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Spatial-Temporal Characteristics of Urban Rail Transit Passenger Flow in Wuhan Based on IC Card Data

WANG Guan, CHEN Hua, LI Jianzhong, SUN Yilu

Wuhan Transportation Development Strategy Research Institute, Wuhan Hubei 430017, China

Abstract: To assess the urban rail transit operation in Wuhan and promote reasonable rail transit network planning and construction planning, as well as reveal potential problems of management, this paper reviews the development of Wuhan urban rail transit and analyzes spatial-temporal characteristics of passenger flow at network, corridor, and segment levels respectively using IC card records and geographic database. The paper develops a job-housing model to show the spatial distribution of residential communities and employment areas. Based on the travel characteristics such as travel time, distance, direction, roundabout during morning and afternoon peak hour, and transfer, the paper discusses the urban land use layout. Finally, the paper provides suggestions on urban rail transit development including diversifying operational modes, developing an integrated public transit system, promoting land use development along rail transit lines and facilities construction, and encouraging coordinated development among different regions. **DOI:** 10.13813/j.cn11-5141/u.2018.0411-en

Keywords: public transit; rail transit; spatial-temporal characteristics of passenger flow; IC card data; job-housing distribution; Wuhan City

0 Introduction

Timely acquisition of operation data and accurate mastery of passenger flow characteristics are the basic premises for rail transit network planning and construction planning, as well as the important basis for evaluating the operation organization and the construction effectiveness [1]. According to the method to acquire basic information, rail transit operation data collection went through three stages. At first, the passenger flow of transit lines and stations was collected by revenue counting and manual survey [2]. Since then, integrated circuit cards (hereinafter referred to as “IC cards”) have been gradually used and various information systems have been established to analyze the characteristics of passenger flow data [3]. Finally, under the guidance of “Internet +”, data mining has been integrated to promote the innovations in decision-making and to support the development of plans, which has become the trend of urban development [4].

In recent years, many scholars have conducted valuable research on public transit passenger flow based on IC card data. Reference [5] studied urban job-housing relationship and commuting behaviors from the perspective of rail transit passenger flow; Reference [6] induced spatial and temporal characteristics of urban rail transit passenger flow; Reference [7] studied rail transit network operation regulations; and References [8–9] established probability-based path selection models in rail transit network. Wuhan is currently in a period to develop its urban master plan, land use plan and transportation plan simultaneously, and in the meantime Wuhan is constructing its intelligent transportation system. During this period, trip information based on IC card data plays an important role in the evaluation of urban space utilization. Based on Wuhan rail transit IC card data, network data and operational data, this paper analyzes the characteristics of rail transit passenger flow and urban spatial layout.

1 Development trend of the rail transit in Wuhan

Since 2012, at least one subway line has been built every year in Wuhan. As of January 2018, 7 rail transit lines (237 km in total) and 167 stations (including 19 transfer stations) have been in operation, and Wuhan has entered the stage of networked operation. According to *The Reply of National Development and Reform Commission on the Wuhan Urban Rail Transit Phase III Construction Plan* (2015–2021) (Development and Reform Foundation [2015] No. 1367) [10], Wuhan will form a rail transit network consisting of 10 lines with the total length of 400 km (see Fig. 1) by 2020. A multi-mode rapid rail transit system will gradually be established.

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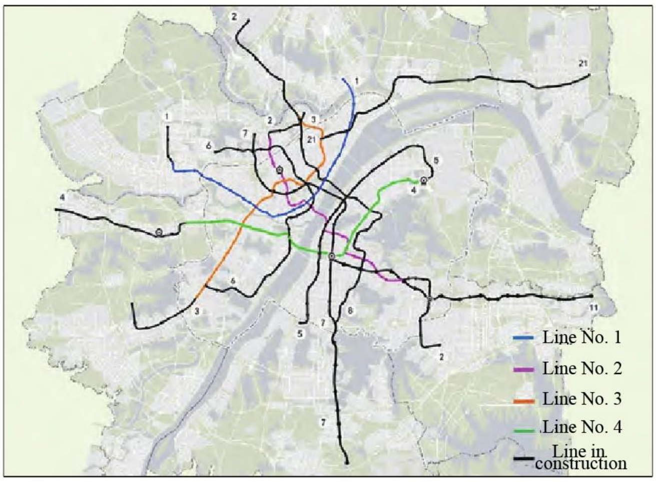
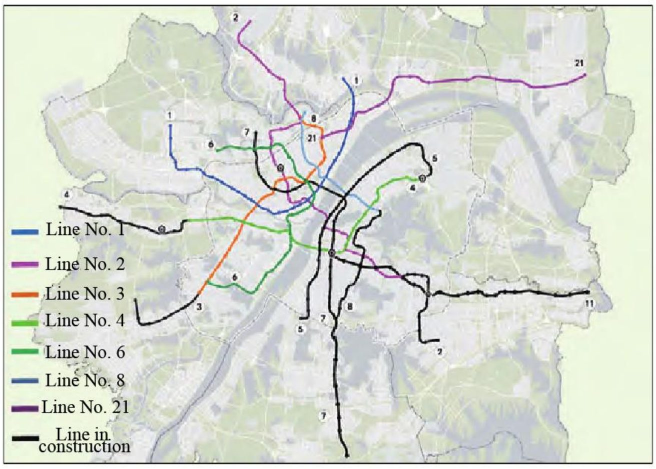
First author: WANG Guan (1984–), male, from Wuhan Hubei, PhD, engineer. Research interests: intelligent transportation, traffic model, traffic control and simulation. E-mail: ballackguan@126.com



(a) In 2018



(b) In 2020

Fig. 1 Existing and planning rail transit network in Wuhan

Source: Reference [10].

During the rail transit construction in Wuhan, lines with different types and functions have different impacts on the total passenger flow. However, the passenger flow intensity presents a continuous upward trend with the accumulation of operation time and the scale expansion of the network. At the end of 2012, Line No. 2 which links Hankou and Wuchang Districts was opened and formed a fast passenger transportation channel connecting the north and south sides of the Yangtze River. At the end of 2015, the opening of Line No. 3 promoted the rail transit network to be interlocked, and the overall attraction was further enhanced. In the past 5 years, with the increase in land development intensity along rail transit lines, the total passenger volume of the entire network increased rapidly. It increased from 230 thousand trips per day to 2.05 million, an increase of 8 times. The passenger flow intensity increased from 8.1 thousand per km to 16.3 thousand per km, with an average annual growth rate of 20.5% (see Fig. 2). The average travel distance increased along with the expansion of the line network, presenting a continuous upward trend which increased from 8.3 km to 10.9 km. In 2016, the transfer rate of the entire network reached 1.38, which was significantly higher than the 2012 level at 1.13 when only two rail transit lines were in operation. In a word, the rail transit network has led to more frequent exchange of regional passenger flows, the network benefits have emerged, and the rail transit passenger flow was in a stage of rapid development.

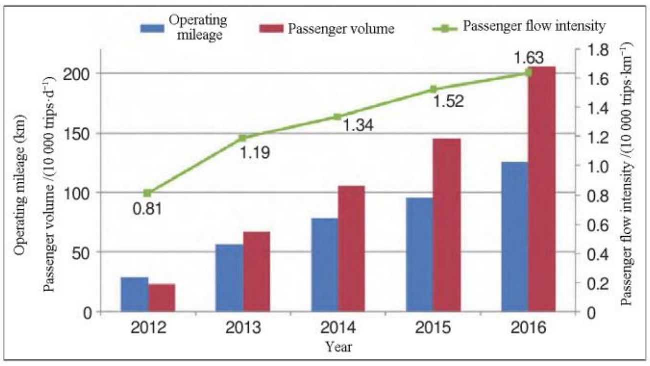


Fig. 2 Mileage and passenger volume of rail transit network in Wuhan from 2012 to 2016

Transit riders need to use IC cards or electronic tickets when they enter and when they exit a station. Through the long-term accumulation and mining analysis of ticket data, the complete passenger flow information can be obtained. This paper studies the routes currently in operation, and analyzes the passenger flow distribution and regional exchanges, as well as the urban spatial layout reflected by commuting characteristics.

2 Spatial characteristics of Wuhan rail transit passenger flow

Before analyzing the relationship between rail transit commuting and urban spatial layout, the general characteristics of rail transit passenger flow awere summarized from the following two aspects.

2.1 Cross section passenger flow

In Wuhan, the demand for passenger exchanges between the two sides of the Yangtze River is very strong. However, rail transit Line No. 2 is currently the only fast public transit channel connecting the two sides (Hankou and Wuchang), which leads to the concentration of high cross section passenger flows on Line No. 2 (see Fig. 3). The length of the segment between Xunlimen Station and Jiedaokou station is 11.5 km, and this segment has 8 stations. The passenger flows for all cross sections on this segment are above 300 thousand trips per day. Among these cross sections, the cross section between Hongshanguangchang Station and Zhongnanlu Station has the highest passenger intensity, reaching 411 thousand trips per day. The second is the cross section of the Yangtze River (between Jianghanlu and Jiyuqiao), with 359 thousand trips per day. As a result, the average daily ridership on Line No. 2 is more than 800 thousand, accounting for 40% of the total ridership on the entire network. On the other hand, stations with large passenger flows are also concentrated on Line No. 2. Based on the data collected from electronic monitoring systems on some sections and manual survey data, rail transits account for 54.3% of the motorized trips along the Line No. 2 corridor, and cars account for 11.7%, which is lower than the average level (23.1%) of the city [11]. The effects of rail transit on relieving traffic pressure and guiding low carbon travels are obvious.

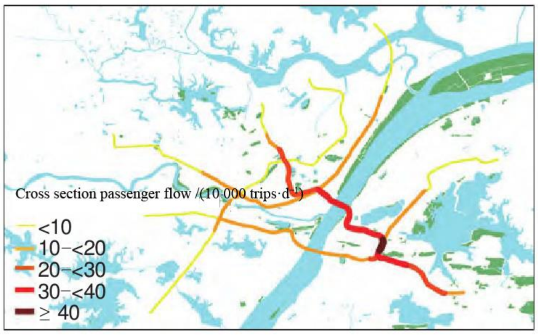


Fig. 3 Distribution of rail transit passenger volumes

Compared with Line No. 2, the passenger intensities of other lines are much more balanced and less than 300 thousand trips per day. The cross sections with high passenger flow on Line No. 1 and Line No. 4 are all adjacent to Line No. 2. For example, the segment between Chuhehanjie Station and Wuchang Railway Station on Line No. 4 is 4.1 km long, and its passenger flow intensity is the highest on Line No. 4. The newly opened Line No. 3 is in the passenger flow cultivation period, so its supply capacity is relatively abundant.

2.2 Regional passenger exchanges

Based on the urban regulatory planning zones, the exchange distribution of rail transit trips flow is shown in Fig. 4. It shows that the rail transit system not only serves long-distance trips crossing districts, but also supports short-distance passenger exchanges among adjacent planning zones.

For example, about 50 thousand trips are generated each day between the Tazihu Zone which is a typical residential area and the Luoyu Zone which has a large number of employments. The distance between these two zones is 22 km, but it only takes 49 min by rail transit. The rail transit has a lower generalized cost than buses and cars, and has become an important choice for trips crossing districts. Hongshan Zone and the Louyu Zone are adjacent zones with dense population. The rail transit trips between these two zones account for 31.5% and 28.5% of the total trips in each zone respectively. The rail transit trip distance is 6 km and the travel time is 17 min, which provides convenience to short distance travelers.

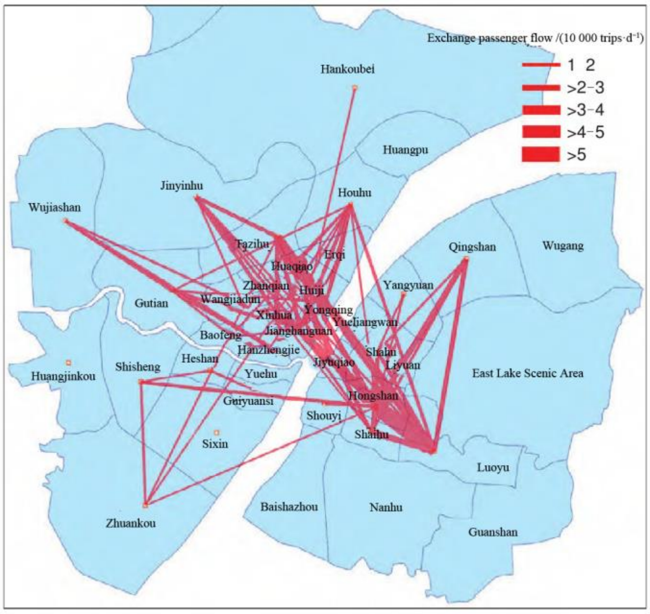


Fig. 4 Passengers' D of rail transit (greater than 10 thousand persons per hour) in central city

3 Analysis of job-housing distribution and commuting patterns

Land use and development intensity along rail transit lines directly affect the characteristics of passenger flow. With the improvement of the rail transit network, the population in the 1 km radius around stations has increased from 0.73 million in 2010 to 3.49 million in 2015 [12]. As a result, the passenger flow has grown significantly.

On one hand, the effect of planning and construction can be effectively evaluated through the change of passenger flow. Survey results showed that over 60% of the transit trips are mandatory trips such as work and school trips [11]. As a convenient transportation mode with high speed, large capacity, good safety and on-time performance, the rail transit has been widely favored by workers and students. People aged 25–55 is the main group of rail transit riders [11]. On the other hand, commuting characteristics reflect the process and efficiency of urban development and infrastructure construction. Based on rail transit commuting, the study on job-housing distribution is an important basis for the urban spatial layout, as well as the optimization and adjustment of the public transit network.

The all-day, complete-sample trip chain data collected on continuous working days showed that rail transit commuters accounted for about 40.3% of the total passenger flow. In this section, individual OD behaviors were studied to deduce group commuting patterns and identify job-housing distribution based on rail transit stations. Furthermore, the status of urban space development was analyzed by studying the characteristics of commuting trips.

3.1 Job-housing identification based on rail transit stations

In order to determine the land use type around rail transit stations, the residential area and employment area in this section refer to the residential-based areas and employment-based areas around rail transit stations, respectively. The job-housing identification model was established based on Reference [5] (see Fig. 5).

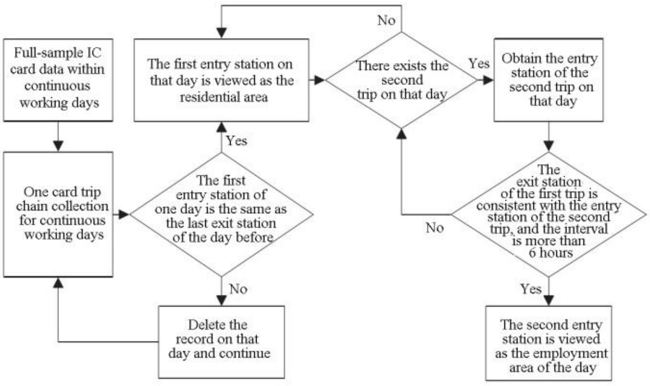


Fig. 5 Job-housing identification model based on rail transit stations

Source: Reference [5].

For an IC card (assuming one person has only one card), a trip is defined as a process that starts when the IC card is used to enter a station for the first time on a working day, and ends when there is no entry record one hour after an exit record. A trip may include multiple OD pairs, and enter and exit stations for multiple times. For example, a passenger may drop off his/her child at school before going to work.

For an IC card, if the last exit station of the previous working day (16:00–20:00) is the same as the first entry station of the current working day (6:00–10:00), the zone where the station is located is marked as a residential area. If the dwell time exceeds 6 hours at a station, and the station is or is adjacent to the first exit station on that day (it is possible for a passenger to go shopping first before going home), the zone where the station is located is then marked as an employment area.

The abovementioned algorithm is used to infer the residential and employment information of an IC card (a person) over continuous working days. Then this IC card's residential and employment areas can be deduced based on statistical probabilities, which is conducted for all IC card samples. In the end, all rail transit stations are classified into three groups: 38 residential-type stations, 18 employment-type stations and 11 mixed-type stations (see Fig. 6).

The urban ring roads can be used to describe the job-housing spatial distribution. The residential rail transit stations are mainly located between the First and Third Rings, the employment stations are within the Second Ring, and the mixed-type stations are around the Third Ring. There is a certain degree of job-housing separation, and the land use in some areas is relatively simple.

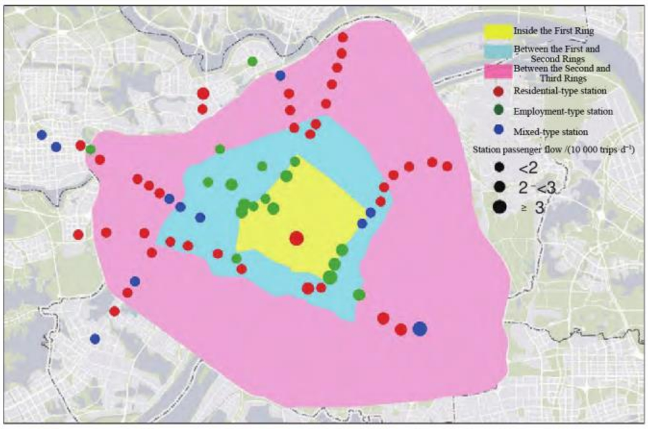


Fig. 6 Spatial distribution and commuting volumes at different types of rail transit stations

3.2 Rail transit commuting characteristics based on job-housing distribution

3.2.1 Travel time and distance of rail transit commuters

The travel time and distance of rail transit commuting trips show an increasing trend as the residential and employment areas are further away from the urban center, i.e., they gradually increase as the urban ring roads expand outward. This reflects the attraction effect of employments at the urban center (see Tab. 1).

Tab. 1 Rail transit commuting volumes at rail transit stations adjacent to residential and employment areas

Spatial scope	Residential area		Employment area	
	Commuting travel time /min	Commuting travel distance /km	Commuting travel time /min	Commuting travel distance /km
Inside the First Ring	19.7	7.7	22.7	8.4
Between the First and Second Rings	22.1	8.2	23.5	8.8
Between the Second and Third Rings	24.4	9.4	24.7	9.5
Outside the Third Ring	29.6	12.5	30.5	13.0

Rail transit commuting trips are mainly trips with short and medium distances. The average travel time is 24.1 min, which is lower than that for all motorized trips on the entire roadway network (29.4 min). The average travel distance is 9.2 km, which is also lower than the entire network (10.9 km). In general, 70.6% of commuters' travel times are less than 30 min, and 80.6% of their travel distances are less than 14 km (see Fig. 7).

3.2.2 Generations and attractions of commuting passenger trips during morning peak hours

According to the job-housing distribution, commuting behaviors during peak hours can better reflect urban spatial characteristics. In this section, commuting behaviors on working days during the morning peak are studied from the aspects of temporal distribution, spatial distribution and directional imbalance.

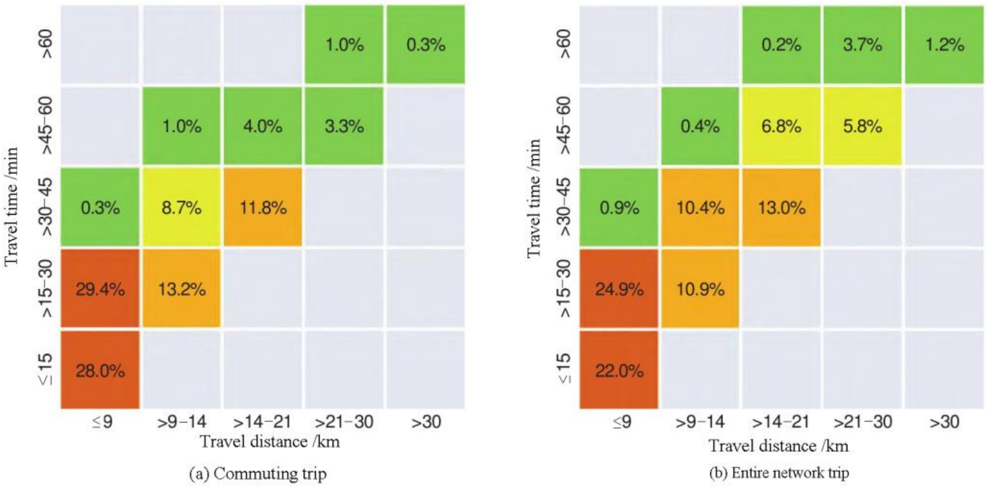


Fig. 7 Travel time and distance of rail transit users

1) Temporal distribution

As shown in Fig. 8, rail transit commuting trips are mainly concentrated at 7:15–8:45 on working days during the morning peak, which basically coincides with the peak hours of all commuting trips. The departure peak hour from home is 7:30–8:30, and 53.9% of commuters enter residential-type stations during this period. The arrival peak hour to destination is 8:00–9:00, and 54.5% of commuters exit the rail transit through employment stations.

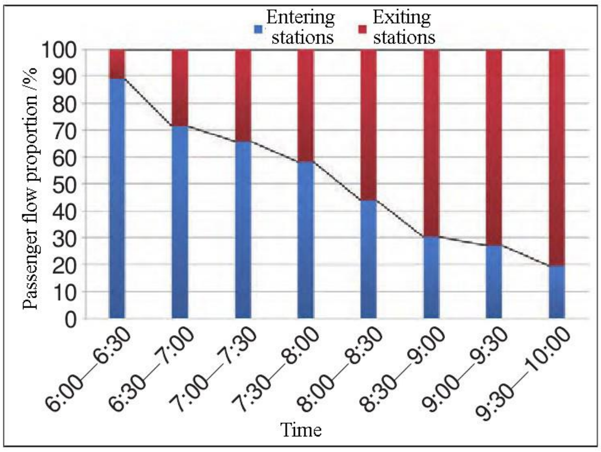


Fig. 8 Commuting volumes entering/exiting stations during morning peak hours

During peak hours, the cross section passenger volume between Jianghanlu Station and Jiyuqiao Station (a segment that crosses the Yangtze River) accounts for 32.6% of the daily volume. The most crowded hour for this segment is 7:30–8:30, accounting for 41.2% of the total volumes in peak hours. Most of these commuters are making mandatory trips since their jobs and homes are located in Hankou and Wuchang, which are separated by the Yangtze River.

2) Spatial distribution

During the morning peak hours, the top three travel directions with large commuting passenger flows are from the area between the Second and the Third Rings to the area between the First and Second Rings, from the area between the Second and the Third Rings to the area within the First Ring, and from the area between the First and Second Rings to the area within the First Ring. The sum of these three directions exceeds 40% of the total commuting volume, which indicates that the commuting trips during the peak hours are centripetal to a certain degree.

In terms of attractions, the commuting destinations from residential areas are different. However, in addition to the centripetal feature, some commuting trips show a characteristic of working close to home. As shown in Fig. 9, Jinyintan Station is located outside the North Third Ring, and about 48.2% of residents around this station choose to work in adjacent areas, such as Wangjiadun, Xinhua and Jianghanguan. Yangjiawan Station is located outside the East Second Ring. About 17.6% of residents around it choose to work at the Guanggu area, which is only one station away, and about 29.1% choose to work at the neighboring Hongshan area.

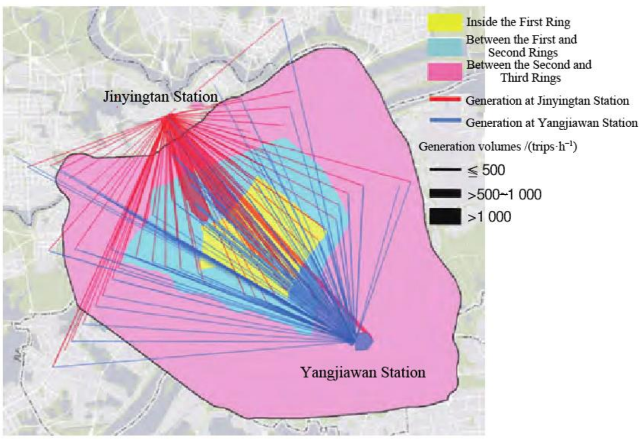


Fig. 9 Generation of commuting volumes at stations adjacent to residential areas during morning peak hours

In terms of generations, the attraction range of an employment area is related to its location, function, scale and other factors. As shown in Fig. 10, Chuhehanjie Station is in the cultural core area of Wuchang District, so it has a balanced attraction in all directions. Youyilu Station is located in the core business area of Hankou District, which has slightly shorter attraction range than Chuhehanjie Station, but has a stronger attraction to areas in Hankou District.

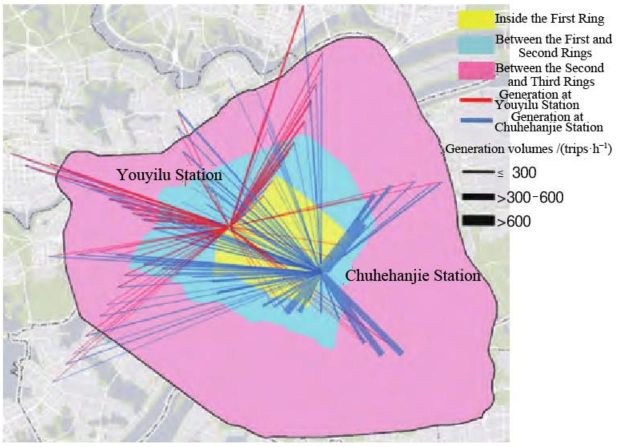


Fig. 10 Attraction of commuting volumes at stations adjacent to employment areas during morning peak hours

Due to the characteristic of working close to home, the rail transit travel times and distances around the Third Ring are not significantly greater than the area inside the First Ring. For example, the commuting characteristics of Jinyintan Station and Yangjiawan Station are not obviously different from that of Chuhehanjie Station and Youyilu Station which are inside the First Ring (see Tab. 2).

Tab. 2 Commuting characteristics at typical stations adjacent to residential and employment areas during morning peak hours

Item	Residential area		Employment area	
	Yangjiawan Station	Jinyintan Station	Chuhehanjie Station	Youyilu Station
Travel time /min	21.1	26.7	22.0	22.5
Travel distance /km	8.1	10.9	8.2	9.1
Passing stations	7	9	8	9
Commuting volume proportion /%	56.2	45.8	57.2	46.1

3) Directional imbalance

Unbalanced job-housing distribution directly leads to the apparent tidal pattern of corridor passenger flow [13]. The difference of passenger flow entering and leaving each ring roadway during morning peak hours is obvious (see Fig. 11). The ratio of commuting passenger flow entering and leaving the South Second Ring is the largest, which is as high as 3.6:1. Outside of the South Second Ring in Wuchang District, there are many residential areas, such as Nanhu and Guanshan. Most of the residents work inside of the Second Ring, resulting in the one-way congestion on rail transit lines from the south to the north in the morning peak. In the case of scheduling the rail transit according to regular rules, this tidal character not only increases the difficulty in the organization of public transit, but also causes a waste of the transportation capacity.

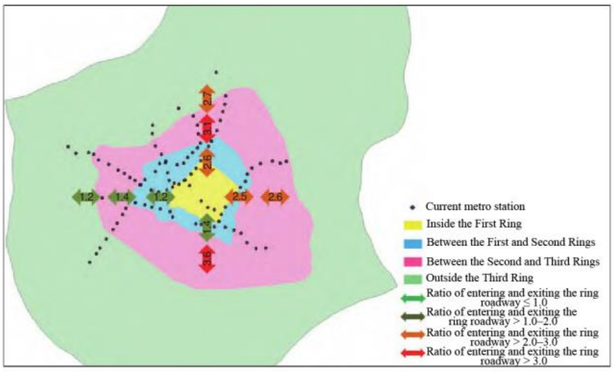


Fig. 11 Commuting volumes entering/exiting each ring roadway during morning peak hours

Insufficient infrastructure and low level of regional integrated development are also key factors causing the tidal characteristics in job-housing corridors. Although Yuejiazui Station and Dongting Station in the east of Wuchang District are mixed-type stations, they are located on a corridor that connects Hongshan (an employment area) and Yangyuan (a residential area), so their travel demand during peak hours shows a tidal pattern. The rail transit accessibility in this area is insufficient. Lines No. 5, No. 7 and No. 8 are planned transit lines directly going through the city from the north to the south, and their constructions should be promoted. On the other hand, Lines No. 1, No. 3 and No. 4 are all serving the southwest area of the city, which includes mixed-type areas around the Third Ring, such as Zhuankou, Huangjinkou and Wujiashan. There are many mixed-type stations in this region, such as Dongwudadao Station, Wuhuandadao Station, and Dongfenggongsi Station. In this region, most people live and work in the same areas, and the passenger flow during peak hours is relatively balanced.

3.2.3 Transfers of commuting trips

Because of the coverage limitation of rail transit stations, the rail transit trip is only a part of an entire trip chain, and cannot fully reflect the commuting needs. A survey shows that 70% of motorized trip chains that contain rail transit trips transfer from or to public transit (excluding taxis) [11]. Based on the proportion of the rail transit trip in the public transit system, rail transit commuting trips are classified into three categories for further analysis: direct access without transfer (entering and exiting the same metro line, one-line mode), transfer among rail transit lines (transfer among different metro lines, multi-lines mode), and transfer between rail transits and buses (transfer between metro and bus, rail transit–bus mode).

For rail transit commuters, the "direct access without transfer" mode can meet the requirement of mandatory trips on short travel times and distances, and it accounts for more than 50% (see Tab. 3). Among trips in the "transfer among rail transit lines" mode, 93.8% need to transfer only once to reach destinations. In addition, based on the public transit GPS data and card swiping data within 30 min or 500 m, the transfer demand between rail transits and buses accounts for 23.5% of the total rail transit commuting trips. The transfer demand should not be ignored, especially around the end of rail transit lines, transportation hubs and large business districts.

Tab. 3 Characteristics of rail transit commuting by different transfer modes

ransfer mode	Travel time /min	Travel distance /km	Commuting volume proportion /%
Direct access without transfer	19.4	7.7	51.0
Transfer among different metro lines	32.3	11.6	25.5
Transfer between metro and bus	52.8	17.1	23.5

Guangguguangchang Station, the last station on Line No. 2, has excessive hub functions which attract too many passengers and buses. Therefore, its passenger volume is as high as 150 thousand trips per day. There are 12 bus stations and 26 bus routes within the 500 m radius of Guangguguangchang Station. Most of the bus routes lead to the Guanshan area which is in the southeast. During peak hours (7:00–9:00), almost 50 thousand people make transfers at Guangguguangchang Station, and form a commute corridor that connects the Guanshan area with the city center and connects the south and the north of the city (see Fig. 12). Under the circumstances that the south extension of Line No. 2 has not yet been completed, the people in colleges, residential areas, and research institutes in the southeast part of the Guanshan area have gradually formed the transfer habit of "rail transit + bus". In this region, the passengers of large-scale attraction points, such as the South-Central University for Nationalities, Wuhan Textile University, Guanggu Software Park, almost all make transfers at Guangguguangchang Station. Although "rail transit + bus" has initially realized cross-regional travel, the average travel time is as high as 72.6 minutes due to road congestions and transfer waiting times, and the travel cost is still too high.

By now, since urban rail transits have not covered all surrounding areas of the Third Ring, buses undertake the task of connecting to and extending the rail transit network. In Wuhan, an urban public transit system is gradually taking shape which takes mass rail transits as the backbone, buses as the mainstay, ferries and taxis as the supplement, and walking and bicycles as the connection to the network.

4 Thoughts and suggestions

Based on the analysis of passenger flow data, this paper focuses on the regular behaviors of commuters. The characteristics of rail transit trips are summarized as follows.

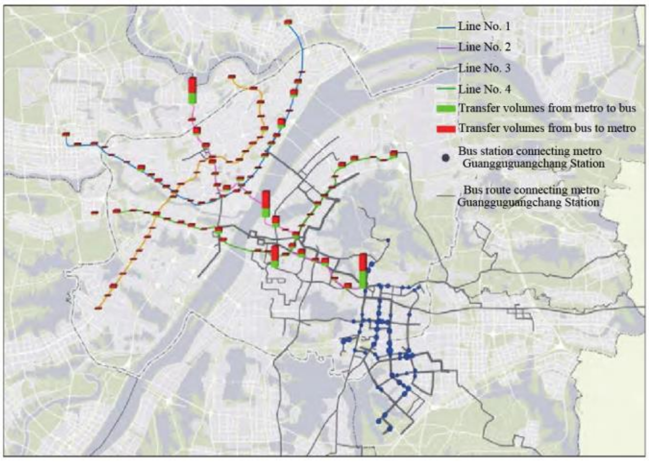


Fig. 12 Commuting and transfer characteristics at each rail transit station

1) Commuting trips account for a large proportion of rail transit trips, and they are usually short and medium distance trips with travel distances below 15 km. Compared with other travel modes, the rail transit is more attractive and efficient in serving urban commuters.

2) The construction of the rail transit network in some areas lags behind urban development, which causes the supply and demand imbalance. For some rail transit segments, the cross section volumes and the proportion of fully loaded trains are too high. The integrated transfer scheme for the public transit system has not yet been implemented.

3) The crowded transit rail lines and the tidal characteristics during peak hours are related to the layout of the urban space and rail transit network. The job-housing balance has not been achieved in the south of the main city and the surrounding areas of the Outer Ring, and the supporting facilities around rail transit stations still need to be improved.

According to a prediction model, the total daily passenger flow of the entire network will reach 6.5 million per day by 2020. It is necessary to improve the operation, organization and network planning based on the master plan to meet the increasing travel demand.

1) To improve the operation and organization according to passenger flow characteristics

In general, the current rail transit supply capacity is adequate in Wuhan. However, due to the imbalance in time and space of passenger trips and the lack of a rapid response mechanism for dynamic demand, the organization and management mismatch the real demand to some degree. For example, the passenger intensity and peak hour coefficient of Line No. 2 are the highest in the entire network, and it is very crowded over the segment crossing the Yangtze River during peak hours. On the other hand, the capacity of Line No. 3 is close to Line No. 1 and No. 4, which are about 15 000 passengers per hour. However, the passenger flow intensity of Line No. 3 is only 60% of Line No. 1 or No. 4. It is suggested that a variety of operation patterns should be adopted according to the distribution characteristics of passenger flow, such as dispatching trains with different capacities, passenger-cargo alternation and dynamic headway.

The internal connection of the public transit system is not tight enough. Transfers between buses and rail transits have not been organized efficiently. It is suggested to learn from other cities' advanced experience to develop the integrated transfer for the public transit system. In the meantime, it should promote the implementation of Park and Ride (P & R) plans and strengthen the operation management, in order to attract more car travelers to take the rail transit.

2) To optimize the network structure and urban layout

The development of urban space is expanding from the central area to the periphery. The rapid construction has changed the distribution and quantity of population and employment. Particularly, the growth is more significant in urban expansion zones and new districts. The travel demand has also changed accordingly. The average trip distance of the public transit system has increased from 8.4 km in 2008 to 10.8 km in 2018. It is recommended to continuously optimize and improve the rail transit system along with urban development, including the simultaneous development of land along the new rail transit line. For example, with the rail transit Line No. 8 long-term project, the Huangjiahu area outside the South Third Ring will be built as a subway town. On the other hand, it is suggested to adjust the rail transit construction plan according to urban spatial development. For example, the construction of rail transit Line No. 21 can be conducted ahead of schedule to strengthen the connection between the main city and the new town in the north.

Currently the urban rail transit system in Wuhan mainly focuses on connecting residential and employment areas within the Third Ring, which accounts for 81.7% of the total rail transit trips. However, the areas outside the Third Ring and the main city have not been connected actively and conveniently by the rail transit yet. While maintaining the high concentration of employment within the central city, it is suggested to develop industries that fit the regional characteristics, guide residents around the Third Ring to work close to home, and gradually form a space with balanced development similar to the Wujiashan area. At the same time, along the urban space development corridor, it should construct a passenger transportation system that takes the mass rail transit as the main mode, promote and optimize land use and spatial layout around stations, and encourage axial urban development.

5 Conclusions

Through the collection, integration and analysis of public transit data, such as IC card records, network structure, and operation and organization information, this paper quantitatively studies the overall development trend of the rail transit system in Wuhan, including the spatial-temporal characteristics of passenger flow, job-housing distribution and commuting patterns, etc. This paper studies the current status of the rail transit, explores the relationship between urban spatial distribution and travel activities, and analyzes the urban spatial layout and rail transit network construction from the perspective of travel characteristics.

With the arrival of the big data era, more information can be accumulated in the near future. For example, the mobile phone signaling data will be adopted to study complete trip chains, and to refine the study of travel rules of individuals and their spatial-temporal labels. Following one's traces and mastering one's trajectory will make the parameter calibration of prediction models more accurate, and provide more scientific and reasonable guidance on planning and decision-making.

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