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Research on Signal Timing Optimization and Traffic Efficiency Improvement at Highway Intersections under the Background of Intelligent Transportation

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Abstract: This paper aims to enhance highway traffic efficiency by integrating a project focused on signal timing optimization at highway intersections. Supported by intelligent technologies, a reasonable optimization system is constructed. Practical application demonstrates that the signal timing optimization at highway intersections under this system yields significant results, substantially improving traffic efficiency. This provides a reference for subsequent signal timing optimization at highway intersections, aligning with the development needs of the intelligent transportation context.

Keywords: Highway intersections; Signal timing optimization; Intelligent transportation; Dynamic signal timing

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1. Introduction

1.1. Preface

As critical nodes in modern urban transportation networks, the traffic efficiency of highway intersections directly influences the overall performance of urban traffic. With the accelerating urbanization and the continuous increase in vehicle ownership, traditional signal timing plans can no longer meet the actual management and control needs of traffic flow at highway intersections. Traffic congestion during peak hours and excessive delays in vehicle passage have become common occurrences. The development of intelligent transportation technologies offers technical support to address such issues. Against the backdrop of intelligent transportation, by implementing reasonable measures for multi-source data collection and preprocessing, and utilizing traffic prediction models and dynamic signal timing optimization algorithms, signal timing can be effectively optimized to enhance traffic efficiency [1]. Therefore, researchers should, based on the current context of intelligent transportation and the actual conditions of highway intersections, develop reasonable intelligent signal timing plans supported by advanced data collection technologies, intelligent algorithms, and models. Additionally, through project practice, the implementation effects of intelligent timing plans should be validated, and their adaptability in intelligent transportation scenarios should be further improved through continuous optimization and refinement, serving as a reference for subsequent similar projects.

2. Project overview

A certain highway intersection is located at the intersection of major roads in the eastern part of the urban area, serving as an important connecting channel between the eastern district and the city center. Currently, this intersection has four entrance lanes and two exit lanes. The east-west direction is a two-way, six-lane road, while the north-south direction is a two-way, four-lane road. The traffic volume can reach 32,000 vehicles per day, with peak hours occurring from 7:30 to 9:00 AM and from 5:30 to 7:00 PM. The traditional signal timing plan for this intersection employs fixed-time signal timing, with a cycle length of 120 seconds. The green light duration for each phase is allocated based on the historical average traffic volume. Through on-site research, it was found that during peak hours, the average delay time at the entrance lanes of this intersection can exceed 80 seconds, with the maximum queue length reaching 230 meters. During off-peak hours, common issues such as green light wastage and redundant vehicle waiting times are observed, indicating a significant gap from the current requirements for intelligent and refined traffic management. To address these issues, the traffic management department set dynamic traffic flow adaptation and improved traffic efficiency as fundamental goals. They spent one month comprehensively collecting traffic data and establishing an intelligent signal timing optimization system, followed by one week of on-site application verification. Ultimately, a signal timing optimization plan that meets the actual optimization needs of the project was formulated, significantly enhancing the intersection's traffic efficiency.

3. Construction of an intelligent optimization system for signal timing at highway intersections

Based on the project's basic conditions and signal timing optimization requirements, the traffic management department constructed a comprehensive intelligent optimization system for signal timing from three dimensions: data, models, and algorithms. The specific composition and construction methods of this system are as follows.

3.1. Multi-source data collection and preprocessing

Multi-source data provides foundational support for the intelligent optimization of signal timing. In this project, the traffic management department comprehensively collected core traffic flow data and related auxiliary data for the highway intersection, while simultaneously implementing data simplification and preprocessing to ensure the quality of the multi-source data.

Collecting platform data through core equipment. Set up video detectors on the entrance roads to collect real-time traffic flow data, including traffic volume, queue length, average speed, etc., with a collection interval of 5 minutes. Additionally, utilize geomagnetic detectors to supplement lane-level data, preventing missed detections due to video obstruction [2]. Integrate with the traffic management platform of the city where the project is located to obtain relevant information such as regional weather and holiday indicators from the platform, providing a basis for analyzing the impact on traffic flow in special scenarios. Comprehensively extract timed signal timing parameters at intersections for the six months preceding the project's launch to provide historical data support for subsequent optimization comparisons.

For the collected multi-source data, preprocessing is primarily implemented in two steps. The first step involves handling outliers and missing values, where data points deviating more than three times the mean standard deviation are identified as anomalies and removed. The second step is data normalization, which maps data with different magnitudes, such as traffic volume and speed, to the [0,1] interval. This effectively eliminates the adverse effects of magnitude differences on the analysis model, resulting in a structured dataset with a granularity of 5 minutes to support subsequent traffic flow prediction and signal timing optimization.

3.2. LSTM traffic flow prediction model

To ensure the effectiveness of dynamic signal timing at intersections, reasonable traffic flow prediction is crucial. Based on this, the project primarily establishes a prediction model using a simplified Long Short-Term Memory (LSTM) network to accurately predict the traffic volume on entrance roads for the next 30 minutes. The model architecture consists of three layers: the first layer is the input layer, which uses traffic volume and vehicle speed data monitored in the previous hour as feature data for input; the second layer is the hidden layer, which contains 64 LSTM neurons. It utilizes gating mechanisms to capture long-term dependencies in traffic flow, addressing the gradient vanishing problem in traditional recurrent networks; the third layer is the output layer, which outputs the predicted total traffic volume on the entrance road for the next 30 minutes with the support of a fully connected layer.

During model training, the traffic monitoring data from intersections over the past month needs to be divided into three parts: training set, validation set, and test set, with a ratio of 7:2:1. The mean absolute error is used as the loss function, and the predicted traffic volume is calculated using the following formula:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} | y_{ture,i} - y_{pred,i} | \quad (1)$$

In the formula, MAE represents the mean absolute error; n represents the data volume; $y_{ture,i}$ represents the actual traffic flow at moment i; and $y_{ture,i}$ represents the predicted traffic flow at moment i. One hundred iterations are performed using the Adam optimizer with a learning rate of 0.001. After validation with the validation set and testing with the test set, it is determined that the value of MAE is less than 5 pcu/5min, indicating that the prediction accuracy of this model meets the dynamic signal timing requirements for intersections in this project.

3.3. Dynamic signal timing optimization algorithm

For traffic flow prediction data supported by the LSTM model, this project primarily designs a dynamic signal timing optimization algorithm for intersections with the support of an improved genetic algorithm, with the main objective of minimizing intersection delay time [3]. The objective function of this algorithm is simplified based on the principle of minimizing the mean total delay time at intersections, and the simplified objective function is as follows:

$$\min D = \sum_{i=1}^{4} D_i \quad (2)$$

In the formula, min$D$ represents the minimum mean total delay time at intersections; D_i represents the mean delay time for the i-th entry lane.

Based on the above objectives, the following three core constraints are set:

(1) The green light duration for each phase should be no less than 15 seconds to ensure pedestrian crossing safety;
(2) The signal cycle should be controlled between 60 and 180 seconds;
(3) The sequence of the three fixed phases is set as east-west straight travel → east-west left turn → north-south straight travel → north-south left turn, which aligns with actual traffic flow habits.

For this improved genetic algorithm, the specific calculation steps mainly include the following four during implementation.

(1) Encoding and initialization

Represent the green light duration for each phase with chromosomes, encode them using real numbers, and generate 50 initialized individuals that meet the constraints.

(2) Selection operation

Use the roulette wheel selection method to retain high-quality individuals based on individual fitness. The shorter the delay time, the higher the individual fitness and the better the quality.

(3) Crossover and mutation

Generate offspring individuals through single-point crossover with a probability of 0.8 and Gaussian mutation with a probability of 0.05.

(4) Iterative output

After 50 iterations, output the optimal green light duration and cycle plan. The timing parameters should be updated every 30 minutes to ensure dynamic signal matching [4].

3.4. Verification of improved traffic efficiency under the intelligent optimization system for signal timing at highway intersections

(1) Verification plan

For the intelligent optimization plan for signal timing at intersections formulated this time, the traffic management department conducted verification from May 10 to May 16, 2025, with a verification period of one week. The effectiveness of the system was verified by comparing three different plans. The first plan is a traditional fixed-time signal timing plan, with a fixed cycle length of 120 seconds, 28 seconds each for east-west straight and left-turn movements, 38 seconds for north-south straight movement, 23 seconds for north-south left-turn movement, and 3 seconds of yellow light for each phase. The second plan is a traditional Webser plan, where the cycle length and green light duration are calculated using the Webser minimum delay formula. The cycle length is reasonably set according to peak and off-peak traffic periods, with the former set at 130 seconds and the latter at 100 seconds. The third plan is the intelligent optimization signal timing plan formulated this time, which dynamically adjusts signal timing using multi-source data, an LSTM prediction model, and an improved genetic algorithm, updating timing parameters every 30 minutes. Through the multi-source data collection method during the data collection and preprocessing phase, traffic data for the intersection over the previous month was collected with the support of video detectors and geomagnetic devices. Data was collected and recorded every 5 minutes, and the aforementioned methods were used for preprocessing to ensure the objectivity and comparability of the preprocessed data [5].

(2) Efficiency comparison

After collecting, statistically analyzing, and comparing the traffic data at the intersection over one week during the verification period using the aforementioned three plans, the comparison results of key traffic efficiency indicators are shown in **Table 1**. All data represent the average timing parameters over 7 days for each time period.

Table 1. Comparison of key traffic efficiency indicators under three signal timing plans during the verification period of the project

No.	Period	Timing scheme	Average queue length (m)	Average delay time (s)	Average stop frequency (times/h)	Traffic capacity (pcu/h)
1	Morning peak	Fixed-time	215.3	82.5	1.8	1850
		Traditional webster	178.6	65.2	1.5	2100
		Designed intelligent timing	120.5	42.8	1.1	2580
2	Off-peak	Fixed-time	102.1	45.3	1.2	2000
		Traditional webster	85.4	38.6	1.0	2200
		Designed intelligent timing	60.2	25.1	0.7	2650
3	Evening peak	Fixed-time	230.5	88.7	1.9	1800
		Traditional webster	185.2	68.9	1.6	2050
		Designed intelligent timing	128.7	45.3	1.2	2520

By comparing the above data, it can be seen that, compared with the other two signal timing plans, the intelligently designed timing plan demonstrates more significant advantages in traffic efficiency during practical application. In terms of delay duration control, its delay durations during morning peak, off-peak, and evening peak hours are all significantly shorter than those of the other two plans. Regarding traffic capacity, its capacities during morning peak, off-peak, and evening peak hours are all higher than those of the other two plans. Additionally, in terms of queue length and number of stops, this plan also achieves significant optimization compared to the other two plans, as shown in the comparative data chart. (**Table 2**)

Table 2. Summary of traffic efficiency improvements of the intelligent timing plan compared to the other two plans for the project

No.	Efficiency metric	Period	Improvement vs. fixed-time scheme	Improvement vs. webster scheme
1	Average delay reduction rate	Morning peak	48.1%	34.4%
		Off-peak	44.6%	35.0%
		Evening peak	48.9%	34.3%
2	Average queue length reduction rate	Morning peak	44.0%	32.5%
		Off-peak	41.0%	29.5%
		Evening peak	44.2%	30.5%
3	Traffic capacity increase rate	Morning peak	40.0%	22.9%
		Off-peak	32.5%	20.5%
		Evening peak	40.0%	22.9%
4	Average stop frequency reduction rate	Morning peak	38.9%	26.7%
		Off-peak	41.7%	30.0%
		Evening peak	36.8%	25.0%

(3) Verification conclusions

Through the analysis of data from this project verification, the traffic management department has primarily drawn the following two conclusions. Firstly, in the optimization of signal timing at at-grade intersections in intelligent transportation systems, the intelligent optimization system demonstrates outstanding effectiveness [6]. Through data preprocessing, traffic flow prediction, and dynamic signal timing optimization modes, this plan enables the signal timing at intersections to dynamically match the actual traffic flow conditions, significantly reducing delay times, shortening queue lengths, enhancing traffic capacity, and decreasing the average number of stops compared to traditional signal timing plans. Consequently, it provides intelligent technical support for the refined management of at-grade intersections, meeting the signal timing and traffic management needs in the context of intelligent transportation systems [7]. Secondly, the intelligent timing plan exhibits stronger adaptability in signal timing during traffic peak periods. Facing significant fluctuations in traffic flow during morning and evening peak hours, the intelligent timing plan can dynamically adjust every 30 minutes to prevent situations such as red-light congestion or green light wastage, thereby better controlling vehicle queue lengths and the number of stops. This results in a significant improvement in traffic efficiency compared to traditional timing plans [8]. From this, it can be seen that the intelligent signal timing plan developed this time is applicable not only to this project but also to the optimization of signal timing at at-grade intersections on highways in similar projects. By reasonably introducing this plan into signal timing optimization projects at intersections and adjusting relevant parameters based on actual conditions, it can demonstrate stronger functionality and advantages compared to traditional timing plans [9]. In subsequent applications and developments, traffic management departments can also reasonably integrate real-time weather data into this plan to further enhance the model's robustness, continuously improve its adaptability in complex traffic management scenarios, and contribute to the development of smart transportation [10].

4. Conclusion

In summary, this study focuses on the low traffic efficiency issue of traditional signal timing plans at at-grade intersections on highways within the context of current smart transportation. Combining practical projects, an intelligent signal timing plan has been designed. The intelligent timing system under this plan primarily encompasses processes such as multi-source data collection and preprocessing, an LSTM-based traffic flow prediction model, and optimization using an improved genetic algorithm. Supported by the aforementioned processes, the intelligent timing plan offers greater application advantages compared to traditional timing plans. It can reasonably optimize control schemes for delay, queuing, passage, and parking at at-grade intersections on highways, significantly improving traffic efficiency and meeting the demands of smart transportation.

Disclosure statement

The author declares no conflict of interest.

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