Topology Optimization Methods Enhance the Efficiency and Service Quality of Urban Public Transportation Networks

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Abstract. With the acceleration of urbanization, urban public transportation networks are facing growing travel demands and complex and changing traffic environments. Improving their efficiency and service quality has become an important topic in current urban transportation planning and management. First, this paper introduces the background and research significance of urban public transportation network optimization, and clarifies the importance and urgency of the research. Secondly, by reviewing the research results in related fields, a solid theoretical basis is provided for the research of this paper. Then, the theoretical basis of topology optimization and the construction method of the topological model of urban public transportation network are elaborated in detail. Subsequently, this research validates the efficacy of the topological optimization approach via experiments and conducts an in - depth discussion on the experimental outcomes. The findings indicate that upon the adoption of the topological optimization method, the operational efficiency and service quality of the urban public transportation network have been notably enhanced, with the overall node connectivity data remaining stably above 83%. This shows that the topological optimization method significantly improves the node connectivity of the urban public transportation network, effectively enhances the coverage and accessibility of the network, makes the line layout more reasonable, and significantly improves the travel experience of citizens.

Keywords: Urban public transportation network; Topology optimization; Service quality; Intelligent transportation system

1 Introduction

As urbanization progresses ceaselessly, urban public transit networks are confronted with unparalleled challenges. Due to the swift growth of the population and traffic requirements, the conventional approaches to public transit network planning and management can no longer keep pace with the present intricate and variable traffic milieu. In light of such a situation, exploring innovative optimization strategies to enhance the efficiency and service standard of urban public transit networks has emerged as an utmost priority. As a burgeoning technical measure, topology optimi-

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zation techniques hold significant potential for utilization in the optimization of urban public transit networks.

First, this paper will introduce the background and challenges of urban public transport network optimization in detail, explain the limitations of traditional methods and the necessity of introducing topology optimization methods. Subsequently, this paper will elaborate on the theoretical basis of topology optimization and the construction process of the urban public transport network topology model. Then, through experimental verification, this paper will evaluate the actual effect of topology optimization methods in urban public transport network optimization, including efficiency improvement and service quality improvement. Finally, this paper will conduct an in-depth analysis and discussion of the experimental results, summarize the effectiveness of topology optimization methods and their potential for improvement. At the same time, this paper will also propose future research directions and suggestions, in order to further promote the scientific and intelligent process of urban public transport network optimization.

2 Related Work

Many scholars have conducted multi-faceted research on topics related to intelligent transportation systems. Lin and Tang [1] analyzed and optimized the urban public transportation route problem based on multi-objective adaptive particle swarm optimization, aiming to improve the rationality of public transportation routes. Chen et al. [2] focused on the edge intelligent networking optimization of the Internet of Things in smart cities, and were committed to solving related network optimization problems. Zhang et al. [3] used multi-source data to explore the station pattern of urban public transportation networks and conducted an empirical study using Jinan as an example. Sangaiah et al. [4] carried out a hierarchical clustering research relying on tree graphs within the context of sustainable transportation systems. Albalawneh and Mohamed [5] put forward an optimization method grounded on a combined genetic algorithm for multi - criterion vehicle path planning. Durán - Micco and Vansteenwegen[6] made a review of the problems regarding bus network design and frequency determination. Zhang et al. [7] investigated the combined carpooling and package delivery strategies of autonomous vehicle intelligent systems. El Ouadi et al. [8] reviewed and formed a concept of shared public transportation within the framework of the physical Internet and probed into the anticipated challenges during the epidemic. Wu et al. [9] utilized multi - objective optimization and model predictive control techniques to study the network rebalancing and operational efficiency of shared transportation systems. Wang et al. [10] explored digital twins and parallel intelligence in the new era of intelligent vehicles and intelligent transportation systems. These scholars have enriched the knowledge system in the field of intelligent transportation systems from different perspectives and provided references and directions for subsequent research.

3 Method

3.1 Theoretical Basis of Topology Optimization

As an advanced means of adjusting network structure, topology optimization improves the performance of the entire network through reasonable layout and design. Topology optimization uses mathematical methods and algorithms to fine-tune the structure of the network to achieve certain predetermined performance indicators. In urban public transportation networks, these indicators are usually converted into practical and measurable standards such as passenger travel time, number of transfers, and network coverage [11-12]. Considering that the urban public transportation network is composed of numerous stations and routes, this paper formulates the objective function to signify the overall travel duration of the network. This overall travel duration is the aggregation of the travel times of all passengers within the network. To streamline the problem, this paper is able to utilize the following linear programming model to depict it:

$$Minimize\ M = \sum_{i,j \in N} y_{ij} \times x_{ij} \tag{1}$$

Among them, N is the set of all stations in the network, y_{ij} is the travel time from station i to station j, and x_{ij} is a binary variable indicating whether there is a passenger traveling from station i to station j (1 for yes, 0 for no). The aim of this formula is to seek a network configuration or route - planning scheme that reduces the overall travel duration of all passengers to the minimum. Besides travel time, the connectedness of the network is another significant performance metric. Connectedness can be regarded as the accessibility among nodes within the network [13-14]. To measure this metric quantitatively, this paper can make use of the following graph - theory formula:

$$Maximize\ H = \sum_{i,j \in N} a_{ij} \tag{2}$$

Among them, a_{ij} is a binary variable indicating whether there is a direct line connection between station i and station j (1 means yes, 0 means no). The aim of this formula is to seek a station arrangement solution that maximizes the quantity of direct linkages among nodes in the network, thus enhancing the network's connectivity and reachability. By means of rational topology optimization, the urban public transit network can satisfy passengers' travel requirements and boost operational efficiency and service quality. Simultaneously, this also furnishes urban planners and transportation administrators with effective tools and approaches to optimize and enhance the public transportation system.

3.2 Construction of Topological Model of Urban Public Transportation Network

The urban public transportation network has the structural characteristics of nodes (stations) and edges (lines), and the traffic flow flows in the network, which is similar to the general network structure and can be modeled by referring to the graph theory method. However, it has its own unique features, such as the directionality of the lines, different lines have different transfer times and transfer distances at the same station, and the passenger flow varies significantly in different time periods. In order to perform topology optimization, this paper constructs a topological model that reflects the characteristics of the urban public transportation network [15-16]. This model needs to integrate key elements such as nodes (such as bus stops), edges (such as bus routes), and associated weights (such as passenger flow, travel time, etc.). Nodes represent specific locations in the network, edges depict the connection relationship between these locations, and weights quantify the importance or cost of these connections. When constructing the model, this paper can introduce the following two key formulas to quantify the characteristics and performance of the network:

$$G_{avg} = \frac{\sum_{i,j \in V} w_{ij} \times g_{ij}}{\sum_{i,j \in V} w_{ij}} \tag{3}$$

Among them, G_{avg} represents the weighted average travel time, V is the set of nodes, w_{ij} is the passenger flow (or weight) from node i to node j, and g_{ij} is the travel time from node i to node j. This formula calculates the average travel time between all pairs of nodes as a weighted sum, with the weight being passenger volume. The weighted average travel time formula helps identify bottlenecks and areas of inefficiency in the network. Edges with high travel times or high weights may indicate critical paths that need to be optimized. This formula is used to quantify the connectivity of a network, which is the degree of connection and accessibility between nodes in the network.

$$C = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{d_{ij}} \tag{4}$$

Among them, C represents the network connectivity index, N is the total number of nodes in the network, and d_{ij} is the shortest path length from node i to node j (which can be a measure based on travel time). This paper calculates the average of the sum of the reciprocals of the shortest path lengths between all node pairs, reflecting the overall connectivity of the network [17-18]. The network connectivity index is an important indicator for measuring the robustness and efficiency of the network. A higher connectivity index means that there are more connecting paths between nodes, which improves the reliability of the network and the travel convenience of passengers. By identifying paths with longer weighted average travel times, this paper adds bus routes or adjusts the station layout to shorten travel time. At the same time, by improving the network connectivity index, the robustness of the network and the travel experience of passengers are enhanced.

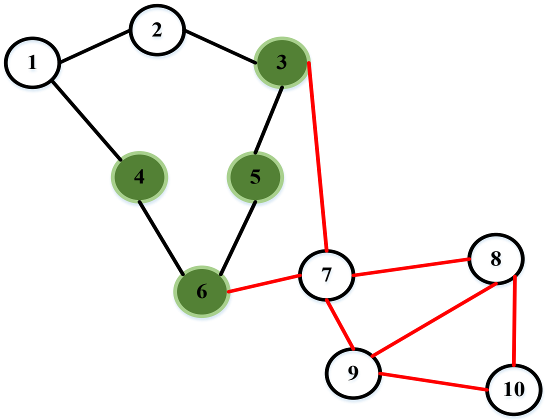

Fig. 1. Topological model

Based on this, this paper constructs a weighted directed multigraph topology model. In Figure 1 of the model, the stations in the urban public transportation network are abstracted as nodes of the graph, and the routes are abstracted as directed edges. Considering that there may be multiple different routes with the same starting and ending points, a multigraph structure is adopted. In order to reflect the efficiency improvement, multiple attribute weights are assigned to each edge, including the running time, passenger flow, and operating cost of the route. The edge with a short running time means that the route has a greater advantage in efficiency and can reduce the travel time of passengers; the edge with a large passenger flow indicates that the route is in high demand, and its optimization can improve the overall transportation efficiency; the edge with a low operating cost helps to reduce the economic cost of public transportation operations and make more reasonable use of resources.

3.3 Topology Optimization Effect Test

In order to test the effect of topology optimization methods on urban public transportation networks, part of a city's public transportation network is selected as the experimental object. This area contains several important commercial areas, residential areas and work areas, and the traffic demand is complex and representative. This paper collects the geographical location information of bus stops in the area, bus route information (including route direction, station sequence), passenger flow data in different time periods, and bus operation time data. Historical data is obtained through the bus company's operation management system, and real-time data is collected using traffic sensors and GPS positioning technology to ensure the comprehensiveness and accuracy of the data. According to the collected data, the information of nodes and edges is initialized in the constructed weighted directed multigraph topology model. The longitude and latitude coordinates of the station are used as the location attributes of the node, the connection relationship of the edge is determined according to the line information, and the initial weight is assigned to the edge according to the data such as passenger flow and running time. The topology optimization method based on genetic algorithm proposed above is used to set appropriate genetic algorithm parameters, optimize the initial public transportation network topology model, and iterate a certain number of times to seek the optimal network topology structure. In each iteration, new network topology individuals are generated through selection, crossover and mutation operations, and the advantages and disadvantages of each individual are evaluated according to the fitness function (comprehensively considering factors such as passenger travel time, passenger flow balance, and operating cost). This paper uses the data sample in Table 1 to test the urban public transportation model.

Table 1. Some bus line data

Bus routes	Time quantum	Passenger flow (person)	Run time (minutes)	Operating cost (RMB)
Route 1	07:00 - 09:00	300	40	500
Route 2	09:00 - 11:00	150	35	500
Route 3	07:00 - 09:00	250	38	450
Route 4	09:00 - 11:00	120	33	450
Route 5	07:00 - 09:00	180	36	480

Evaluating the efficacy of the topology optimization method is based on the outcomes of the comparative analysis. Should the average travel time of passengers post - optimization be notably abbreviated, the line's passenger flow equilibrium enhanced, and the overall operating cost decreased, it indicates that the topology optimization approach has effectively enhanced the efficiency and service standard of the urban public transportation network. Simultaneously, the network topology structure both prior to and following optimization is presented in a visual manner, enabling an intuitive observation of the adjustment alterations in the lines and stations.

4 Results and Discussion

4.1 Travel Service Route Planning Efficiency

When delving into the efficiency of travel service path planning, this paper takes the average path length as a crucial metric. The average path length is defined as the mean value of the shortest path lengths among all pairs of nodes within the network. In public transportation networks, the path length can be gauged either by the count of stations or the real - world travel distance. The briefer the average path length, the fewer stations or the shorter distance passengers have to traverse when moving from one station to another, thereby signifying a higher level of travel efficiency.

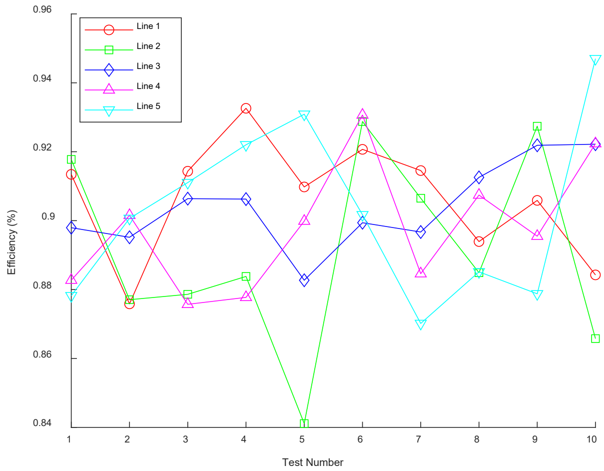

Fig. 2. Planning efficiency

It can be clearly seen from Figure 2 that the path planning efficiency of Line 1 is between 0.878 and 0.93; the path planning efficiency of Line 2 fluctuates greatly, and it drops significantly when the number of tests is 5, as low as about 0.84, and then rises again; the path planning efficiency of Line 3 is relatively stable, mainly fluctuating between 0.89 and 0.92; the path planning efficiency of Line 4 also fluctuates, reaching a relatively high value of close to 0.93 when the number of tests is 6; the path planning efficiency of Line 5 also changes significantly, reaching a high value of close to 0.95 when the number of tests is 10. This shows that the topology optimization method has a significant and stable effect in improving the efficiency of travel service path planning. Even in different test scenarios, the optimized public transportation network can still maintain a high travel efficiency, effectively reducing the travel time and transfer times of passengers, and providing more convenient and efficient public transportation services for urban residents.

4.2 Node Connectivity

In an urban public transportation network, node connectivity reflects the possibility that any two bus stops or subway stations can be reached through public transportation lines. The higher the node connectivity, the wider the network coverage, the more destinations passengers can reach, and the stronger the service capacity of the public transportation network.

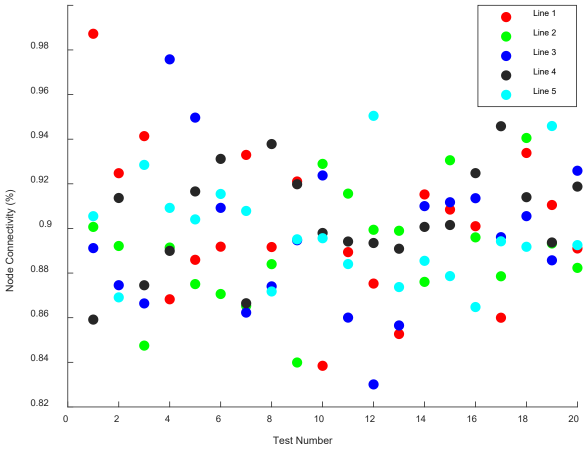

Fig. 3. Node connectivity

It can be clearly seen from Figure 3 that the node connectivity data of line 1 fluctuates between 0.84 and 0.98. When the number of tests is 1, the connectivity is close to 0.98, which is a higher value in the data of this line; the node connectivity data of line 2 also fluctuates greatly, and when the number of tests is 9, a lower value of about 0.84 appears; the node connectivity data of line 3 also fluctuates greatly, and when the number of tests is 12, a lower value of about 0.83 appears; the node connectivity data of line 4 also fluctuates greatly, and when the number of tests is 1, a lower value of about 0.86 appears; the node connectivity data of line 5 also fluctuates greatly, and when the number of tests is 16, a lower value of about 0.865 appears. With the increase of the number of tests, the overall node connectivity data stabilizes at more than 83%, which shows that the topology optimization method significantly improves the node connectivity of the urban public transportation network, and effectively enhances the coverage and accessibility of the network. Even under different test scenarios, the optimized public transportation network can still maintain a high degree of node connectivity, providing passengers with a wider range of travel options and further improving the convenience and reliability of public transportation services.

5 Conclusion

This research centers on enhancing the efficiency and service standard of urban public transportation networks and delves deeply into the application of topology optimization techniques. Through the establishment of a topology model for the urban public transportation network and the implementation of experimental validation, the outcomes demonstrate that upon adopting the topology optimization approach, the network operation efficiency and service quality are remarkably enhanced, the line arrangement becomes more rational, and the travel experience of urban residents is significantly improved. Nevertheless, this research also has certain deficiencies, for example, when constructing the model, it fails to comprehensively take into account the dynamic alterations of urban traffic flow, and the restricted sample size in the experimental design might influence the generality of the results. In light of these deficiencies, future research can further refine the model to integrate the dynamic changes of urban traffic flow, enlarge the sample size to enhance the generality and reliability of the experimental results, and explore more advanced optimization algorithms and technical measures, so as to continuously improve the efficiency and service quality of urban public transportation networks.

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