Research on Evaluation Method for Rational Layout of Urban Bayonet Devices

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Abstract

The layout of traditional traffic bayonet devices is determined entirely based on manual experience without a systematic quantitative analysis framework. This inevitably leads to persistent problems such as unreasonable resource allocation incomplete monitoring coverage, and redundant equipment deployment. Based on field-collected data of Weifang City, this paper constructs a comprehensive evaluation index system from four dimensions: spatial distribution balance, traffic flow bearing adaptability, facility operation efficiency, and road network coordination adaptability. A hierarchical scientific evaluation model is established by adopting a grid discretization model and the Analytic Hierarchy Process (AHP). The empirical results show that the overall evaluation score of bayonet layout in the study area is 65.2, reaching a "basically reasonable" level, while prominent deficiencies still exist, including insufficient monitoring coverage on main roads and overloaded operation of bayonet facilities on arterial roads. Based on the above analytical findings, a targeted technical improvement scheme for the existing traffic bayonet system is proposed. The research results can provide data support for the integration of stock resources and the site planning of new bayonet devices in the field of urban intelligent transportation, and further promote the construction of basic databases for scenarios such as vehicle license plate recognition.

Keywords

Traffic bayonet equipment, layout evaluation, spatiotemporal big data, road network coverage, Analytic Hierarchy Process.

1. Introduction

With the advancement of urbanization and the continuous growth of motor vehicle ownership, high-definition road checkpoints have become an indispensable technical tool for modern traffic management. They deliver significant functional value in numerous scenarios including law enforcement evidence collection, vehicle tracking and traffic flow monitoring, and have gradually evolved into one of the primary data sources for the construction of smart transportation systems.

At present, most regions in China still adopt a traditional operation and maintenance mode relying on manual on-site surveys and empirical judgment for checkpoint layout deployment. A host of drawbacks emerge due to the absence of unified quantitative evaluation criteria. On one hand, frequent installation of additional cameras along major arterial roads results in severe redundant collection of valid information, which escalates data storage load and computational costs. On the other hand, communities in old urban districts or remote areas are equipped with insufficient monitoring points, hindering the rapid identification of illegal activities. Moreover, devices installed at low-traffic intersections remain idle for extended periods, pushing operation and maintenance costs to persist at high levels [1].

Existing research predominantly focuses on image processing and behavioral feature analysis, while few studies explore the development of efficient, practical layout schemes for urban checkpoint networks from the perspective of rational deployment of sensing terminals. Establishing a systematic monitoring point optimization model based on real traffic flow data can substantially improve the accuracy of target vehicle trajectory recording and greatly enhance the overall performance of fake license plate recognition systems, thus bearing profound theoretical research significance and practical application value.

This paper mainly focuses on constructing a four-dimensional quantitative evaluation system for traffic bayonet layout and developing a grid coverage algorithm to accurately calculate spatial distribution parameters. The Analytic Hierarchy Process (AHP) is adopted to determine the weight of each evaluation index and establish a hierarchical decision-making model. Field-collected vehicle passing data of Weifang City are applied for empirical verification, and targeted optimization strategies are proposed accordingly. The core innovation of this research lies in the integration of dynamic traffic flow data and static Geographic Information System (GIS) simulation technology. Breaking the limitation of a single spatial dimension, this study incorporates vehicle trajectory characteristic analysis into the evaluation framework. It constructs a comprehensive evaluation system covering multiple key factors, including coverage scope, traffic flow density, infrastructure deployment status and road network topology, and realizes hierarchical efficiency evaluation. The proposed model generates evaluation results autonomously based on historical vehicle passing records, which avoids the drawbacks of traditional manual on-site investigation. This research provides scientific data support and technical guidance for the optimal planning of intelligent traffic monitoring networks.

2. Data Sources and Preprocessing

2.1. Description of Original Dataset

The experimental sample selected in this paper consists of the full-day vehicle passing records collected by urban road checkpoints in Weifang City on October 29, 2016. This dataset records detailed information including vehicle passage time, license plate number, body color, travel route, entry and exit directions at checkpoints, collection equipment serial number, geographic coordinates, average vehicle speed and other attributes, and covers major traffic arteries such as Beihai Road, Weizhou Road and Baotong Street as well as surrounding road sections. Data analysis indicates that the sample contains data of local vehicles with Shandong Lu-prefixed license plates and a small number of records of out-of-town vehicles. Its spatially heterogeneous distribution enables investigation into the traffic flow structure within the study area. The format of the adopted data strictly complies with the standard specifications for extracting key fields via video surveillance systems stipulated in GB 37300-2018 *Safety Technical Specifications for Motor Vehicles in Operation* [2]. A specific example is provided as follows:

```
datetime,plate_number,color,street_x,street_y,camera_pos,camera_id,device_id,gps_x,gps_y,speed
2016-10-29 08:00:55,LuXXX427,Blue,Beihai Rd.,Fenghuang St,S,3,370700000000015232,119.166161,36.65744,86
2016-10-29 08:00:56,LuXXX67H,Green,Baotong St.,Qingnian Rd.,E,2,370700000000015040,119.105721,36.676048,59
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2.2. Data Preprocessing

To guarantee data quality, the following processing procedures are required:

(1) Removal of dirty data: Eliminate data entries caused by license plate recognition failure, missing body color labels, GPS positioning drift, and abnormal travel speeds. Redundant records generated by repeated monitoring of the same target vehicle by a single acquisition terminal within the same time period are also discarded.

(2) Aggregation and statistics of monitoring points: Take camera_id and device_id as grouping variables to calculate the total traffic volume of each checkpoint. Detailed analysis is conducted on key indicators including periodic traffic fluctuations, the proportion of non-local vehicles, and the count of low-speed vehicles.

(3) Road network spatial matching: Convert raw GPS observation data into road network format, establish a three-tier classification system consisting of arterial roads, secondary roads and branch roads, and label intersection types in detail.

(4) Grid discretization: Tessellate the study area with standard 50 m × 50 m grids to provide basic spatial units for subsequent coverage calculation [3][4].

3. Design of Evaluation Index System

Relying on a four-dimensional model, this paper constructs 11 core evaluation indicators and adopts quantitative methods to assess the model. All indicators are calculated based on vehicle passing records and spatial information of monitoring points, taking into account the operational requirements of traffic control and fake license plate tracking [5].

3.1. Spatial Coverage Dimension

- Road Network Full-area Coverage Rate: It represents the ratio of covered vehicle dynamic grid units within the jurisdiction to the total number of vehicle dynamic grid units. The calculation method of this indicator is as follows:

$$R_{all} = \frac{N_{cover}}{N_{total}} \times 100\%$$

N_{cover} denotes the number of traffic grids covered by monitoring devices, and N_{total} stands for the total number of traffic grids.

- Branch Road Coverage Deficiency Rate: Refers to the percentage of the total area occupied by grid units not recorded by the monitoring system. The higher the value of this indicator, the more severe the existing security vulnerabilities.
- Point Overlap Degree: It is used to evaluate the coverage status of a certain area covered by multiple devices, representing redundant overlap generated during resource allocation.

3.2. Traffic Adaptation Dimension

- Capture Frequency Per Unit Time: An indicator reflecting the operating speed and processing capacity of equipment.
- Traffic Matching Coefficient: The ratio of total passing vehicles on a road section to the number of bayonet checkpoints, a core metric for evaluating the rationality of checkpoint layout.
- Peak-Valley Traffic Volume Difference: It reflects the traffic fluctuation between morning/evening peak hours and off-peak hours, serving as an indicator to judge whether road facilities match residents' travel time patterns.

3.3. Equipment Efficiency Dimension

- Effective Capture Rate: The ratio of successful captures with complete license plate numbers and vehicle body color information to total capture attempts. It reflects the quality of equipment layout and hardware performance.
- Continuous Track Recognition Rate: An indicator for evaluating the tracking accuracy of cloned vehicles. It refers to the proportion of instances where a specific vehicle is continuously identified and recorded across different monitoring nodes.

- Abnormal Vehicle Capture Volume: The total number of captured key regulated vehicles such as non-local vehicles and yellow-label vehicles.

3.4. Road Network Matching Dimension

- Compliance Rate of Monitoring Deployment at Intersections: An indicator to judge whether the installation ratio of bayonet cameras at cross and T-junctions on arterial roads complies with the standard specifications specified in the technical requirements for security video monitoring systems.
- Road Grade Distribution Index: It reflects the matching degree between the number of bayonet cameras on roads of each grade and the corresponding road network length.
- Blind Zone Risk Index: An indicator used to assess the occurrence probability and impact degree of fake-plate vehicles in high-density traffic networks and monitoring blind areas, which measures the threat level caused by their evasion routes[6].

4. Construction of Comprehensive Evaluation Model

4.1. Hierarchical Architecture of the Model

The comprehensive evaluation model (Figure 1) adopts a three-layer progressive structure.

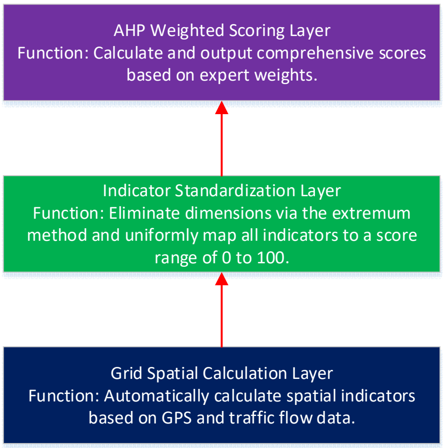

Figure 1. comprehensive evaluation model

The underlying architecture relies on a grid spatial analysis model to fuse GPS positioning information and real-time traffic flow data, so as to dynamically acquire regional characteristic parameters. The middle layer adopts the extremum normalization algorithm to integrate diverse heterogeneous data sources, realize consistent conversion of numerical scales, and map all values to a standardized range of 0 to 100. The top layer applies the Analytic Hierarchy Process (AHP) to determine the weight distribution of each indicator, and finally generates a comprehensive systematic evaluation result.

This workflow enables automatic and digital inspection of the existing bayonet monitoring system, and provides quantitative evaluation criteria for data integrity of the case-related vehicle identification system.

4.2. Grid Coverage Sub-model

This study adopts a standardized grid-based analytical framework combined with pre-defined spatial operation criteria, with the following procedures:

(1) Quantify a series of geographic indicators. Taking the GPS coordinates of traffic checkpoints as reference points, a 150-meter buffer zone is extended on both sides of each road to form the valid monitoring range.

(2) Discretize the entire study area using 50 m × 50 m grid cells.

(3) Evaluate the coverage of checkpoint surveillance for each grid cell, and label each cell by its coverage status including full-area coverage, multi-region overlapping coverage, or partial coverage gap.

(4) Count the number of grid cells of each type, and calculate three core indicators: overall coverage rate, coverage overlap rate, and branch road missing rate.

Sub-models constructed based on existing data resources support automatic computation, eliminating the need for conventional manual field surveys and significantly reducing the cost of evaluation work.

4.3. Indicator Standardization Method

(1) For positive indicators (e.g., coverage rate, effective capture rate), the standardization formula is as follows:

$$S_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \times 100$$

where X_i denotes the original value of the indicator, and X_{max}, X_{min} represent the regional maximum and minimum values of the corresponding indicator, respectively.

(2) For negative indicators (e.g., coverage overlap rate, missing rate), the following formula is adopted:

$$S_i = \frac{X_{max} - X_i}{X_{max} - X_{min}} \times 100$$

After indicator normalization, all evaluation dimensions are converted into dimensionless values with uniform dimensions, which lays a solid foundation for subsequent weight assignment and the construction of the multi-dimensional comprehensive evaluation system.

4.4. AHP Weight Determination

This study constructs a comprehensive evaluation system covering spatial layout, traffic flow distribution, facility efficiency, and road network coordination to analyze the construction effectiveness of the intelligent transportation system. Based on GPS trajectory data and traffic flow distribution characteristics, a primary sub-objective framework consisting of 11 quantitative parameters is established. To ensure the scientificity and objectivity of the evaluation model, five experts from five relevant professional fields were invited to participate in model construction. The Analytic Hierarchy Process (AHP) with a 1–9 scale was adopted to establish a pairwise comparison judgment matrix, and the maximum eigenvalue and consistency ratio were calculated accordingly [7]. Statistical results show that the consistency ratio (CR) of the criterion layer is 0.072, which is less than the threshold of 0.1, indicating good internal consistency of the model. In accordance with the weight assignment principle, the weight proportions of each dimension are determined as follows: spatial coverage (42%), traffic flow adaptation (30%), facility efficiency (20%), and road network matching (18%). The established evaluation system possesses solid theoretical basis and practical operability.

4.5. Comprehensive Scoring and Grade Classification

Calculation Formula for Comprehensive Score:

$$S_{total} = \sum_{j=1}^{4} w_j \left(\sum_{i=1}^{k} w_{ji} \cdot S_{ji} \right)$$

where w_j denotes the weight of the criterion layer, w_{ji} represents the weight of sub-indicators, and S_{ji} stands for the standardized score.

The evaluation grading criteria are specified as follows: scores ranging from 80 to 100 correspond to the grade of "Excellent"; scores from 60 to 79 are rated "Qualified"; scores from 40 to 59 are marked "Needs Improvement"; scores below 40 are defined as "Unqualified".

4.6. Complete Operation Process of the Model

(1) Import vehicle passing data, GPS data and road network data, and complete data cleaning, grouping and aggregation.

(2) Invoke the grid sub-model to calculate the original spatial indicators.

(3) Statistically calculate the original values of other indicators concerning traffic flow, facilities and road networks.

(4) Conduct extreme value standardization to achieve unified dimensions of all indicators.

(5) Substitute the AHP weights to calculate the comprehensive scores of single points and regional areas respectively.

(6) Evaluate the layout level by referring to the grading standards and identify problematic points.

(7) Generate optimization suggestions including new addition, deletion and displacement adjustment of monitoring facilities.

5. Empirical Analysis and Optimization Strategies

5.1. Measured Results of Core Indicators

Based on the field-measured dataset of Weifang City, the core results output by the model are summarized as follows:

• Overall road network coverage rate: 68.3%

• Branch road coverage missing rate: 31.7%

• Monitoring point overlap rate of arterial roads: 26.9%

• Average daily traffic volume at suburban low-flow checkpoints: the minimum is merely 42 vehicles, with an average of fewer than 50 vehicles

• Number of key intersections without monitoring coverage: 12

• Regional comprehensive score: 65.2, rated as “Basically Reasonable”.

The scores and corresponding contributions of each dimension are specified as follows: the spatial coverage dimension scores 62.5 (weight: 42%, contribution score: 26.25), the traffic flow adaptation dimension scores 68.2 (weight: 28%, contribution score: 19.10), the facility efficiency dimension scores 70.1 (weight: 18%, contribution score: 12.62), and the road network matching dimension scores 65.3 (weight: 12%, contribution score: 7.84).

5.2. Main Existing Problems

(1) Unbalanced spatial distribution: Surveillance cameras are densely deployed along major thoroughfares such as Beihai Road, yet obvious gaps exist in monitoring coverage around residential areas and suburban branch roads. Uneven resource allocation allows vehicles with fake license plates to evade tracking via secondary roads, frequently breaking pursuit routes and severely hindering target identification and positioning.

(2) Redundant and wasted resources: Dense equipment deployment within the same area, with multiple cameras installed within a hundred-meter radius, leads to redundant data collection, imposing heavy loads on storage space and real-time computing capacity [8].

(3) Mismatched traffic flow allocation: Major arterial roads with heavy traffic suffer from insufficient monitoring points, while detection facilities in low-traffic suburban areas remain severely underutilized. This unbalanced resource allocation has become an urgent problem requiring resolution.

(4) Missing road network node coverage: The absence of essential bayonet monitoring cameras at T-junctions and residential compound entrances impedes comprehensive collection of vehicle travel trajectories, creating major obstacles for tracing cross-regional illegal cases involving counterfeit license plates.

5.3. Optimization Suggestions

(1) Redundant Point Removal: For monitoring points with an equipment overlap rate exceeding 30% and a daily traffic volume of fewer than 80 vehicles, adjustment or dismantlement of the corresponding equipment is recommended. This measure reduces redundant data generation and improves the computing resource utilization efficiency of the monitoring platform.

(2) Blind Spot Coverage Supplement: Additional bayonet monitoring equipment shall be installed on branch roads, urban-rural fringe areas, and other sections with heavy traffic flow. This can compensate for the deficiencies in the existing monitoring resource layout, enhance the continuity of vehicle trajectory tracking, and provide a more reliable data support system for the identification of vehicles with forged license plates [4].

(3) Relocation of Idle Equipment: Traffic monitoring facilities deployed on low-traffic road sections can be relocated to major urban entrances, exits and core road nodes to optimize the spatial matching of monitoring resources and regional traffic flow distribution [9].

(4) Hierarchical Deployment Standards: This study adopts a hierarchical layout principle of "full coverage for arterial roads and priority coverage for secondary roads", aiming to achieve an optimal balance between service efficiency and construction and operation costs.

6. Conclusion

Based on the spatiotemporal big data of urban traffic bayonets, this paper proposes a four-dimensional quantitative evaluation method for the layout of urban traffic bayonet facilities. A hierarchical evaluation model is constructed by combining the grid algorithm with the analytic hierarchy process (AHP), which realizes intelligent evaluation using traffic sensing data without on-site observation for the first time. The application results in Weifang City indicate that the proposed method can accurately reflect the current configuration status and major problems of bayonet facilities relying on existing monitoring records, including insufficient coverage of branch roads, redundant equipment deployment on arterial roads, and unbalanced distribution of equipment utilization rates. The developed technical tool can provide a scientific basis for optimizing bayonet deployment strategies, significantly improve the data collection efficiency of license plate recognition systems, and lay a foundation for the construction of traffic management information systems in smart city development.

There are still some limitations in this study. The experiments are mainly carried out based on short-term traffic flow data of single-day commuting periods, without considering the actual operational conditions during holidays, extreme weather and other special scenarios. In future research, the sample size will be expanded, and a long-term trend prediction module will be introduced to improve the applicability of the research conclusions. In addition, the current analysis fails to design resource allocation optimization schemes under the constraints of construction and operation and maintenance costs. Economic benefit factors will be incorporated into the theoretical model in subsequent studies to improve and perfect the system. To meet the demand for improving the real-time response performance of the system, it is recommended to build an efficient distributed processing platform based on Spark, adopt on-demand triggered monitoring, and embed the platform into the unified business process of public security departments. Furthermore, dynamic layout adjustment strategies based on reinforcement learning can be explored to further enhance the self-adaptive capability of the system, so as to improve the flexibility and accuracy of the overall system operation.

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