

Coordinated optimisation of multi-level rail transit network and Regional spatial: International contextual differences and the case of Shanghai¹

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Abstract:

As the urbanisation rate in China continues to rise, there is an urgent need to enhance the rail transit system to facilitate the growth of major cities and regions. This study examines the contrasts and interconnections between China's rail transit system concepts and those of other countries, as well as the discrepancies in the histories of construction and operational approaches. Based on a clear understanding of these differences, the study employs multiple data sources to analyse the rail transit network in Shanghai. It finds that the network is well-developed, particularly in high-speed railways and metros. However, it lacks an intermediate level. To address this issue, the study proposes a multi-level rail transit network and spatially coordinated optimisation strategy tailored to urban demands. This strategy encompasses rail transit networks at three spatial scales, with specific strategies determined by the availability of urban resources. In conclusion, the study proposes a multi-level rail transit network and spatially coordinated optimisation strategy tailored to urban demands. This strategy encompasses rail transit networks at three spatial scales, with specific strategies determined by urban resources. The study emphasises the significance of recognising contextual variations and tailoring solutions to local requirements.

Keywords: Regional integration; Rail transit network; Metropolitan areas; Cross-cultural comparison; Shanghai

1. Introduction

Currently, China's urbanisation rate has exceeded 60%. As the functions of large cities expand, their spheres of influence expand accordingly, and this expansion has led to the blurring of the boundaries between cities and their neighbourhoods. Against this background, the Chinese government has made coordinated regional development an important national strategy. China's major cities, including Shanghai, emphasise development strategies from a 'city-region' perspective (Shanghai Municipality People's Government, 2018). As a vital transportation network for supporting the growth of large cities and regions, the planning and construction of rail transit systems must be expanded to align with the transportation and development needs of the city and its surrounding areas.

Rail transit plays a pivotal role in public transportation and serves as a crucial infrastructure for supporting the spatial development of cities and regions. Existing research indicates a

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significant influence relationship between rail transit and urban space (Urena, Menerault, and Garmendia, 2009; Cao,2023). Consequently, the rail transit system should be adjusted following changes in urban development orientation. China's megacities, including Shanghai, are attempting to plan and build rational rail transit systems in their urban areas to support efficient inter-city connectivity through rail transit systems and effectively promote regional development.

It should be noted that urban rail transit is a term that encompasses various types of local rail systems that provide passenger service within and around urban or suburban areas. In China's national standard, "Nouns and Terms Commonly Used in Urban Public Transport," urban rail transit is defined as "a general term for fast and high-capacity public transport that is usually powered by electric energy and operates on wheeled rails." The scope of this study is defined as the Shanghai metropolitan area, Shanghai city area and central Shanghai, with reference to official data. Given the different spatial scales that can be effectively served by different rail transport types, the study focuses on four rail transport types: national high-speed railway, inter-city railway, suburban railway and metro. Due to the differences in spatial scale and administrative authority, there are differences between Chinese and foreign cities in terms of rail transit concepts and service situations. For example, the understanding and construction of the four types of rail transit described in the previous section are not the same in China and abroad.

Furthermore, the construction and operation entities and existing problems are also different. Furthermore, research has indicated that the functional structure of the Shanghai metropolitan area is not a 'centre-periphery' commuting circle structure, in contrast to other metropolitan areas that exhibit a concentrated and significant centripetal commuting flow. Therefore, in the Chinese context, the scale and structure of the metropolitan area differ from that of foreign countries (Niu, Yue and Li,2020). Understanding these differences is a crucial prerequisite for comparing other countries' cases and discussing the Chinese scenario.

The objective of this study is to examine the similarities and differences between China and other countries in terms of concepts related to rail transit systems. Additionally, the study will compare the differences in the construction history and operation of rail transit in different countries. Based on elucidating the discrepancies, the pivotal concerns confronting the construction of Shanghai's rail transit system are analysed through multi-source data. It is necessary to summarise the influential relationship and basic laws between rail transit networks and spatial development, proposing reasonable solutions as well.

The subsequent analysis presents the current development status of rail transit in Shanghai, focusing on the contextual differences between international and local conditions. This analysis also proposes a strategy for optimising a multi-level rail transit line network within the context of the Shanghai metropolitan area. The initial section of the study examines the international contextual differences of rail transit systems, considering similarities and differences in spatial scales, development history, and the relationship between rail transit networks and urban development. Additionally, case comparisons are made. In the second part, an assessment is made of the service capacity of Shanghai's rail transit system, the current problems of the rail transit system are analysed, and the focus of future optimisation is deduced, all based on multi-source data. In the third part, a problem-oriented approach is taken, and an attempt is made to propose a solution consisting of goals and layout strategies for rail transit at different spatial levels.

2. International Contextual Differences and Case Comparison of Rail Transit Systems

The modern metropolitan area represents a novel interpretation of the 'city region' concept in the context of globalisation and information technology. The concept of the metropolitan area or metropolitan region is multifaceted and ambiguous, encompassing a variety of administrative, functional and spatial entities, as well as other connotations (Zhang Wang and Hu, 2022). China's rail transport planning and construction are similarly closely related to administration, function, and space. Therefore, the scope of the study was determined based on official information, including the extent of the Shanghai metropolitan area as defined in the Spatial Cooperation Plan of Greater Shanghai Metropolitan Area (Shanghai Municipality People's Government, Jiangsu Province People's Government, Zhejiang Province People's Government, 2022), as well as the extent of Shanghai city and central Shanghai area as defined in Shanghai 2035 (Shanghai Master Plan 2017-2035)(Shanghai Municipality People's Government, 2018) (Figure 1). High-speed railways and inter-city railways primarily serve the Shanghai metropolitan area and beyond. Suburban railways primarily serve the Shanghai city area, while the metro primarily serves the central Shanghai city.

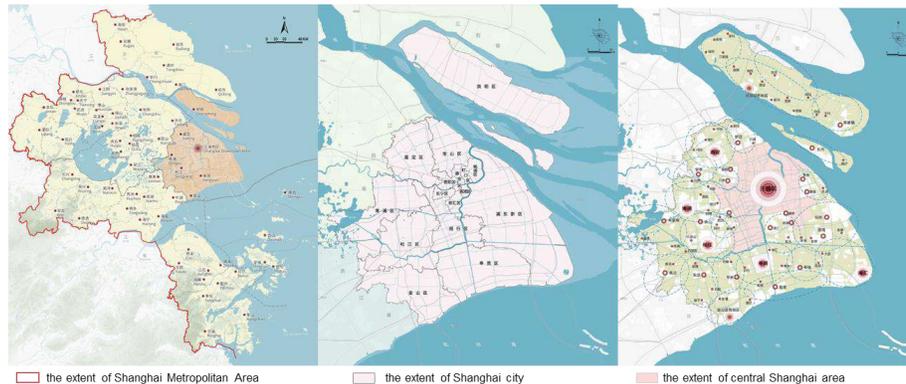


Figure 1. Scope of the study.

Tokyo (Cao,2023) , Paris (Sun, 2024), and London (Chen, Shi and Liu, 2010) have constructed multi-level rail network systems across various rail transport levels within the scope of integrated regional development. These systems serve different travelling scopes with clear functional planning and achieve regional connectivity through line layouts and hub construction. They serve as appropriate reference cases. The selection and construction of the Shanghai Metro at the early stage involved the participation of departments or companies from Japan, France, Germany, and other countries (Yu, 2023). A comparison of the differences between Shanghai and other developed cities in terms of spatial scale, development history, rail transit network structure and suburban railway construction will assist in understanding the development of Shanghai's rail transit. It will serve as the basis for subsequent research.

2.1 Spatial Scale

The discussion of the spatial scale constitutes the foundation of the case study. Analysing administrative units and populations covered by similar spatial layers through analogies helps eliminate comprehension biases arising from international contextual differences, aiding in

scientifically determining the scope of comparison and reference

Using a radius of 30 km for comparison, this circle can cover the main urban area of Shanghai, the Tokyo metropolitan area and surrounding areas, the Greater Paris area (The Metropolis of Greater Paris) and surrounding regions, as well as the Greater London area (The Metropolis of Greater London) and surrounding regions, covering approximately 14.47 million people, 20 million people, 8 million people, and 10 million people, respectively. Using a radius of 50 km for comparison, this circle can cover most of the Shanghai metropolitan area, most of the Tokyo metropolitan area, most of the Île-de-France region, and most of the London metropolitan area covering approximately 25 million people, 30 million people, 12 million people, and 14 million people, respectively. Regarding spatial scale and population coverage, the central Shanghai area is comparable to the metropolitan areas of the other case cities. Similarly, the Shanghai city area is analogous to the metropolitan area boundaries of the other case cities. In China, rail transport is typically approved and projected by the central government and constructed and operated by state-owned enterprises. The national railway system, which includes high-speed railways, general-purpose railways and comprehensive transport hubs, is planned in the Medium- and Long-Term Railway Network Planning. The urban rail transit system in various population densities reflects the overall distribution of the urban population, which is related to the demand for rail transit service capacity.

The overall population density within different spatial circles in Shanghai is higher than that of Tokyo, Paris and London, particularly in the core and central urban areas. Job density indicates the segregation of employment opportunities within a city, which may result in a greater distance between workplaces and residential areas, placing additional pressure on the rail system during peak commuting hours. From the perspective of job density, Shanghai has an overall job density lower than Tokyo but higher than Paris and London, with the difference in job density particularly pronounced in the core urban areas compared to Tokyo. This reflects a more significant polarisation in the population distribution centre in Shanghai (Figure 2), while the job distribution centre in Tokyo is even more pronounced (Figure 3).

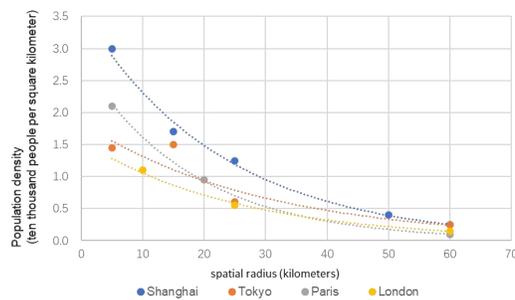


Figure 2. The spatial distribution of population density.

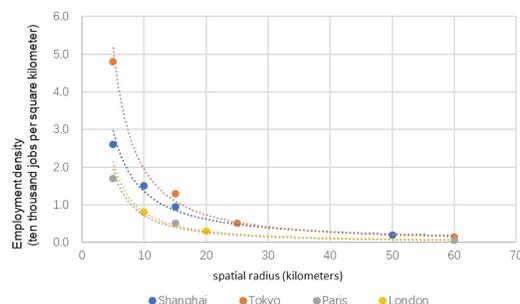


Figure 3. The spatial distribution of job density

The study concludes that the scope of the Shanghai city is comparable to that of other metropolitan areas, based on an analogy between spatial scales. Consequently, the efficiency of the rail system in Shanghai should be at least as high as that of other global metropolitan areas in the future. Additionally, the rail transit system should have a competitive advantage over car trips. It must be mindful of the potential increase in post densities and commuter trips, which could lead to pressure.

2.2 Development History

A review of the development history of rail transport systems can assist in understanding the process of planning and construction of existing rail transport systems, as well as in evaluating the priorities for future rail transport in the context of the city's development stage.

In China, the government is typically responsible for approving and projecting rail transport projects, with state-owned enterprises assuming the role of construction and operational responsibility. China's national railway, which is comprised of a comprehensive national network deployed in a unified manner, with resource property rights belonging to the state and the objective of connecting China's major cities through extensive new infrastructure development, represents a significant national strategy for China. It is now at a first-class level in terms of scale and service capacity (Perl and Geotz, 2015). The metro network of each city is a public service, and the responsibility for this lies with the local government. The city's level of development and the locality's financial capacity are, therefore, critical factors in determining the extent of the metro network. Over the past two decades, the metro service capacity of major Chinese cities, including Shanghai, Beijing, Guangzhou, and others, has undergone a significant expansion, reaching a high level of development. However, the scale of suburban railways built and operated in China is tiny, influenced by factors such as urbanisation, government priorities, and the difficulty of cross-regional intergovernmental collaboration.

To illustrate, the city of Shanghai initiated the preliminary programme of metro planning in 1956, established the Shanghai Metro Company in 1985, and commenced trial operations for the inaugural metro line in 1993. Since then, the construction and operational mileage of the Shanghai metro has increased rapidly, especially with the opportunity presented by the 2010 Shanghai World Expo. The Shanghai government identified rail transit development as a critical strategy to address urban transportation issues. Plans were made to complete more than 400 kilometres of metro lines before the Shanghai World Expo, marking the beginning of Shanghai Metro's transition from a single line to the formation of a network. By 2022, the total length of

the Shanghai metro network will have reached 831 kilometres (Yu, 2023) (Figure 4). Similarly, the construction of high-speed railways related to Shanghai is of a considerable scale and has a robust service capacity. In contrast, the construction of the suburban railway in Shanghai commenced relatively late, and its long-term sustainability has been questioned due to concerns about the potential for development uncertainty. This is attributed to the separation of power and responsibility, the mismatch between the time distribution of the remaining capacity and the demand, the financial risk associated with the general efficiency of the passenger flow, and the poor integration of the track with the city's spatial layout (Li, 2022).



Figure 4. Statistics on operating mileage and passenger volume of Shanghai rail transit lines

A comparison of the population and rail transport development of the Shanghai suburban railway, the Tokyo metropolitan area and the Île-de-France region reveals that the urbanisation process in Tokyo and Paris has seen the construction of railways at an earlier stage and the formation of a larger scale of municipal rail systems. It can be assumed that suburban railways have supported the development of the metropolitan area to a certain extent. In contrast, Shanghai initiated the construction of its rail transit system only after its population reached 10 million on a smaller scale. This requires that the operational service of the Shanghai suburban railway, compared to private cars, should have a particular competitive advantage in terms of convenience and timeliness (Figure 5).

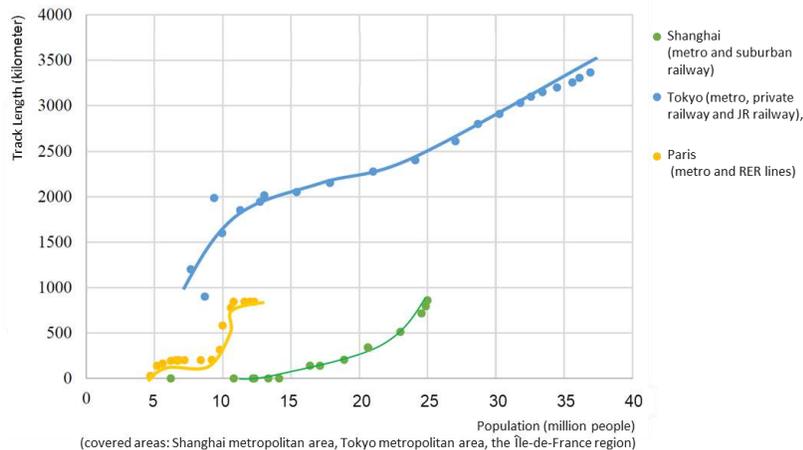


Figure 5. Relationship between track length of rail transit construction and population growth

2.3 Relationship between Rail Transport Network and Urban Development

There is a close relationship between urbanisation and the development of the rail transit system, which is reflected in the discussion on the development history and generally recognised by the existing research (Gu and Kou, 2017; Hu et al., 2023). Understanding the role of the rail transit network in the spatial structure of the city will assist in clarifying the functional positioning and mode of Shanghai's regional rail, thereby further enhancing the scientific nature of Shanghai's rail transit planning and construction programme.

In terms of rail transit types, subways typically provide high-density homogeneous services to the core areas within a 5km radius, radiating to the central city within a 15km radius. Shanghai's subway construction has reached this level. Suburban railways usually radiate outward, connecting suburban centres and new urban nodes along different development corridors. This requirement aligns with Shanghai's goal of elevating the development level of new cities. This section analyses and refers to the multi-level rail transit networks in Tokyo and Paris as case studies. This is in line with the goal of the Shanghai Municipality of simultaneously upgrading the development level of the new towns. Consequently, this section employs Japan and Paris case studies as a point of reference for analysing their multi-layered rail networks. At this spatial level, the rail transit in Paris consists of the RER (Réseau Express Régional) line and the Transilien line. The RER, as a regional rapid railway, is a hybrid commuter rail and rapid transit system serving Paris and its suburbs. Its purpose is to alleviate the city's population concentration and achieve urbanisation of its suburbs. It is planned to serve Paris and its suburbs at the same time as the RER line. In terms of online network structure, the RER line penetrates deep into and through the centre of Paris, connecting with the metro network through the core hubs. This is due to the better engineering conditions in Paris, which allowed the RER line to be built under the metro in the centre of the city, forming a two-tiered network of municipal rail and metro. At first, rail transport serving the Tokyo metropolitan area comprised national railway lines, private railway (私鉄 *Shitetsu*) lines, and underground lines. However, the National Railway was split and privatised due to poor management, resulting in the formation of the Japan Railway Group, from which the JR lines were derived. Initially, the private railway lines had no access to the city centre. They could only connect to central Tokyo via the National Railway Yamanote Line (now JR Yamanote Line), which led to a sharp rise in passenger pressure on the private railway and Yamanote Loop. This was later attempted to be resolved through the operation of a suburban private railway and a city underground running directly through the city (Cao, 2023). Nevertheless, the Yamanote Line continues to experience significant passenger pressure in terms of city rail service. The Yamanote Line is connected to 15 radial lines of JR railways and private railways, which are situated within 30-50 km and 50-80 km circles around the periphery of the Tokyo metropolitan area. These radial lines connect the system of centres in the Tokyo metropolitan area to form a de facto ring-shaped central belt. The periphery of the Tokyo metropolitan area generates a significant centripetal commuter flow within the Tokyo metropolitan area. The cross-section of the city line into the centre of the metropolis reaches its maximum in the vicinity of the Yamanote Loop (5 km radius circle) (Zhang et al., 2023),

Analogous to the rail transit networks of Shanghai, Paris, and Tokyo, the study concludes that there are significant differences between the rail transit systems constructed in Shanghai and those in cities such as Paris and Japan. These differences are primarily related to the construction of municipal railways. Consequently, it is imperative to exercise greater caution when considering the construction of municipal railways and their relationship with other

railways. At the same time, the construction of railways must be viewed as a policy tool for urban resource allocation, particularly in the context of the urbanisation rate of Shanghai. Given that the city's urbanisation rate has already exceeded 89%, the construction of municipal railways in the city can be considered to have the potential to influence the spatial resources of the city and demographic changes to a greater extent. In light of this, it is crucial that the municipal railways effectively connect the city centre, suburban centres and new town areas.

2.4 Construction and Operation of Suburban Railway

Based on the preceding analysis, it can be concluded that the construction focus of Shanghai's future rail transport will be the city-area rail. Consequently, the discussion will be specifically centred on the city-area transport. Firstly, to facilitate comparison, the Tokyo metropolitan area, which has a larger total population and a more developed rail transit system at the same level, is chosen as a case for comparison. This enables the analysis and discussion of possible situations that may arise in the future development of Shanghai's municipal rail transit. Secondly, to provide a reference for the construction and operation of Shanghai's municipal rail transit, the rail transit service capacity and management and operation mode of Tokyo, Paris and other cities are compared.

With regard to the spatial structure reflected by the travel flow, it can be observed that both the central city of Shanghai and the periphery of the Tokyo Metropolitan Area Department are distributed with more central nodes. However, the nodes in the periphery of Shanghai have a lower energy level, and the number of trips flowing into the central city is also smaller. Compared to the million-strong populations of Yokohama, Saitama, and Chiba on the periphery of the Tokyo Metropolitan Area Department, the new towns around the Shanghai central city are all less than 500,000 people, representing a smaller scale. Furthermore, the daily trips from the new towns into the central city of Shanghai are approximately 100,000-300,000, considerably smaller than those into the Tokyo Metropolitan Area Department. The reasons for this phenomenon are numerous, and the related factors interact in complex ways. On the one hand, the failure of Shanghai's new towns to reach their expected scale is related to poor transport timeliness. On the other hand, Shanghai hopes that the new towns will become independent and integrated node cities directly connecting to other cities in the region rather than relying on the nodes in the central city of Shanghai. This necessitates the enhancement of rail transport efficiency and the implementation of effective support mechanisms for Shanghai's new towns while concurrently avoiding the creation of high-intensity commuter traffic. The imbalance in the job-to-population ratio has resulted in large-scale long-distance commuting and high-intensity rail traffic in Tokyo. Shanghai has a more balanced job-to-life ratio than Tokyo, with smaller differences in job-to-life ratios across the city. Therefore, the impact of rail on the job-to-life balance should be carefully considered in the process of developing the city region.

Using Tokyo, Paris, London, and New York as examples, discuss the service capacity of suburban railways, emphasizing the need for timeliness and sustainability in the construction of Shanghai's suburban railway system (Table 1). Therefore, the construction of a city-region railway in Shanghai should also be undertaken with the aim of ensuring timeliness and sustainability. In order to ensure timeliness, the travelling speed of the city-region railway should be significantly increased compared to the metro (30km/h), up to about 50km/h. This will alleviate the connectivity obstacles caused by spatial distance and ensure a high frequency of train departures. From the perspective of the stage of development and the interval between train departures, it is necessary to avoid opening too many urban lines when the new city's level

of competence is insufficient to ensure the sustainability of the urban railway setup. There is a certain contradiction between the insufficient capacity of the new city and the sustainability of the urban railway setup. On the one hand, the construction of a large number of new lines may result in the inefficient utilisation of resources in the context of a limited volume of the new city. Conversely, if the number of urban railway trips is insufficient, it will be unable to support the development of the new city. This contradiction should be considered from the perspective of the more significant regional level, i.e., through the inter-city railway connecting the new city and other cities, to support the development of the new city in line with the development of the new city into a new city. This is also consistent with the objective of developing the new city into an individual and integrated node city.

Table 1. Comparison of suburban railway service capacity

City	Paris	Tokyo	London	New York
travel speed	40—50 km/h	45—60 km/h	—	45—70 km/h
peak hour departure frequency	3—5 min	2—5 min	4—8min	8—20min
off-peak departure frequency	—	—	20—30min	30—60min

In terms of management and operation, two points require clarification: the sustainability of construction and operation and the manner in which management and operation are coordinated. With regard to the construction and operation of rail transit networks in metropolitan areas, there is considerable variation between different cases in terms of the public and private sectors involved. However, there is a consistent reliance on financial support and development along passenger routes in order to ensure the sustainability of rail transit development. In China, rail transport is typically approved and projected by the central government, with state-owned enterprises assuming responsibility for construction and operation. The national railway system, comprising high-speed railways, ordinary-speed railways and comprehensive transport hubs, is planned in the Medium- and Long-Term Railway Network Plan. The urban rail transit system is organised and formulated based on urban master plans and urban transport development plans. Consequently, there are specific challenges in the cross-area and cross-line operation of rail transport between the national railway system and the urban rail transport system, which serves the metropolitan area and the metropolitan region.

3. Current Situation of Megacities in China: A Case Study of Shanghai

Shanghai is the largest economic centre in China and an emerging global city. It is also the core city of the Yangtze River Delta city cluster. In the Shanghai Urban Master Plan, also known as 'SHANGHAI 2035,' formulated by the Shanghai government, the goal vision of 'Striving for the Excellent Global City' is proposed. As a significant component of the public transport system, the rail transport plan must consider Shanghai's development strategy and address the challenges in the planning and construction of the existing rail network. Furthermore, it also helps to summarise a model suitable for Chinese cities.

A review of the historical development of Shanghai's rail transport reveals that it can be divided into three periods, each characterised by a distinct relationship between the rail system and the spatial development of the city. The period between 1993 and 2010 represents the initial integration phase between Shanghai's rail network and urban space. This involved the

construction of comprehensive metro corridors with the objective of enhancing connectivity in critical areas of the central city. Additionally, the metro was designed to address deficiencies in public transport services in these areas. From 2011 to 2020 is the second stage, which is characterised by the enhancement of the metro network. During this period, the metro network underwent continuous encryption in order to accommodate the rising demand for rail travel in central Shanghai. This resulted in a gradual shift in the proportion of rail travel compared to ground bus travel. Shanghai is in the third stage of rail transit and urban spatial development. This stage is characterised by a shift in the rail transit system from lagging behind spatial development to optimising and guiding spatial development. It can be observed that the Shanghai government has identified the optimisation of the rail transit network as a significant undertaking. This period presents an opportune moment for adjusting the rail transit network in Shanghai. During this period, it is crucial to analyse the current situation in accordance with the development goals and to consider the synergistic relationship between rail transit and space.

3.1 International Perspective: China's Interface with International Markets

'Dual circulation' is a national economic strategy proposed by the Chinese government. The Economist summarised the strategy as 'keeping China open to the world (the "great international circulation") while reinforcing its own market (the "great domestic circulation")'. As China's largest economic centre and an important node supporting the 'dual circulation' policy, Shanghai should efficiently connect domestic and foreign markets.

From the perspective of hubs, the analysis of the connection between Shanghai's main hubs and regions suggests that Shanghai's major external hubs face significant pressure and exhibit low passenger flow decomposition efficiency. The external hubs analysed here include Shanghai Pudong International Airport and Shanghai Hongqiao Integrated Transportation Hub. Nevertheless, the introduction of rail transit lines still requires discussion, and the main corridors are predominantly westward, with inadequate connections to the north and south.

Shanghai Pudong International Airport, the largest international airport in the Yangtze River Delta region, serves as one of the most critical international gateways in the area. Situated in the eastern coastal area of Shanghai, it is yet to be linked by high-speed rail. Connecting to other cities in the Yangtze River Delta and Hongqiao Station requires traversing through the main urban area of Shanghai, resulting in inefficiency and adding to the city's traffic burden. Currently, Shanghai is constructing the Dongfang Transportation Hub, aiming to effectively alleviate passenger flow by introducing high-speed rail and urban rail transit.

The Shanghai Hongqiao Integrated Transport Hub encompasses the airport, railway station (Hongqiao Station), metro stations, and long-distance bus stations. It serves as the primary transport hub connecting domestic destinations in Shanghai. Currently, it is facing challenges due to the presence of multiple overlapping passenger flows and difficulty in expanding capacity. All high-speed rail lines operating in Shanghai, including the Beijing-Shanghai High-Speed Railway and the Shanghai-Hangzhou-Ningbo High-Speed Railway, terminate at Hongqiao Station. In terms of passenger flow, Hongqiao Station handles nearly 60% of Shanghai's railway passenger transportation demand, with daily passenger throughput approaching 90% of its design capacity (430,000 passengers per day). The annual passenger throughput at Hongqiao Station is two to five times that of Shanghai's other two railway stations, with passenger flows exceeding ten million, namely Shanghai Station and Shanghai South Station (Figure 6). The passage resources at Hongqiao Hub are extremely limited, making it challenging to meet the increasing connectivity demands. This also reflects the inability of

Shanghai's other railway hubs to fulfil a synergistic role.

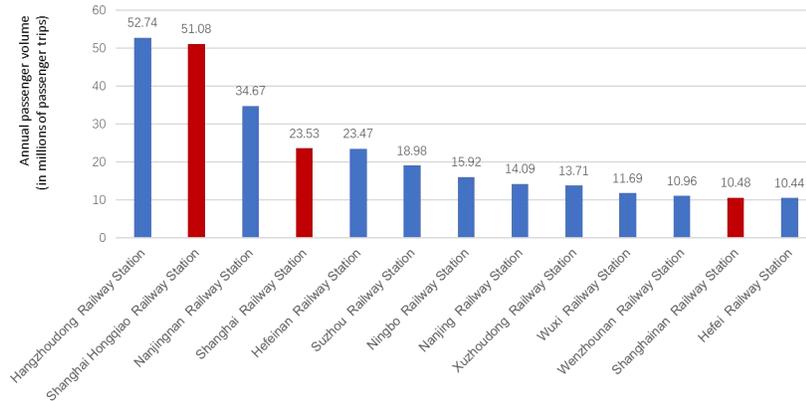


Figure 6. Annual passenger flow statistics of major railway stations in the Yangtze River Delta Urban Agglomeration (2021)

3.2 Regional Perspectives: Capacity to Lead Regional Development

As the core city of the Yangtze River Delta urban agglomeration, Shanghai should effectively lead regional development. Therefore, from a regional perspective, an evaluation is made of the connectivity of rail transit with major cities in the region and its impact on the urban spatial system.

Firstly, there are few intercity and suburban railways, making it difficult to meet the demand for direct connections between major cities in the Yangtze River Delta urban agglomeration. At the metropolitan level, the construction of major national high-speed railways has basically met the connectivity demand of core cities. The proportion of rail transit trips between Shanghai and cities such as Suzhou, Wuxi, and Changzhou in the Yangtze River Delta urban agglomeration has reached 20.7%, 29%, and 41.1%, respectively. However, it is currently unable to effectively connect various levels of nodes through rail transit. The proportion of current rail transit hubs entering node centres is only one-third. Studies suggest that travel efficiency should correspondingly increase with the development of urban agglomerations and the increase in urbanisation rates. The single high-speed rail model of metropolitan areas should evolve towards a multi-network direct connection approach, i.e., transitioning from interconnection between high-level cities and connecting high-level cities to the next-level nodes through various types of rail transit. This poses requirements for intercity and suburban railways in metropolitan areas (Chen Zhou and Qiao, 2017). There is still a significant gap between the Shanghai metropolitan area and the Tokyo metropolitan area (Figure 7).

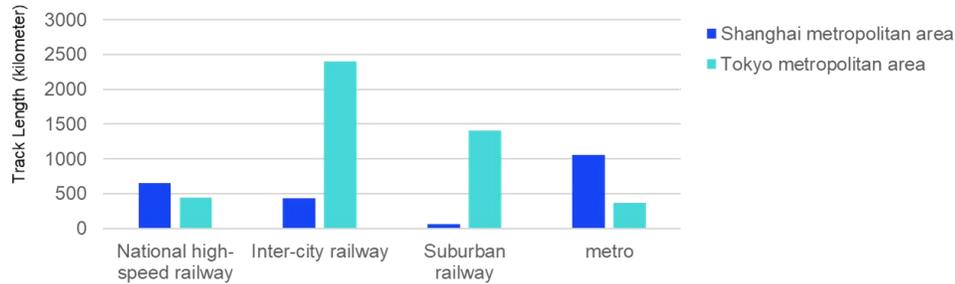


Figure 7. A comparison of the operational development of rail transit in the Shanghai metropolitan area and Tokyo metropolitan area

Secondly, under the background of regional integration, rail transit still cannot support the construction of new cities to become independent nodal cities, and there is a risk of marginalisation for new cities in Shanghai. As mentioned earlier, Shanghai hopes that new cities can become independent, comprehensive nodal cities, which requires good internal and external connectivity to enhance the radiation capacity of new cities. On one hand, the timeliness of the connection between new cities and the central area of Shanghai is poor. Compared with other cities near Shanghai, new cities lack competitiveness, and the travel time from each new city to the main railway stations of Shanghai exceeds several times that of cities near Shanghai. Rail transit travel is less competitive than car travel in new cities. The rail transit connecting new cities is all subways. For example, in the central, vibrant area of Shanghai, People's Square, driving or taking rail transit from new cities to strategic nodes of the city takes nearly an hour, exceeding the time taken by driving from new cities (Figure 8). On the other hand, new cities lack high-level hubs and have insufficient external radiation capacity. External transportation in new cities mainly relies on expressway networks and lacks high-level railways to meet multifunctional demands. Compared with cities of similar population size, new cities lack transportation hubs that match the city's scale and level to support external connections.

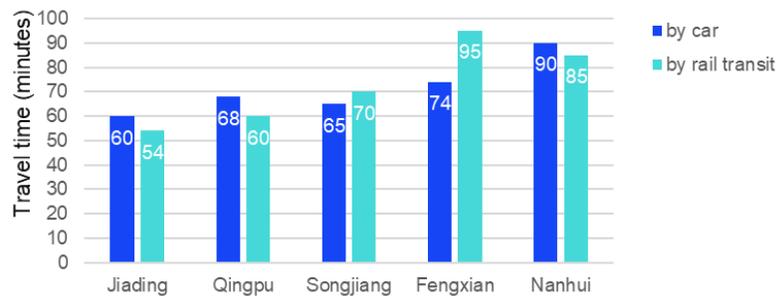


Figure 8. Comparison of travel time from the new city to the central urban area of Shanghai using different modes of transportation

3.3 Urban Perspective: Railway Network Efficiency

As a megacity, Shanghai is subject to considerable pressure in terms of transportation. The capacity of public transportation, particularly high-capacity rail transit services, is crucial. This is closely related to the city's operational efficiency, livability, and sustainability. Consequently, it is of paramount importance to evaluate the efficiency of the rail transit network and to analyse its service capacity.

As a megacity, Shanghai is subject to considerable pressure in terms of transportation. The capacity of public transportation, particularly high-capacity rail transit services, is of crucial importance. This is closely related to the city's operational efficiency, livability, and sustainability. Consequently, it is of paramount importance to evaluate the efficiency of the rail transit network and to analyse its service capacity.

On the one hand, there is a considerable demand for long-distance commuting within the central city of Shanghai. The existing metro network is unable to adequately support the development of new urban strategic spaces. Due to operational speed and station stops, the metro network's efficient service range to urban agglomeration spaces is limited to a radius of less than 20km. As a consequence of the expansion of Shanghai's strategic space in the suburban areas, there has been a notable increase in long-distance commuting, resulting in a situation where a considerable number of long-distance commuters occupy the capacity of stations along the lines. By calculating the cumulative congestion contribution of each sub-district, it was found that the density of the metro network in the central ring area of Shanghai had significantly decreased, which was closely related to road congestion. Conversely, there is a considerable volume of travel between Shanghai and its surrounding areas, yet there is a dearth of rapid rail transit modes for rapid connections. Currently, the fastest mode of travel between Shanghai's sub-centres and new cities and areas near Shanghai, as well as between new cities and areas near Shanghai, is by road, which is a lengthy process.

4. A Viable Approach: Multi-level Rail Transit Network and Spatial Co-optimisation Strategies

4.1 Relationship Discussion

Complex mutual influences exist between rail transit networks and urban spaces, influenced by node levels and functions, reflecting requirements on time elements. When urban and regional development needs are reflected in rail transit networks, these demands are manifested not only in spatial connections but also in requirements for connection time and intensity. From a practical perspective, reflecting this relationship can be achieved by discussing the composition of multi-level rail transit networks from a spatiotemporal perspective.

Research suggests that the rail transit system of a megacity should consist of at least three levels corresponding to three spatiotemporal scales, each level containing different types of rail transit and serving different functions. These levels should contain various rail transit types and serve different functions, with the levels interconnected through hubs. Firstly, the central level consists of dense rail transit networks formed by metro and suburban lines. These lines are primarily used for daily life and commuting trips, with service capacity reaching specific locations within an hour. Secondly, the metropolitan level, which should not be divided by administrative boundaries and also includes adjacent metropolitan areas, consists of a well-structured rail transit network composed of suburban and intercity lines, supplemented by metro lines. This network mainly serves longer-distance daily life and commuting trips, connecting

central cities, new cities, and peripheral cities. It also connects urban nodes within 1 hour. Thirdly, the regional level, which encompasses metropolitan areas and beyond, is characterised by the linking of major city nodes through intercity or high-speed rail lines, the construction of transportation corridors, and the provision of services primarily for business travel, with service capacity reaching urban transportation hubs within one hour.

4.2 Possible Key Points and Methods for Synergistic Optimisation

Based on the analysis of case studies and the discussion on the relationship between rail transit networks and urban spaces, a multi-level rail transit network and spatial synergistic optimisation strategy for megacities is proposed, including five possible critical areas of focus.

Before detailing the specific areas of focus, it is essential to emphasise that while the mutual influence between rail transit networks and urban spaces is established, the construction of rail transit should be based on the development goals and layout strategies of cities and regions, taking into account the specific development situation, financial resources, and construction capabilities of the city. A study on Spain suggests that Spain's ambitious layout and construction of high-speed rail systems have led to inefficient route construction and high costs (Perl and Goetz, 2014). Conversely, Shanghai and its surrounding area have a well-developed infrastructure, extensive transportation networks, a stable economic environment, and an appropriate institutional framework, which provides an ideal context for a comprehensive discussion on rail transit systems.

(1) Regional Corridors and Urban Strategies

The construction and optimisation of regional corridors are inextricably linked to urban vision and development goals. As a case in point, the city of Shanghai has set forth objectives about regional leadership, economic development, ecology, and culture. Consequently, it is essential to consider the provision of adequate and rational support for external gateways, the establishment of corridors of an appropriate type that align with the pattern of regional industries, ecology, and culture elements, and the prioritisation of corridor development based on urban functions and travel demands.

(2) Multi-level Networks and Urban-Town Systems

Based on spatial circle layers, it is necessary to consider urban-town systems, propose requirements for connection time and intensity for rail transit networks, and reflect these in rail transit types and operating modes in order to ensure efficient connections between different nodes. It is recommended that rail transit channels be constructed according to the varying connectivity characteristics of metropolitan areas, with a particular focus on strengthening channel connections for key development areas.

(3) Hub Systems and Element Allocation

Rail transit is connected to urban spaces through stations, and hub systems of rail transit with different functions and levels are more efficient compared to single large hubs and can more effectively influence urban resource allocation. Possible hub types include regional comprehensive hubs, linking international, national, and regional travel; regional essential hubs, linking major cities in the region; regional new city hubs, serving as essential nodes for new cities to integrate into the region; urban multifunctional hubs, linking suburban railways and

subways; urban subway hubs, connecting multiple subway lines.

(4) Improvement of Rail Network Efficiency in Central Areas

With urban development, the construction of metro networks often becomes an essential means to alleviate urban transportation pressure in central areas. Therefore, most megacities have well-developed metro networks in central areas, with limited space underground. Analysing urban travel demands, coordinating with urban central systems, and focusing on improving travel efficiency in strategic functional areas of cities are important directions for rail transit optimisation. In addition, the construction of suburban railways is also an effective way to improve the efficiency of rail networks in central areas.

(5) Development, Construction and Operation Mode

The delineation of clear development, construction, and operation methods is crucial for the sustainability of rail transit construction. In the context of China, the delineation of administrative powers is of particular importance, requiring clarity on the responsibilities between central and local governments, as well as among local governments. Furthermore, the establishment of coordinated organisations and methods, along with the determination of lead departments to coordinate multiple management and operation entities, are essential. Third, in the coordination process, it is essential to clarify technical solutions, dispatch responsibilities, and service standards in order to guarantee the reliability of coordination. Fourth, in addition to providing essential financial support, it is necessary to implement a reasonable development strategy along the line in order to ensure the sustainability of rail transit development.

5. Conclusion

The comparison reveals differences in the concept of spatial scale, administrative authority and understanding of rail transport types between megacities in China and other countries. With regard to spatial scale, the city limits of Chinese megacities are comparable to the metropolitan area limits of cities such as Tokyo, Paris and London. Furthermore, the population distribution is more concentrated.

The differences in regional administration and development styles are reflected in the development history of rail transport, which in turn affects the different sequences of spatial development and rail transport system construction in different cities. In the case of Shanghai, the critical difference lies in the fact that the high-speed railway and metro are very well-developed in the rail transit network. However, there is a lack of intermediate level, i.e., the urban rail within a service radius of 50 km. This affects the construction of the hub system accordingly, and ultimately, the service efficiency of Shanghai's rail transit system fails to reach the level of other urban metropolitan areas.

The study proposes an optimisation idea, namely a strategy of multi-level rail transit network and spatial co-optimisation. The rationale behind this strategy is that there is a complex interrelationship between the rail transit network and urban space. This is reflected in the impact of the rail transit system on the spatial and temporal characteristics of the region, as well as the requirements of the regional cities and the development needs of the region in terms of the linkage of the rail transit network. The strategy comprises a three-tier rail network construction model corresponding to the three spatial and temporal scales. It also includes specific synergistic optimisation points and methods. Specific optimisation points relate to the

construction objectives and layout strategies of cities and regions. For example, in Shanghai, these include (1) regional corridors related to urban development strategies, (2) multi-layer rail transit networks related to the urban system, (3) rail transit hub systems related to urban resource allocation, (4) rail transit network efficiency, and (5) development, construction and operation modes.

The study highlights that Chinese megacities such as Shanghai have a favourable foundation for development, a dense transport network, a relatively stable economic climate and an appropriate institutional framework. Consequently, it is possible to discuss a strategy for optimising the rail transport system in an idealistic manner that is as comprehensive as possible. The logic of multi-level rail transit networks with spatial co-optimisation is appropriate for other regions. However, caution is needed in terms of the way it is achieved and the specific strategy.

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