Research Article

Analysis of Passenger Flow Characteristics of Urban Rail Transit Based on Spatial Data Dynamic Analysis Technology

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Based on spatial data dynamic analysis technology, the characteristics of urban rail transit passenger flow are analyzed. This study analyzes the passenger flow characteristics of urban rail transit from the perspective of operation and planning by using the dynamic analysis technology of spatial data, combined with social and economic development. Based on the analysis of research data from the study of passenger traffic and passenger traffic data measurement, the characteristics of passenger traffic from urban railways are derived from the time distribution, spatial distribution, and transfer of passengers waiting on the platform. The final length of line 3 is 39.7 m, the passenger volume is 102, with 11 people/day, the passenger flow density is 1.8/2.3, and the high section in peak hours is 2.4/3.2. By considering the various influencing factors, efforts should be made to develop urban rail transit projects to promote the growth of social and economic benefits.

1. Introduction

Urban transportation is one of the most important infrastructure services to maintain the importance of the city and the life of the city [1]. The development of multilevel, three-dimensional, and smart modern transportation will be the goal of urban planning and development. The development of a good transport system with various modes suitable for large, medium, and small passenger transport will be an important measure to achieve the abovementioned goals. Road expansion alone cannot solve the problem of improving traffic in the city. Modern cities need modern transportation that adapts to modern life, create transportation patterns that are coordinated with urban development, and combine the goals of long-term planning with new regulations and developments. We must make a network of roads that are convenient for traffic in the city, gradually improve public transportation services, organically participate in transportation planning, expand the conditions of the use of space, and pay attention to the construction. Public transport will be the basis of rail transport, and metro transport models and trains with large and medium passengers will be more active. With the rapid development of urban construction, many large cities in China are planning to build large- and medium-volume subway or light rail transit projects. More than 20 big cities have continuously invested a lot of human and material resources to carry out the preliminary work and feasibility study of rail transit project construction to varying degrees, but there are still some problems in project selection, system scale, and construction standards. With the development of the economy, more and more cities plan to build rail transit [2, 3]. Therefore, it is necessary to put forward some guiding construction guidelines and policies, so that macrocontrol can be more scientific and the construction units and consulting and design departments in all regions can establish a relatively unified understanding of the development goals and requirements of urban rail transit so as to avoid the adverse consequences of the wrong guidance of construction standards while stressing the necessity of construction. So, how do you create the conditions for urban rail planning? And how do you get the benefits? Whether it can support the development of the land along the successful line of the plan is a major problem that needs to be solved now.
2. Passenger Flow Analysis during Urban Rail Transit Operation Stage

During the operation of the railway, real-time monitoring of changes in passenger traffic, quality control, and awareness of the changes in passenger rights are the basis for the integration of transportation in the railway [4]. The flow of passengers changes in time and place, which is a reflection of the economy of the city and the characteristics of the railway itself. The basis of passenger identification is to analyze the physical and spatial distribution of passenger traffic.

2.1. Passenger Flow Survey

2.1.1. Flow Is Dynamic. Through the analysis of passenger traffic research data on urban rail traffic, the law of changes in passenger traffic in time and space can be understood [5]. At the same time, the analysis of the operating passenger flow characteristics of the existing lines can also provide reference data for the subsequent implementation of the line or the planned road network of other cities, so as to provide a reference for many aspects such as the control of the line network scale, the adoption and layout of infrastructure projects and equipment, and transportation organization. The types of passenger flow surveys are as follows.

2.1.2. General Education of Passengers. Airline passenger research is a comprehensive study of passenger traffic on all lines, often involving a sample of passenger surveys. Researching passenger vehicles, in general, is time-consuming and intensive and requires many researchers. However, through the collation and statistical analysis of the survey data, we can have a comprehensive and clear understanding of the current situation and the law of passenger flow. A comprehensive passenger flow survey includes an onboard survey and a station survey. The onboard survey is to investigate all passengers getting on and off the train during the whole day operation at the door, and the station survey is to investigate all passengers getting on and off the train during the whole day operation at the station ticket check-in [6]. The latter is often used in the comprehensive passenger flow survey of the rail transit system. Generally, the survey should be carried out for two or three consecutive days. During the whole day of operation, the location and ticket type of all passengers at all stations along the line should be investigated.

2.1.3. Sample Survey of Passengers. A sampling survey uses samples to approximately replace the population, which is conducive to reducing the human, material, and time consumption of passenger flow survey [7]. The sampling survey of passengers’ situations is usually carried out with a questionnaire, and the survey content mainly includes two aspects: the composition of passengers and the riding situation. The investigation of passenger composition is generally carried out at the station. The survey content includes age, gender, occupation, residence, and travel purpose. The survey time can be selected in the operation period with relatively stable passenger flow. The investigation of passengers’ riding conditions can be classified according to needs or carried out at a specific time and place. In addition to age, gender, and occupation, the survey content can also include family address, family income, average daily bus times, boarding station and getting off station, the way and time to reach the station, and the way and time to reach the destination after getting off the train.

2.1.4. Section Passenger Flow Survey. Section passenger flow survey is a regular sampling survey of passenger flow, and one or two sections can be selected for the survey. Generally, the maximum passenger flow section is investigated, and the investigators use the direct observation method to investigate the number of passengers in the vehicle [8, 9].

2.1.5. Holiday Passenger Flow Survey. Holiday passenger flow survey is a special passenger flow survey, focusing on the passenger flow during the Spring Festival, New Year’s day, national day, weekend holidays, and several folk festivals. The contents of the survey include the vacation arrangements of institutions, schools, enterprises, and other units, the development of urban tourism and entertainment industry, and the changes in the lifestyle of urban residents, which are generally obtained through questionnaires.

2.1.6. Sudden Passenger Flow Survey. The sudden passenger flow survey is mainly a special passenger flow survey conducted for stations with rapid passenger flow distribution, such as cinemas and stadiums. This survey mainly involves the correlation between the scale of cinemas and stadiums and the passenger flow impact degree and duration of nearby rail transit stations.

2.2. Passenger Flow Time Distribution

2.2.1. Hourly Passenger Flow Distribution in a Day. Hourly passenger flow is used to determine the capacity of urban rail transit entrances and exits, channels, and other equipment, and it is the basis for calculating the full-day driving plan and vehicle allocation plan [10]. The hourly passenger flow changes with the rhythm of urban life and fluctuates in a day. The passenger flow at night is scarce, increases gradually before and after dawn, and reaches its peak at the time of going to work and school. Later, the passenger flow decreases gradually, and there is a second peak at the time of going to work or school, and the passenger flow at night decreases gradually. The transportation capacity of rail transit, the route direction, the characteristics of the transportation corridor, and the land use nature of the station are the main factors affecting the distribution of passenger flow in rail transit. Considering the different types of railways with different transport capacities, the following five types of passenger traffic time distribution can be achieved.
(1) Unidirectional Peak Mode. When the railway is located where the train track is tidal, or when the area around the station is single, the distribution of passengers at the station is concentrated, and it has the highest alighting and alighting levels in the morning and evening, as shown in Figure 1.

(2) Bidirectional Peak Mode. If the station is located in a general service area, the passenger traffic is similar to other modes of transportation. As shown in Figure 2, there are two pairs of combinations in the morning and evening.

(3) Full Peak Type. When the rail transit line is located in a highly developed transportation corridor on the land, or the station is located in an area where public buildings and utilities are highly concentrated, then there is no obvious trough in the passenger flow distribution and the two-way boarding and alighting passenger flow is large throughout the day, as shown in Figure 3.

(4) Peak Type. The station is located near large public facilities such as stadiums, cinemas, and theatres. At the end of performances or sports competitions, there is a sudden rush hour for a short duration. After a period of time, some other stations may have a sudden drop-off peak, as shown in Figure 4.

(5) No Peak Mode. When the railway capacity is low or the station is located in an underdeveloped area, the flow of people is not clearly visible and the two-way passenger flow is low throughout the day, as shown in Figure 5.

For different types of hourly passenger traffic distribution, a one-way distribution of interline passenger traffic inequality can be used to determine the total passenger flow for the day. The formula is as follows:

\[ \alpha_1 = \frac{\sum_{i=1}^{H} P_i / H}{P_{\text{max}}} \] \hspace{1cm} (1)

As \( \alpha_1 \) tends to zero, the uncertainty of passenger flow in the one-way intermediate segment increases [11, 12]. When \( \alpha_1 \) is small, that is, when the number of passengers in the maximum one-way split time is not equal, a small marshal and a large car arrangement can be used to understand the reasons for transportation organization and marketing; that is, more trains are operated during the peak passenger flow period to meet the passenger transport demand, while in the low passenger flow period, the number of trains is reduced to improve the average load factor of vehicles.

2.2.2. The Distribution Law of Passenger Flow throughout the Week. Since people work and rest in a weekly cycle, the regularity of this activity must be reflected in the changes of daily passenger flow in a week. On the rail transit lines with commuting passenger flow, the passenger flow on weekends will be reduced, as shown in Figure 6 [13]. On the rail transit lines connecting commercial outlets and tourist attractions, the passenger flow on weekends tends to increase. In addition, the morning peak hour passenger flow on Mondays and after holidays and the evening peak hour passenger flow on Fridays and before holidays will be larger than that on other weekdays according to the uneven distribution and regular changes of the whole day passenger flow in a week.

2.2.3. Imbalance of Seasonal or Short-Term Passenger Flow. In a year, there is still a seasonal change in passenger flow. For other reasons, the passenger flow in June is usually the lowest throughout the year. The increase in population will increase the passenger flow of rail transit lines when major events are held or the weather changes suddenly [14].

2.3. Spatial Distribution of Passenger Flow. Each line of the urban railway has a different passenger flow and distribution because of its different urban passenger traffic and different land uses along the line [15, 16]. The passenger traffic characteristics of each line can be analyzed from the passenger traffic data during operation.

In the railway line, because of the direction of the passenger traffic, the passenger traffic in the up and down
directions is usually not equal. On the radial train lines, the disparity between the passenger flow in the upstream and downstream in the morning and in the evening is particularly obvious. The inequality between the upstream and downstream of the railway line can be used to explain the passenger balance between the upstream and downstream of the railway line, and the calculation model is as follows:

\[ \alpha_2 = \frac{P_{\text{superior}} + P_{\text{down}}}{\max\{P_{\text{superior}}, P_{\text{down}}\}} \tag{2} \]

The more \( \alpha_2 \) tends to zero, the greater the imbalance of passenger flow in the largest section in the upstream and downstream directions will be [17]. When \( \alpha_2 \) is small, that is, when the maximum section passenger flow in the upstream and downstream directions is unbalanced, it is difficult to allocate transport capacity economically and reasonably on the straight line, but measures to arrange different transport capacity on the inner and outer ring lines can be taken on the ring line.

The passenger characteristics of each section are based on the railway lines. Due to the difference in the development of the section that the line passes through, the difference in the distribution point of the passenger flow, and the difference in the number covered, it is important that passengers run on different lines at each station. Each line
2.4. Distribution of Passengers Waiting on the Platform. It is a periodic dynamic change process from passengers entering the platform to boarding and from passengers getting off the train to leaving the platform. Due to the different functions and passenger distribution status in different periods, the process can be divided into the following three passenger distribution status ports.

In the first state, passengers waiting for the train are evenly distributed before the train arrives at the station. Generally, passengers gradually enter the boarding and landing area of the platform, and the distribution of passengers gradually changes from sparse to dense. As the train did not arrive, passengers had a certain time before taking the bus to find a suitable carriage position or to avoid the crowded situation. In this way, some passengers will move in a small range, which makes the distribution of passengers on the platform tend to be uniform. In this case, the passengers waiting on the platform can be approximately considered as evenly distributed.

The second stage is the assembly state before boarding. When the train pulls in and stops, passengers crowd to both sides of each door to assemble, get out of the door, and wait for the other passengers on the train to get off. The distribution of passengers on both sides of the door is similar to the two sectors.

In the third state, when passengers arrive at the station to get off and pass, the door width can meet the requirements of two people getting off at the same time. In the actual observation, the passengers getting off are not finished, and the passengers getting on have already got on at the same time.

3. Passenger Flow Analysis in Urban Rail Transit Planning Stage

3.1. Passenger Flow Forecast. Passenger transport by high-speed rail mainly includes passenger transport, transfer passenger transport, and spurred passenger transport. Passenger transport refers to the increase in the passenger flow at train stations and lines, and passenger flow refers to the change in passenger flow because of medium- and long-distance passengers often use underground buses and bicycles for rapid transportation. Railways offer the advantages of speed, punctuality, safety, and comfort; with the construction of high-speed railways, the level of service has improved, creating the conditions for cross-regional travel and allowing for a nonstop increase in the number of passengers. Movement of residents: urban riders are highly dependent on urban land use and traffic management. At the same time, according to the rapid and large volume of urban passenger transportation, the railway has changed the access along the railway, which will have some influence on urban planning; for example, it will accelerate the process of urbanization, improving the development of suburbs and land along the railway, thereby affecting the production and distribution of passenger trains. The urban passenger transport structure and the flow direction of urban passenger flow are comprehensively determined by the average travel distance of residents, the service level of transportation facilities, the economic affordability, and values of travelers, as well as the macrocontrol policies adopted by the city. The passenger flow undertaken by rail transit also involves the coordination relationship with other transportation modes in the city. Therefore, the generation, distribution, mode, and route selection of urban passenger flow is not a one-way mechanism, but a dynamic balance mechanism of mutual feedback. Therefore, the formation of rail passenger flow is based on the urban spatial layout, transportation development strategy, the characteristics of various urban passenger transport modes, and the coordination between them, as well as the economic ability of travelers.

Urban rail transit passenger flow forecasting methods can be generally divided into two types: the centralized model and the noncentralized model. The characteristics of the two types of forecasting methods are discussed in the following. The typical representative of the aggregate model is the four-stage traffic prediction model, which is commonly referred to as the “four-stage method.” The basic theory of this model is sufficient, which can not only reflect the relationship between residents’ travel and urban land use data but can also provide feedback on the impact of the interaction of different transportation modes on passenger flow distribution. Based on traffic districts, the four-stage model analyzes the current situation and future traffic conditions of cities according to the four stages of travel generation prediction, distribution prediction, mode division, and traffic allocation. Although in recent decades, the research on the four-stage model has been deepening and there has been a method of combining two or more stages for prediction. However, the idea of grasping the travel characteristics of urban residents from a macro perspective and then predicting and analyzing them in stages is still the same. According to the different positions in the four-stage model, it can be roughly divided into four types of models. A nonaggregate model is called a driving model, which directs
workers to work according to the structure, meaning where the person goes, where to go, the means of transportation to be used, and the way to choose and do things. Statistics is based on trips, modes of transport, and distribution of transport to obtain a model of all transport needs. This model theoretically uses the achievements of modern psychology and introduces the concept of utility. It is based on the theory of maximizing utility. It focuses on traveler behavior. Compared with traditional models, the non-aggregated model has advantages such as good behavior, good intermodel relationships, less sample analysis required for model evaluation, and better temporal and regional variability of the model.

The aggregate model is a kind of traditional traffic demand analysis method based on the aggregate behavior model. Its prediction process includes four stages: trip generation, trip distribution, mode division, and traffic allocation. The nonaggregate model takes the individual traveler rather than the traffic community as the research object and takes the random utility theory and the travel utility maximization theory as the research basis. The two methods are different in terms of analysis unit, model parameter calibration method, the scope of application, policy performance ability, etc. At the same time, there are differences in the use efficiency of data and the possibility of importing independent variables, as shown in Table 1 [24].

3.2. Analysis of Prediction Results. The following are the temporal and spatial distribution characteristics of passenger flow: the time distribution of the whole day passenger volume [25]. The main indicator of passenger transport period distribution is the passenger volume period coefficient, whose value is the ratio of passenger volume in each period to the whole day passenger volume, and the maximum value is the peak hour coefficient. Generally, 7:00-10:00 and 16:00-1900 are peak hours, and the rest are peak hours. The balance of demand affects the utilization of facilities and equipment and the interval distribution of passenger flow along the whole line. The interval distribution of passenger flow throughout the line determines the train operation organization and operation plan, as shown in Figure 7.

In the process of urban rail transit planning, design, and management, we are very concerned about the relevant passenger flow during peak hours, so it is very necessary to study the travel structure during peak hours. During peak hours, three modes of transportation are mainly used for work travel, bicycle, bus, and car, with a low proportion of walking, and the three modes which are mainly used for school travel are walking, bicycle, and bus. The purpose of travel is that the two travel groups of going to work and school are concentrated in peak hours. In contrast, in peak hours, conventional public transport and rail transit have similar operating characteristics. Their transport capacity quickly reaches saturation or supersaturation with the arrival of peak hours, and the comfort in the carriage gradually deteriorates and then gradually improves with the passing of peak hours. However, there is a big difference in the attractiveness of rail transit and conventional public transport to travelers. During peak hours, the roads are unobstructed, and the conventional bus is more attractive because of its high convenience and cheaper fares than rail transit. However, with the arrival of peak hours, the roads are gradually crowded, the speed of conventional buses decreases, and the reliability is difficult to guarantee. At this time, the attraction of conventional buses to travelers decreases rapidly. Rail transit also becomes very crowded, and its attraction decreases. However, due to its fast and high reliability, its attraction to travelers will stabilize at a certain level after the decline.

3.3. Passenger Flow Sensitivity Analysis. An urban rail transit network is an orderly and gradual improvement process, which will inevitably produce the passenger flow impact of the subsequent built sections on the completed sections and the subsequent built lines on the existing operating lines. The influence of subsequent lines on the built lines is mainly realized through the transfer station and passenger flow coverage area. Here, another influencing factor is the operation mode. If the lines in the whole network operate in the same line mode, their mutual influence relationship will be greatly different from the independent operation of each line. In order to simplify the analysis process, only the independent operation of each line is discussed here.

Foreign rail transit operation experience shows that most of the users of rail transit are low-income people. Survey data show that more than 90% of the rapid rail transit passengers are former bus passengers, and it is difficult to attract a large number of car and taxi passengers. Therefore, China’s rapid rail transit system will mainly attract middle-income bus passengers and passengers who previously used bicycle transportation. The price of train tickets is most important to passengers as middle-income and low-income people are concerned about the cost of daily commuting.

The level of utilization of urban railways is twofold: One is the good internal services of urban railways, such as departure times, car service, and waiting areas. The second is the external location of the city’s rail transit business, which affects the system’s relative services, such as integration with regular buses and bus service levels. Services in the city’s rail transit system are usually run on departures. An increase in departure times will result in longer waiting times for passengers, more passengers on the train at each stop, and more congestion in the carriages, which will directly reduce the level of service. Due to the characteristics and economics of the city railway, it was determined that it can only be used as the main pillar of public transport and that the scope of the network is limited. The passengers have to change doors or walk to the train station, which is inconvenient to go from door to door. Therefore, it is necessary to have a coordinated connection system to play a good role. If the service of conventional public transport reaches a high level, passengers will inevitably choose a more convenient transportation mode when making travel choices and rail transit will lose its advantages.
Social activities have a significant impact on passenger flow in the transportation policy. Transportation policy can determine the supply level of transportation macroscopically, thus restricting people’s travel choices. For example, the government issued policies to restrict the use of cars and control the number of cars, which can change the urban traffic structure to a certain extent. We can change people’s willingness to travel and then can change people’s travel habits through slogans and initiatives. For example, putting forward the concept of sustainable development, saving energy and protecting the environment, calling on urban residents to travel by public transportation, and minimizing the travel of individual motor vehicles can also change the travel structure of urban transportation to a certain extent, and this can ultimately affect the passenger flow of rail transit.

On the one hand, the economic level of the city should be able to support the construction cost of rail transit; on the other hand, it also has a direct impact on the scale of passenger flow. Due to the huge construction cost of rail transit, its ticket price is generally higher than that of a conventional bus, so the affordability of passengers to ticket price is the key factor to determine the passenger flow.

3.4. Reliability Analysis of Prediction Results. There are many factors that affect the reliability of the prediction results, and corresponding improvements can be made to the problems mentioned above, such as continuously improving the city’s traffic planning model and optimizing model parameters. This study starts with the prediction process and the form of prediction results and makes a preliminary exploration on improving the reliability of prediction results.

Table 2 shows the passenger flow forecast results of an urban rail transit. From the data listed in the table, we can find that each forecast value is very accurate, reaching two decimal places. Compared with the problem analysis in the previous section, the prediction results are often far from the actual operation results. Is it necessary and possible to make very accurate data results on such uncertain data? In mathematical statistics, confidence degree and confidence interval are common. If the results of rail transit passenger flow prediction can be made into a form similar to the confidence degree and confidence interval in mathematical statistics, its reliability will be much better than the current single value. The whole prediction process is shown in Figure 8.

The key to the reliability of control data lies in the control of prediction data input and the prediction model method. It is generally believed that the probability distribution of expert opinions conforms to or is close to the normal distribution, which is the main basis for data processing. In quantity processing, the median and upper and lower quarter point methods are often used to process the answers of experts and calculate the expected value and interval of prediction. After expert evaluation of the data, we can get the
data input deviation and the distortion coefficient of the prediction model, and then we can obtain the final prediction results, as shown in Table 3.

4. Conclusion

Railways have expanded their services, and the quality of service has improved. During the 13th Five-Year Plan period, railway lines (sections) such as Line 8 (Phases III and IV), West Line 6, and Daxing Airport Line have been put into operation, and further work is up to 172.9 km. The number of suburban railway lines has increased to 4, and the inner city run has reached 364.7 kilometers. By the end of the 13th five-year plan, the total mileage of transport (including suburban railways) had reached 1091.7 kilometers. The rail transit operation organization continues to be optimized. The departure interval of 10 lines is less than 2 minutes, and the reliability of train service is nearly 7 times higher than that at the end of the 12th Five-Year Plan period, realizing the full coverage of the city’s rail “one-yard pass” and mobile payment. We should strive to optimize public transport services and must continuously improve the service level. The Third Ring Road, Beijing Tibet expressway, Beijing Hong Kong Macao expressway, Cheng Fu Lu road, and other bus lanes have been completed, and the bus lanes have been gradually connected into a network, with a total mileage of 1005 Lane kilometers. The “master plan of Beijing ground bus network” was issued, and the ground bus lines were continuously optimized. 135 diversified bus lines, including customized shuttle lines, tourist buses, high-speed rail express (Beijing South Railway Station), and hospital special lines, were newly opened, with a total of 455, which greatly met the diversified travel needs of citizens. The significant improvement of ground bus service level effectively helps citizens’ travel convenience.

Data Availability

The labeled data set used to support the findings of this study is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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