Article

The Practical Application of Traffic Flow Forecasting and Capacity Analysis

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Abstract: With the rapid advancement of urbanization and the continuous increase in vehicle ownership, urban traffic systems are facing unprecedented pressure, leading to frequent congestion, increased travel times, and reduced overall transportation efficiency. In this context, traffic flow prediction and road capacity analysis have emerged as essential tools for modern traffic management. These technologies enable urban planners and transportation authorities to anticipate traffic trends, allocate resources more effectively, and design targeted congestion mitigation strategies. This paper conducts a comprehensive analysis of the core methodologies and key technologies involved in traffic flow forecasting and capacity evaluation, including statistical models, machine learning algorithms, and simulation-based approaches. Furthermore, the study illustrates the practical application of these technologies through real-world case studies, highlighting their role in enhancing urban mobility, reducing operational bottlenecks, and supporting the development of intelligent transportation systems (ITS). The findings suggest that scientifically grounded traffic prediction and capacity assessment not only contribute to improved traffic system performance but also lay the groundwork for data-driven urban planning and sustainable city development.

Keywords: traffic flow forecast; capacity analysis; urban traffic management; traffic system optimization; road planning

1. Introduction

With the acceleration of urbanization and the continuous growth of motor vehicle ownership, urban traffic problems have become a major challenge for sustainable urban development. Among these problems, traffic congestion during peak hours is particularly prominent, severely reducing transportation efficiency, increasing energy consumption, worsening air pollution, and ultimately undermining the overall quality of life for urban residents. As cities strive to build more intelligent and sustainable transportation systems, the demand for scientific, data-driven solutions to traffic issues has become increasingly urgent.

In this context, traffic flow prediction and road capacity analysis have emerged as fundamental components of modern urban traffic management. Accurate traffic flow forecasting enables transportation authorities to anticipate and manage traffic patterns in advance, while capacity analysis provides insights into the limits of existing infrastructure and helps optimize the allocation of road resources. Together, these technologies support the formulation of effective policies for congestion mitigation, emergency response, and long-term urban planning [1].

This paper aims to conduct an in-depth examination of the key technologies and methodologies involved in traffic flow prediction and capacity analysis, including statistical techniques, machine learning models, and simulation approaches. By integrating theoretical analysis with real-world case studies, the paper explores how these technologies are applied in practice to address complex urban traffic scenarios [2]. Furthermore, the

study evaluates the effectiveness of these methods in improving traffic efficiency and relieving congestion, thereby providing valuable references for the design and implementation of future intelligent transportation systems.

2. Significance of Traffic Flow Prediction and Capacity Analysis

2.1. Importance of Traffic Flow Forecasting in Urban Traffic Management

In urban traffic management system, traffic flow prediction provides scientific data support for traffic command and strategy formulation. In the face of complex urban road networks, accurate flow prediction can help traffic management agencies grasp the traffic information of each route and region in real time, and then adjust the signal system, change the direction of traffic flow and implement the drainage strategy in advance to reduce traffic jams and accidents [3]. Traffic flow forecasting is also critical to the implementation of intelligent transportation systems (ITS), which integrate technologies such as big data and artificial intelligence to enable dynamic monitoring and real-time management of traffic flows. Therefore, traffic flow prediction can not only improve the road capacity and reduce the accident rate, but also provide decision support for the city's traffic layout and long-term development, and help the construction of smart cities [4].

2.2. The Role of Capacity Analysis on Traffic System Optimization

Capacity analysis can evaluate the maximum load capacity of roads and transportation facilities, and is the core way for transportation planners to optimize the design and layout of transportation networks. This analysis helps to predict the traffic efficiency of roads or intersections under various traffic conditions, identify possible congestion points, and implement improvement strategies accordingly. When dealing with the complex urban road network, by simulating different traffic flows and traffic behavior patterns, capacity analysis can test whether transportation facilities can adapt to future needs and provide a scientific basis for the long-term development of the transportation system [5].

3. Core Methods of Traffic Flow Prediction and Capacity Analysis

3.1. Traditional Traffic Flow Forecasting Methods

The traditional road traffic forecasting method is based on historical data for statistical analysis, and regression analysis is a common technique. Regression analysis builds mathematical relationships between variables and predicts future trends with the help of existing data. Therefore, in the forecast of road flow, regression analysis is often used to analyze the interaction between traffic flow and many factors such as time period, climate conditions, holidays and so on. In general, the expression of the regression model is：

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \epsilon \tag{1}$$

Among them, Y is traffic flow, $X_1, X_2, \ldots, X_n$ Is the factor that affects the traffic flow (such as time, weather, road conditions, etc.), $\beta_0, \beta_1, \ldots, \beta_n$ is the regression coefficient, ϵ is the error term. Through the regression modeling of historical traffic flow data, the regression coefficient can be estimated, and then the future traffic flow can be predicted by the model.

3.2. Modern Traffic Flow Forecasting Methods

Modern intelligent traffic flow forecasting technologies use advanced artificial intelligence algorithms to improve the accuracy of traffic predictions. The technology excels at dealing with complex non-linear connections and achieving accurate predictive results based on big data [6].

3.2.1. Neural Network (NN)

As a typical structure of neural networks, the multi-layer perceptron (MLP) has been widely used in traffic flow prediction. The network uses multiple layers of nodes to process data and effectively capture nonlinear features within the data. The mapping between the input layer and the output layer can be expressed as:

$$y = f\left(\sum_{i=1}^{n} w_i x_i + b\right) \tag{2}$$

Where, y is the traffic flow prediction data, x_i is the various input factors (such as time, weather, etc.) that affect the traffic flow, w_i is the weight coefficient, b is the bias term, f is the activation function. By training the neural network, the weight coefficient is adjusted to effectively analyze and master the complex law of traffic flow change.

3.2.2. Deep Learning (DL)

Deep learning techniques, particularly long short-term memory networks (LSTMS), have demonstrated excellent performance in predicting traffic flow. As a unique variant of recurrent neural networks (RNN), LSTM is particularly efficient in processing time series data. Its advantages lie in its ability to retain information over long periods and to manage the flow of information through a specific gating mechanism. The calculation formula of the output of the LSTM model is expressed as follows:

$$h_t = f(W \cdot x_t + U \cdot h_{t-1} + b) \tag{3}$$

Among them, h_t is the real-time output message, x_t is the input signal, W, U is the matrix composed of weights, b is the bias term. When using LSTM network to forecast traffic flow, it can effectively deal with the dependence problem of long time series, and then achieve higher precision prediction results.

3.3. *Capacity Analysis Method*

Traffic capacity analysis is crucial for improving the efficiency of traffic systems, and traditional methods involve theoretical models (such as the HCM model) and simulation tools (such as the VISSIM system). This type of analysis helps determine the maximum carrying capacity of traffic infrastructure such as roads and intersections, thereby providing the necessary numerical basis.

3.3.1. Model

The Highway Capacity Manual (HCM) model was developed by the U.S. Transportation Research Board as a standardized model that focuses on evaluating the performance of roads and transportation facilities. The HCM model comprehensively considers factors such as traffic flow, driving speed, lane width, and signal control in order to predict the maximum carrying capacity of a road. The core capacity of HCM model is calculated by a specific formula：

$$C = f(V, s, n) \tag{4}$$

Among them, C is the road capacity, V is the traffic flow, s is the lane width, n is the number of lanes. The HCM model is suitable for evaluating the traffic carrying capacity of urban roads and expressways due to its wide applicability and relatively simple calculation process.

3.3.2. VISSIM Model

VISSIM is a traffic flow model based on microsimulation, which is often used for capacity analysis of complex traffic networks. VISSIM evaluates the performance of the entire transportation system by simulating the dynamic behavior of a single vehicle [7]. When performing traffic assessments, VISSIM considers factors such as vehicle volume, signal control, and lane configuration to calculate the actual operational capacity of traffic

facilities under various scenarios. VISSIM's simulation output typically includes key metrics such as traffic density, vehicle delay times, and road efficiency, making it ideal for detailed analysis of complex intersections and urban road networks.

4. Practical Application of Traffic Flow Prediction and Capacity Analysis

4.1. Practical Cases of Urban Traffic Flow Prediction

Based on sensors and big data analysis technology, real-time monitoring of traffic dynamics and rapid data processing provide immediate information support for the command and dispatch during peak traffic hours, which greatly promotes the improvement of urban traffic management efficiency. A variety of monitoring equipment is installed on urban roads, which is mainly responsible for collecting real-time data on the flow speed, quantity and type of vehicles [8]. These real-time data are combined with historical traffic patterns, weather conditions, and event information to build a dynamic traffic flow prediction model using machine learning and data analysis techniques. These models can predict short-term traffic flows and help traffic authorities develop responsive strategies based on the forecast outcomes [9].

Taking the peak period of a city as an example, the forecasted traffic conditions were obtained by aggregating data from sensors across different road sections, along with meteorological and event information, as shown in Table 1.

Table 1. Comparison of traffic flow forecast and actual traffic flow.

Time interval	Forecast flow (vehicles/hour)	Actual flow (cars/hour)	deviation
07:00 - 08:00	5000	4800	-4%
08:00 - 09:00	5200	5300	+1.9%
09:00 - 10:00	4500	4600	+2.2%

Based on real-time forecast data, the traffic management center can implement flexible regulation of traffic signal cycles, adopt specific management measures, and make temporary lane adjustments to effectively alleviate congestion during peak periods.

4.2. Application of Capacity Analysis Method in Road Planning

4.2.1. Road Design and Capacity Calculation

Capacity analysis usually uses standardized methods such as HCM and VISSIM simulation systems, combined with road layout characteristics (such as lane width, intersection type, etc.), traffic flow and signal timing, etc., to comprehensively evaluate road carrying capacity. By using the HCM model, the maximum load limit of the road section can be calculated, and the design optimization is carried out according to the predicted traffic flow data [10]. For example, in the latest urban planning project, the main road is designed with six lanes, and its maximum design speed is 60 km/h. According to the HCM traffic model, the maximum capacity of the road section can be obtained by the following formula:

$$C = \frac{L}{V} \times K \tag{5}$$

Where, C represents the traffic capacity, L represents the road length (unit in kilometers), V is the design speed (unit is), K is the flow adjustment coefficient. This formula allows for predicting road capacity under various traffic conditions, providing a scientific basis for rational road planning to prevent future congestion.

4.2.2. Traffic Bottleneck Identification and Solution Strategies

Through capacity analysis, city planners can identify potential congestion nodes in the road system and implement targeted optimization measures accordingly. For example, if the capacity analysis of a certain intersection shows that the traffic flow has approached

or exceeded the specified load limit, the following are several possible optimization methods:

1) Increase the number of lanes: Widen existing lanes or add new ones to improve intersection throughput.

2) Improve signal control: Introduce intelligent signal control systems that adjust traffic light durations in real time based on traffic flow fluctuations, thereby improving flow efficiency.

3) Optimize intersection layout: Replace traditional signal-controlled intersections with roundabouts to reduce delays caused by signal phasing and improve traffic flow efficiency.

4.3. Flow and Capacity Optimization of Expressway and Urban Traffic Network

4.3.1. Freeway Flow Forecast and Capacity Management

As a vital component of long-distance transportation, the prediction and capacity analysis of expressway traffic play a key role in ensuring the smooth operation of highways. In the field of traffic flow prediction, it can be based on big data analysis and artificial intelligence algorithm to integrate past traffic flow, traffic accident cases, weather changes and other data to achieve accurate traffic flow prediction. Additionally, simulation tools such as VISSIM are used to construct highway models that evaluate road capacity under varying flow conditions, assisting managers in formulating appropriate traffic management strategies. For instance, if forecasts indicate a traffic surge on a highway before a major holiday, traffic authorities can issue early travel advisories, adjust toll rates, or temporarily expand lane capacity to mitigate congestion [11].

4.3.2. Urban Complex Intersections and Road Network Optimization

Complex intersections are bottleneck areas in urban traffic network, usually the traffic flow is concentrated and the congestion is easy to occur. Through capacity analysis, planners can analyze the capacity of an intersection and evaluate it with traffic simulation models such as VISSIM to determine the impact of different intersection designs and signal control schemes on traffic flow.

Urban road network optimization involves evaluating traffic flow and capacity, identifying bottlenecks, and optimizing both intersection layouts and signal control systems. It can be optimized in the following ways:

1) Introduction of roundabouts: The use of roundabouts can reduce waiting times and improve intersection efficiency.

2) Increase dedicated bus lanes: Enhancing public transport infrastructure by allocating dedicated lanes can reduce private car usage and improve overall traffic flow.

3) Intelligent traffic management systems: The implementation of Intelligent Transportation Systems (ITS) allows for dynamic adjustment of traffic signals, speed limits, and road signage, thereby optimizing overall traffic flow.

5. Application Effect Evaluation

5.1. Evaluation of the Effectiveness of Traffic Flow Forecasting Methods

The effectiveness of traffic flow forecasting methods is typically assessed through accuracy testing and error metrics. Common evaluation metrics include Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). For instance, in a case study of urban traffic forecasting, the model maintained an error rate below 3% when compared with actual traffic data, demonstrating high predictive accuracy during peak hours. To further enhance prediction accuracy, the integration of additional real-time and contextual factors—such as weather conditions, public holidays, and special events—is recommended. The adoption of ensemble learning strategies may also contribute to improved

performance. Overall, the forecasting algorithm proves effective in managing traffic flow in real time, particularly during rush hours when traffic conditions are most volatile.

5.2. Evaluation of the Effectiveness of Capacity Analysis Methods

Capacity analysis significantly improves traffic flow through strategic adjustments in road layout and intersection design. For example, after layout optimization, a major arterial road demonstrated a notable increase in traffic throughput [12]. This strategy also facilitates the identification of traffic bottlenecks and enables targeted diversion measures, thereby enhancing overall traffic efficiency. Capacity analysis not only improves traffic efficiency but also contributes to the reduction of traffic accidents. To ensure long-term effectiveness, periodic evaluations and optimizations of the transportation network are recommended to accommodate growing traffic demand and evolving urban development patterns.

6. Conclusion

Accurate urban traffic flow prediction and capacity assessment are crucial for enhancing road utilization efficiency, mitigating congestion, and optimizing road network design. This paper compares traditional and modern traffic forecasting technologies, as well as capacity analysis methods and their practical applications, emphasizing their central role in traffic management systems. Case studies demonstrate that modern technologies—such as big data analytics and intelligent algorithms—significantly improve forecasting accuracy, thereby enhancing overall traffic flow. In the future, as intelligent transportation systems continue to mature, traffic forecasting and capacity analysis methods are expected to evolve further, contributing to more intelligent and precise traffic management solutions.

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