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Metropolitan Rail Service Development: A Case Study of Chengdu–Dujiangyan Rail Transit

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Abstract: The common problems in many built metropolitan rail transit services in China include the vaguely defined functionality and limited role in the urban transportation system. With Chengdu–Dujiangyan rail transit service as an example, this paper comprehensively analyzes the rail line operation, development of cities along the rail line, and connection between the rail line and the urban rail transit system based on the collected information from various passenger flow levels. Based on the analysis results, the paper points out that the comprehensive nature of metropolitan rail transit functions should be addressed early in planning and construction stages. The position of metropolitan rail transit alignment and stations should be fully integrated with the urban functionalities. For the maximum travel efficiency between two rail services, the inter-rail terminal should provide passenger-friendly seamless transfer links. **DOI:** 10.13813/j.cn11-5141/u.2020.0104-en

Keywords: rail transit; metropolitan rail transit; empirical research; characteristics of passenger flow; station-city integration; Chengdu–Dujiangyan railway

0 Introduction

Metropolitan rail is a fast and large-volume commuter rail transit system that provides connection between the urban center and the surrounding towns or between the surrounding towns. It is important in expanding the effective supply of urban transportation, easing urban traffic congestion, and optimizing urban spatial layout. As the main mass transit mode, metropolitan rail plays a significant role in metropolitan areas such as Tokyo, Paris, and New York. In recent years, Beijing, Shanghai, Chengdu, Nanjing, and other major cities in China have started the exploration to convert existing railways to metropolitan railways or to construct new metropolitan railways. However, the common problems of many existing metropolitan rail transit services in China are as follows: Their functional positioning is unclear; the number of train departures is relatively small; the passenger flow is generally low; their role in the urban transportation system is limited.

There have been many studies on the top-level planning [1–2], network structure [3–4], and operation system [5–6] of metropolitan rail, but relatively few studies have been conducted on its case study. Chengdu–Dujiangyan Railway is one of the earliest metropolitan railways operated in China. Since it was put into operation in May, 2010, its stations and number of train departures have been adjusted and changed for many times. Moreover, its functional positioning in the urban transportation system and its role in serving the city have also gradually evolved. This paper starts with the characteristics of passenger flow in different stages of Chengdu–Dujiangyan Railway, analyzes the relevant factors affecting passenger flow, clarifies the function of metropolitan rail in urban areas, and expounds the key problems to be considered in the planning and construction of metropolitan railways.

1 Overview of Chengdu–Dujiangyan Railway

Chengdu–Dujiangyan Railway is the first railway project started in Sichuan Province, China after the "5.12" Earthquake. It is the first high-speed rail passenger corridor connecting the urban center of Chengdu with the surrounding districts and counties, which was opened officially on May 12, 2010. The main line of Chengdu–Dujiangyan Railway is 65 km long. It starts at Chengdu Station, which is laid mainly along Old Chengguan Road. There are 12 stations including Chengdu, Anjing, Xipu East, Xipu, Hongguang Town, Pixian East, Pixian, Pixian West, Ande, Juyuan, Dujiangyan, and Qingcheng Mountain (Figure 1). Chengdu–Dujiangyan Railway adopts CRH6A trains with four rail cars. The maximum operating speed is 120 $km \cdot h^{-1}$ from Chengdu Station to Pixian West Station, 200 $km \cdot h^{-1}$ from Pixian West

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Station to Dujiangyan Station, and 140 km·h^{-1} from Dujiangyan Station to Qingcheng Mountain Station.

2 Comprehensive analysis of passenger flow changes of Chengdu–Dujiangyan Railway

2.1 Analysis of passenger flow and function evolution of Chengdu–Dujiangyan Railway

The railway passenger flow data from 2010 to 2019 (Figure 2) show that the passenger flow of Chengdu–Dujiangyan Railway presented three distinct stages. Through the analysis of the reasons for passenger flow changes in different stages, the main functions of Chengdu–Dujiangyan Railway in different stages are identified.

1) The first stage: In the initial stage after the railway opening, the passenger flow rose slowly.

From 2010 to 2012, the passenger flow of Chengdu–Dujiangyan Railway showed a slow upward trend. There were six railway stations, including Chengdu Station, Xipu Station, Hongguang Town Station, Pixian West Station, Dujiangyan Station, and Qingcheng Mountain Station, with an average station spacing of 13 km and daily departures of 15 to 20 pairs of trains. From the perspective of station passenger flow (Figure 3), the passenger flows of Xipu Station, Hongguang Town Station, and Pixian West Station were far lower than those of Chengdu Station, Dujiangyan Station, and Qingcheng Mountain Station. From the perspective of railway operation, the departure interval was about 1 h and more than 50% of trains were direct trains from Chengdu to Dujiangyan or Qingcheng Mountain, without stopping at intermediate stations. According to the average daily passenger flow on weekdays, weekends, and holidays in 2010 (Figure 4), the passenger flows on weekends and holidays were 30% higher and 75% higher than that on weekdays, respectively. This pattern indicated that Chengdu–Dujiangyan Railway not only undertook the transportation function to connect to the northwest of Chengdu but also had a significant tourism function.

2) The second stage: The passenger flow declined.

From 2012 to 2015, the passenger flow showed a gradual decline trend, mainly due to three reasons. First, Xipu East, Pixian, and Ande Stations were opened during this period and the train stopped at more stations, which increased the total travel time by about 15 min. Under the circumstance that the total number of train departures was unchanged (about 20 pairs per day), the number of fast direct trains was greatly reduced. As a result, the attractiveness of Chengdu–Dujiangyan Railway to passengers declined. Second, the renovation of the trunk roads connecting Chengdu urban area, Pixian, and Dujiangyan, such as Old Chengguan Road and Shaxi Expressway, was completed during this period. As a result, the highway travel time from Chengdu to Dujiangyan was shortened to 1 h. The highway system had the advantage of point-to-point direct access, and its competition led to the decrease in the passenger flow on Chengdu–Dujiangyan Railway year by year. Third, the originating station of some trains was changed from Chengdu Station to Xipu Station, which has a lower hub level and is far away from the Chengdu urban area. This change of originating station significantly reduced the level of service to passengers from various directions of the city. At that time, the transfer between Chengdu–Dujiangyan Railway and Metro Line 2 was inconvenient, and the urban rail transit lines were not networked yet, so the accessibility was low. As a result, the travel modes of passengers within The Third Ring Road changed, and some passengers no longer traveled by rail. Generally speaking, in the second stage, Chengdu–Dujiangyan Railway still undertook the functions of transportation connection and tourism among Chengdu, Dujiangyan, and Qingcheng Mountain, but it failed to fully exert its function to serve urban transportation.

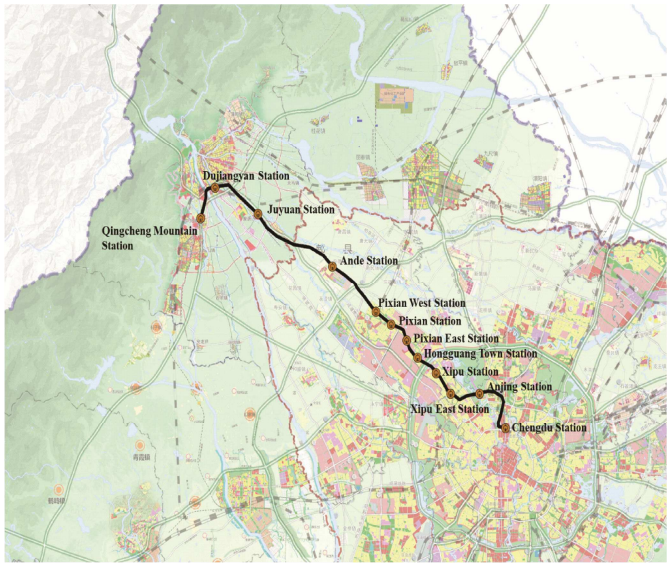


Figure 1 Alignment and stations of Chengdu–Dujiangyan rail transit

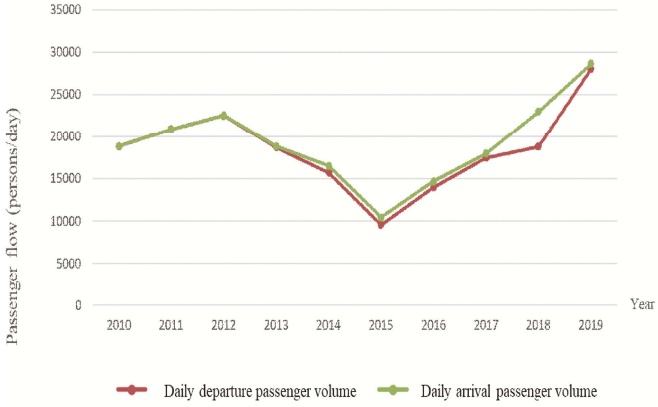


Figure 2 Changes on passenger flow along Chengdu–Dujiangyan rail transit

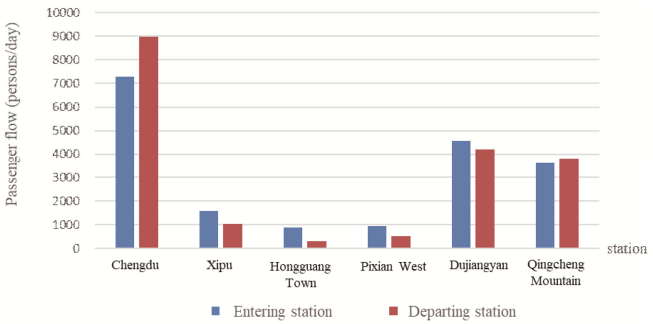


Figure 3 Daily average passenger volume entering/departing each station of Chengdu–Dujiangyan rail transit in 2010

Figure 4 Daily average passenger volume of Chengdu–Dujiangyan rail transit on workdays, weekends, and holidays in 2010

3) The third stage: The passenger flow recovered.

In 2016, the daily number of train departures on Chengdu–Dujiangyan Railway increased from 20 pairs to 30 pairs. In 2017, the application of the bus operation model to rail continued to improve, with 36 pairs of train departures during peak periods and departure intervals of about 28 min. In January 2019, the bus operation model was applied to all trains on Chengdu–Dujiangyan Railway. The daily number of train departures increased to 59 pairs, and the departure interval during peak hours was shortened to 10 min. The application of the bus operation model to rail reduced the waiting time of passengers and increased the number of fast and direct trains. Moreover, it enhanced the attractiveness of Chengdu–Dujiangyan Railway to the passengers along the route and led to the steady increase in passenger flow.

Although the bus operation model has been applied to rail, there were still few trains that could meet the needs of commuters. In terms of the number of trains stopped at each station, only seven to ten pairs of trains stopped at Hongguang Town Station, Pixian Station, Pixian West Station, and Ande Station out of the 44 pairs of trains departing from Anjing Station and Xipu Station in the urban area of Chengdu, most of which were direct trains to Dujiangyan and Qingcheng Mountain as shown in Figure 5 (the originating station of almost all trains was changed to Anjing Station or Xipu Station in 2019 because Chengdu Station was under renovation). In the evening rush hour, there were only two pairs of trains traveling from the urban area of Chengdu to Hongguang Town Station, Pixian Station, Pixian West Station and Ande Station, so commuting was not convenient. Generally speaking, in the third stage, Chengdu–Dujiangyan Railway mainly undertook transportation connection and tourism functions, and it gradually started to undertake some urban transportation functions such as serving commuting and business trips.

2.2 Analysis of land use changes along Chengdu–Dujiangyan Railway

The Dujiangyan section of Chengdu–Dujiangyan Railway is laid along Chengdu–Dujiangyan Expressway. It is restricted by the safety protection and control requirements of the freeway corridor, which causes the separation between Chengdu–Dujiangyan Railway and urban functions. In Pidu District, Chengdu–Dujiangyan Railway is laid along Old Chengguan Road, which is one of the earliest external roads in Chengdu and mainly used by through traffic. The railway passes by the edge of the development groups and is far away from the planned main urban center and sub-centers, so it is difficult for this railway to effectively drive the development of urban functions and urban centers (Figure 6). By identifying the land use changes of Pidu District in 2014 and 2018 based on remote sensing images, we found that 3 166 hm^2 of land was developed between 2014 and 2018 but only 3% of the land was located within 500 m of the stations on Chengdu–Dujiangyan Railway (Figure 7). The newly developed land mainly concentrated in High-tech West Zone, Pitong Community, and Deyuan Town, accounting for more than 50%. The land use growth data show that Chengdu–Dujiangyan Railway has not achieved organic interaction with the urban development. It has weak driving effect on the urban functions and land development along the railway line, and the interaction between the transportation function and the urban function is insufficient.

3 Analysis of relationship of stations of Chengdu–Dujiangyan Railway with functions and land use of surrounding cities

The passenger flows from 2010 to 2019 at each of the stations in Pidu District were analyzed. It was found that the flow of passengers entering and departing a station presents three types of patterns: The passenger flow increases at the beginning then decreases later; the passenger flow stays low for a long time; the passenger flow increases continuously (Figure 8: at each station, the flow of passengers departing from a station shows the same pattern as the flow of passengers entering the station). According to the characteristics of passenger flow changes at each station and the function of surrounding cities, this paper analyzed the relationship between the passenger flow of Chengdu–Dujiangyan Railway stations and the surrounding land.

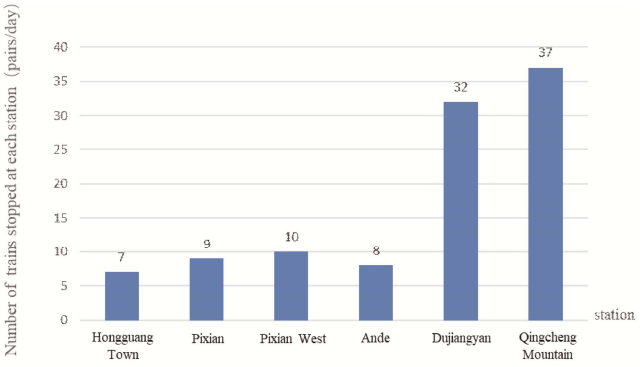
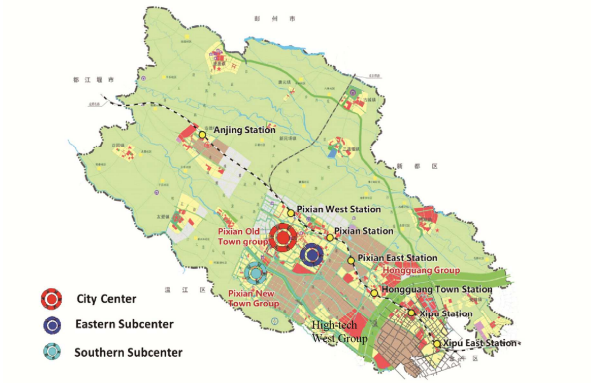
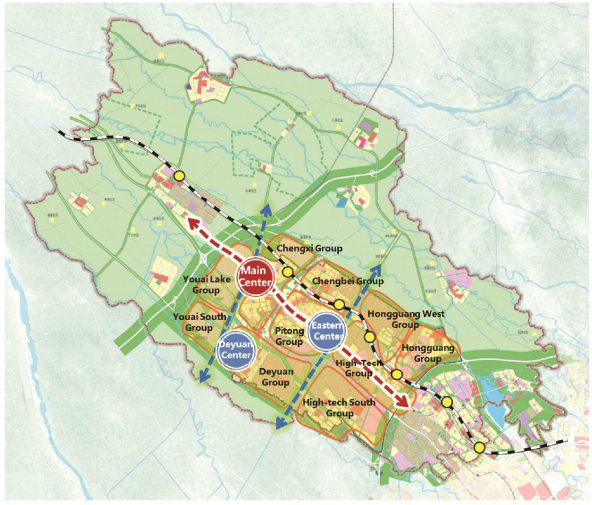


Figure 5 Pairs of trains at each station departing from Anjing and Xipu



a. Year 2010



b. Year 2014

Figure 6 Urban spatial layout in the Pidu District's overall planning document

1) Stations with passenger flow increasing at the beginning and gradually decreasing later

Hongguang Town Station and Pixian West Station are two examples of such stations. Their passenger flows increased from 2010 to 2012 and declined consistently after 2012. The main reason for the continuous growth of the passenger flow in the early stage of these two stations is that the areas around the stations had strong urban functions and complete land functions, which can provide stable passenger flow. Hongguang Town Station is located in the old town area of Hongguang Town and the area around this station was relatively well-developed with a large number of residential and public service functions, which provided a stable source of passengers to the station. Pixian West Station is located on the west side of Pidu District, surrounded by comprehensive urban functions such as residence, public service and commerce, which ensured the stable growth of passenger flow (Figure 9).

After 2012, the passenger flows of Pixian West Station and Hongguang Town Station gradually declined. The main reason is that three stations (Pixian Station, Ande Station, and Xipu West Station) were opened while the number of train departures on Chengdu–Dujiangyan Railway was not increased. As a result, the frequency of train departures from Pixian West Station and Hongguang Town Station was significantly reduced, which lowered the attractiveness of Chengdu–Dujiangyan Railway to the passengers of these two stations.

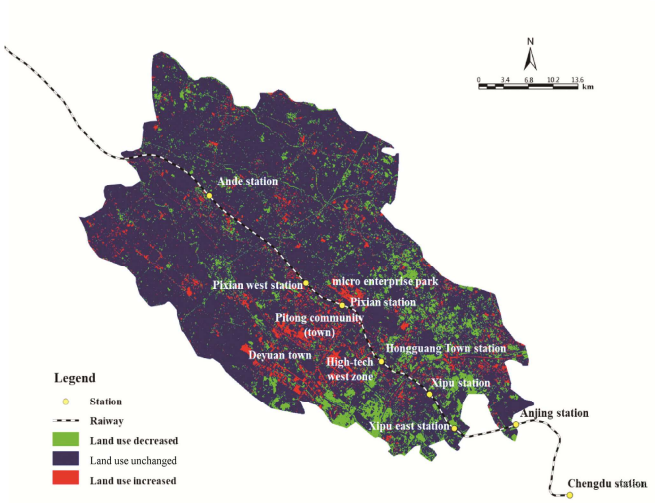


Figure 7 Changes in land use development between 2014 and 2018 in Pidu District

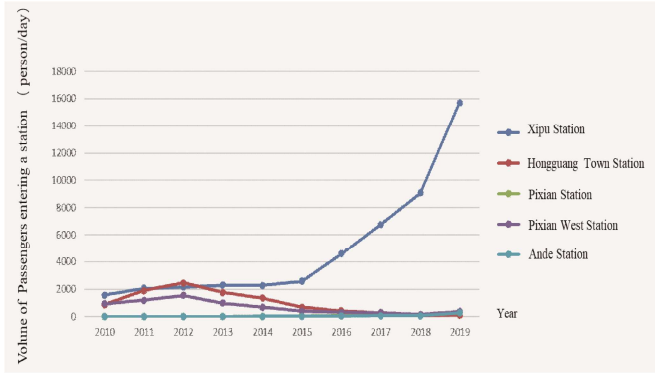
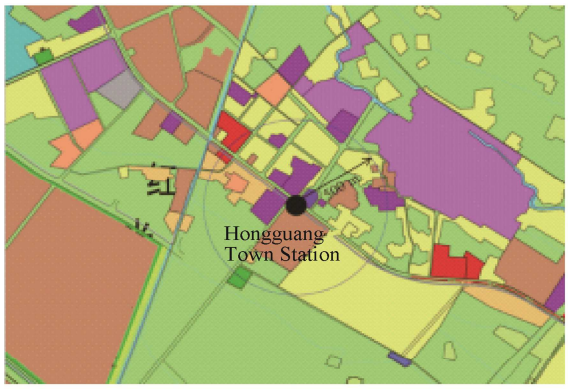


Figure 8 Passenger inflow volume at five stations of Chengdu–Dujiangyan rail transit in Pidu District



a.Hongguang Town Station

b.Pixian West Station

Figure 9 Land use surrounding Hongguangzhen Station and Pixian West Station in 2010

2) Stations with low passenger flow for a long time

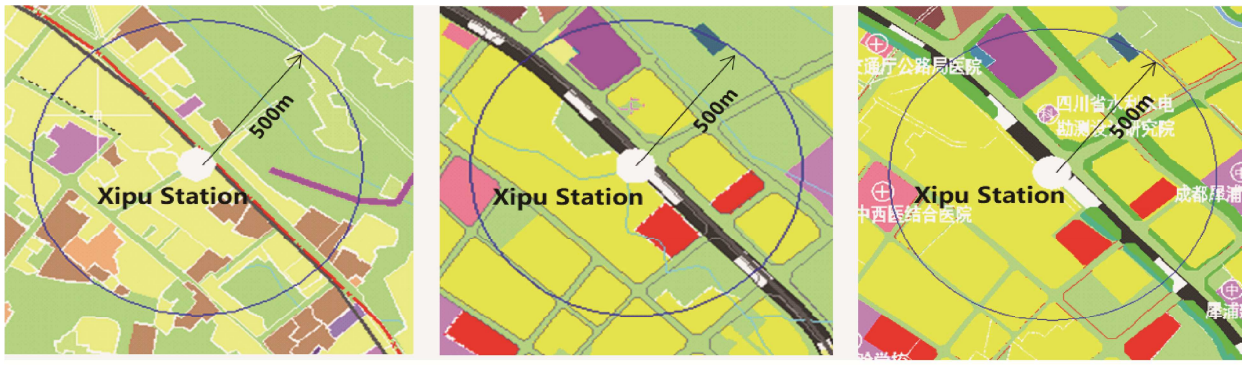
Pixian Station and Ande Station were opened in 2014. Although their passenger flows grew slowly, they have been at a low level with average daily passenger arrival and departure flows both below 300 passengers per day. Both Pixian Station and Ande Station are located in the peripheral areas of the city. When they were opened in 2014, the area around Pixian Station was mainly industrial land, while the urban development and construction had not started around Ande Station. In the meantime, the areas where Pixian Station and Ande Station are located are away from the development center of Pidu District. Therefore, the urban functions around the stations have not been significantly improved and it is difficult for them to provide effective support to the passenger flow.

3) Stations with passenger flow growing continuously and remaining at a high level

The passenger flow of Xipu Station maintained a stable growth trend from 2010 to 2019. Besides transfers and other factors, Xipu Station's location and the urban function and land use of surrounding area also provided effective support to the passenger flow. Xipu Station is located within the beltway, on the east–west axis of Chengdu and in the center of Xipu Industrial City Group, which has strong urban functions. The comparison of the land use around Xipu Station in different periods reveals that the city construction around the station continues to improve. The residential, public service and commercial functions continue to gather, and the development scale continues to increase, which provides stable passenger flow to the station (Figure 10). As the transfer station for Chengdu–Dujiangyan Railway and Metro Line 2, Xipu Station's traffic function interacts with the urban function. They promote each other and ensure the attractiveness of Xipu Station to passenger flow.

4 Analysis of connection between Chengdu–Dujiangyan Railway and urban rail transit

In June 2013, the west extension line of Metro Line 2 was opened. It intersected Chengdu–Dujiangyan Railway at Xipu Station, which became a transfer station. It was inconvenient to transfer between the railway and the metro, and the urban rail transit had not yet networked so the accessibility was weak. As a result, the passenger flow of Xipu Station had not increased significantly. In 2017, Chengdu–Dujiangyan Railway and Metro Line 2 achieved the mutual recognition in security inspection and transfer on the same platform at Xipu



a.Year 2010 b. Year 2014 c. Year 2016

Figure 10 Land use surrounding Xipu Station

Station. Meanwhile, the urban rail transit accelerated its network development and improved accessibility. A large number of passengers transferred from and to the metro, which significantly enlarged the passenger flow at Xipu Station (Figure 11). After the mutual recognition in security inspection was implemented, passengers who took Metro Line 2 to Xipu Station did not need to go through additional complex processes such as exiting the metro, passing the railway security inspection, and entering the railway station. Instead, they could pass through the railway gate to access the EMU platform directly from the metro platform. This seamless integration at Xipu Station reduced the passenger transfer time, improved the convenience of transfers, and promoted the further improvement of the attractiveness of Chengdu–Dujiangyan Railway to passengers.

5 Thoughts on development of metropolitan rail

5.1 Metropolitan rail should focus on multiple functions with the leading function of serving urban transportation such as commuting and business trips

In the initial stage of Chengdu–Dujiangyan Railway, there were few stations and the departure frequency was low. Its main function was to provide transportation connection between Chengdu downtown and Dujiangyan, and its tourism function was also significant. In the later stage, with the growth of the number of stations and the gradual increase in departure frequency, Chengdu–Dujiangyan Railway gradually undertook multiple functions such as serving commuting and business trips. Compared with the initial stage, the current passenger flow increased by 60% and the increment was significant. Therefore, in terms of functional positioning, metropolitan rail should focus on multiple functions to serve the travel between the central urban area and the peripheral groups and the travel between the peripheral groups. Its leading function should be serving urban transportation such as commuting and business trips, along with the function of serving tourism passenger flow, to fully drive the development of cities and towns along the railway line.

5.2 Metropolitan railway lines should be fully integrated with urban functions

In the initial planning stage, the interaction of Chengdu–Dujiangyan Railway with urban functions and land use was not fully considered. The Dujiangyan section of Chengdu–Dujiangyan Railway was laid along Chengdu–Dujiangyan Expressway, resulting in the separation of the railway line and urban functions. The Pidu section was laid along Old Chengguan Road, and the railway line passed along the edge of the urban groups, far away from the urban center. Consequently, the newly added land within 500 m of the stations on Chengdu–Dujiangyan Railway only accounted for 3% of the total newly added land in Pidu District from 2014 to 2018. As a result, Chengdu–Dujiangyan Railway did not play a significant role in leading the development of urban functions and land use along the railway line, and the transportation function did not fit well with the urban function.

Therefore, the route of the metropolitan railway should match the main urban development direction and deeply integrate with urban functions. In the route selection of a newly planned metropolitan railway, the route should not pass by the edge of the city any more. Instead, the integration of the railway and the city should be fully considered, and the connection and coverage of the metropolitan railway to the key areas of the city should be strengthened. Furthermore, the service function of the metropolitan railway should be maximized, and the driving effect of the metropolitan railway to the city development should be realized through the close integration of railway stations and urban functions. The *Detailed Planning of Pidu District* (2016–2035) recognizes the importance of the integration of rail transit and urban functions and places urban functions along Chengdu–Dujiangyan Railway. It connects multiple centers along the railway line and promotes the integration of Chengdu–Dujiangyan Railway and urban functions

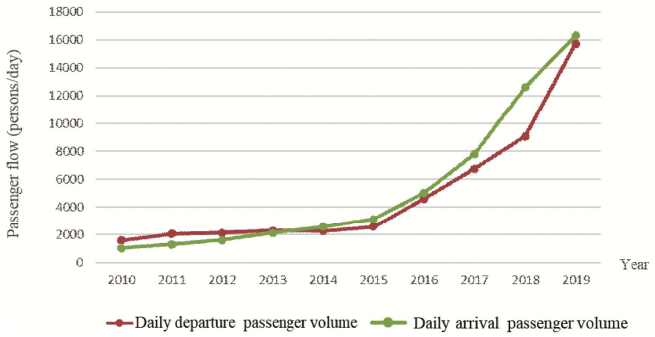


Figure 11 Change in passenger flow at Xipu Station

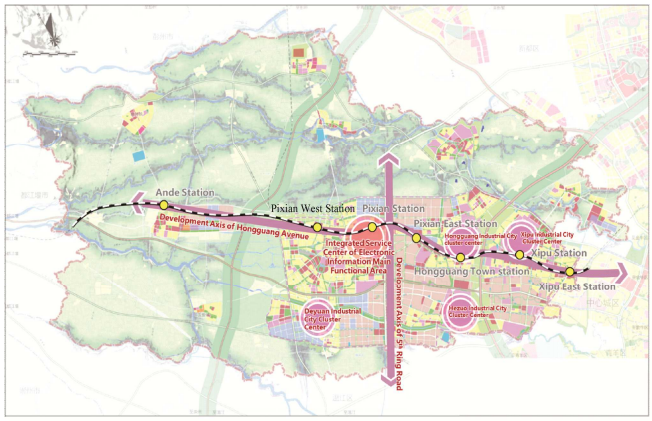


Figure 12 Urban spatial layout in the *Detailed Planning of Pidu District* (2016–2035)

5.3 Metropolitan railway stations should be fully integrated with urban land use

1) The originating station should be placed close to the city center

The originating station of the metropolitan railway should be placed in the large-scale transportation hub in the urban central area. Moreover, it should be effectively connected with major urban functions in this area to enhance the integration of the metropolitan railway and the city and to improve the service level of the metropolitan railway to the city. Meanwhile, the high-density people flow in the urban central area should be used to provide sufficient passenger flow support to the metropolitan railway. The large-scale hub's advantages of dense lines and transfer connections should be exerted to improve the metropolitan railway's attractiveness and coverage to passenger flow in various areas of the city.

2) Non-originating stations should be integrated closely with the urban functions of surrounding cities

After the opening of Chengdu–Dujiangyan Railway, some stations, such as Ande Station, Pixian Station, and Pixian East Station, are obviously disconnected from the surrounding urban land due to the inherent deficiencies in the selection of station locations. Therefore, the passenger flows of these stations are difficult to grow effectively and remain at a low level. On the other hand, Xipu Station is well integrated with surrounding urban land, so it realized the steady growth of passenger flow and became an important hub of Chengdu–Dujiangyan Railway. Through the relationship between the passenger flow changes of Chengdu–Dujiangyan Railway stations and the surrounding urban land use, it can be found that stations should be placed in urban centers or areas with strong urban functions or complete land functions to ensure enough passenger flow effectively. At the same time, the railway station can promote the agglomeration of urban functions in return. The areas around railway stations should make use of the influencing and leading effect of the metropolitan railway to promote the agglomeration of urban public facilities.

As a part of the urban rail transit system, metropolitan rail should play a leading role in urban development, which should achieve the comprehensive development through the integration of the station and urban land. In the future, metropolitan rail should further enhance its function as the urban rail transit hub. The integrated urban design should be developed based on the concept of Transit-Oriented Development (TOD), and major urban public functions should gather around metropolitan railway hub stations. Moreover, a mixed and open functional layout should take shape, and the efficiency of land development should be improved. Then efficient and intensive land development should be achieved. At the same time, rail transit should be taken as the center to create a comfortable spatial environment and people-oriented convenient and green transportation system. The integrated development of stations and cities should be implemented to maximize the benefits of public transportation and land use and to build the areas around rail transit stations into dynamic urban development areas.

5.4 Metropolitan railways should strengthen the seamless connection with the urban rail transit network

When Xipu Station became the transfer station of Chengdu–Dujiangyan Railway and Metro Line 2 in 2013, its passenger flow was low due to inconvenient transfers and poor accessibility of urban rail transit. With the improvement of urban rail transit network and the implementation of the same-platform transfer at Xipu Station in 2017, Xipu Station's passenger flow increased significantly. It indicates that the level of connection between metropolitan rail and urban rail transit is a key factor that affects the attractiveness of metropolitan rail to passengers. In the planning and design of metropolitan rail, attention should be paid to the integration with urban rail transit to enhance the attractiveness of metropolitan rail by improving the transfer convenience.

To further improve the connection between the metropolitan rail and other rail transit, the convenient connection of national rail, metropolitan rail, and metro rail should be strengthened from three aspects: network integration, station integration, and operation integration. Network integration emphasizes the clear division of duties for the lines in the same corridor and reasonable layout. Station integration aims at reducing the transfer distance and improving the convenience of transfer by means of local adjustment of station locations, reservation of interface, and three-dimensional construction of the hub. Operation integration focuses on the service level improvement by implementing mutual recognition in security inspection, improving the ticket system and fare, optimizing operation time, building the integrated information service system, etc. A rail transportation system should be constructed comprehensively, in which national railways, metropolitan railways, and metro railways integrate and complement each other and share resources.

6 Conclusion

Based on the empirical study of Chengdu–Dujiangyan Railway and the analysis of passenger flow characteristics, this paper clarified the main factors that influence the operation of metropolitan rail. First, metropolitan rail should focus on comprehensive functions to meet diversified travel needs, such as commuting and business travel, while ensuring fast and direct access. Second, metropolitan rail should fully integrate with urban functions and fully consider urban function factors in determining lines and station locations to realize the good interaction between the metropolitan rail and the city. Third, metropolitan rail should seamlessly connect with the urban rail transit and maximize its efficiency by integrating with the urban rail transit network. This paper

relied mainly on the data of Chengdu–Dujiangyan Railway and metro lines. It did not consider the connection and transfer relationship between rail transit and buses, which could be addressed by detailed study based on relevant data in the next step.

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