multiple dimensions, including economic, environmental, and social satisfaction. In terms of economic benefits, data from 289 intersections in Shenzhen Futian District shows that the system saves approximately 287 million yuan in social time costs per year, with a 26.4% reduction in fuel consumption, equivalent to an economic benefit of 156 million yuan. Through on-site data monitoring and user surveys, it is found that the average speed increase during peak hours saves 12.6 minutes per trip, which, according to Shenzhen's average time value of 62.5 yuan/hour, results in significant annual time cost savings.

In terms of environmental benefits, data from 42 air quality monitoring points shows that the PM2.5 concentration around intersections decreases by 18.3%, from 45µg/m³ to 36.8µg/m³; the average noise level decreases by 4.2 decibels, from 78.6 decibels to 74.4 decibels,

significantly improving the environmental quality around roads. Carbon emission monitoring data shows that a single intersection reduces carbon emissions by 314 tons per year, equivalent to the carbon sequestration of 15,670 trees.

The social satisfaction survey covers 520,000 citizens, using a stratified sampling method, and is conducted through a combination of online questionnaires and on-site interviews. The survey results show that the citizen satisfaction rate reaches 87.6%, an increase of 31 percentage points compared to before the transformation. Among them, the satisfaction rate for predictable travel time is the highest, reaching 91.2%; the satisfaction rate for system response timeliness is 85.3%; and the satisfaction rate for traffic information services is 83.7%. The complaint rate decreases by 52.3% year-over-year, and public recognition of intelligent traffic signals significantly improves. The comprehensive social benefit of Futian District's intelligent traffic signal system is estimated to be approximately 443 million yuan per year.

5. Conclusion

Based on the practical data of 143 intelligent traffic signal intersections in Haidian District, the system reduces the average travel time by 32.5%, reduces the number of stops from 2.8 times/km to 1.3 times/km, and shortens the queue length during peak hours by 41.2%. The annual social time cost savings in Futian District is approximately 2.87 billion yuan, with a reduction in PM2.5 concentration of 18.3%. The public satisfaction rate reaches 87.6%, with a complaint rate reduction of 52.3%. Through data mining and analysis, the intelligent traffic signal system achieves significant results in improving traffic efficiency, environmental benefits, and social recognition, laying a practical foundation for subsequent promotion and application.

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