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Assessing urban vitality and its determinants in high-speed rail station areas in the Yangtze River Delta, China

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Abstract: Unlike most city centers in countries that pioneer European high-speed rail (HSR) lines, HSR stations in China have mainly been developed in suburban areas. The rationale for peripherally located HSR stations is due to development costs and intentions to speed up urbanization and develop new suburbs. However, it remains unknown whether the HSR-led urban development policy is effective as intended, despite the rise of HSR area suburbs. Taking the Yangtze River Delta (YRD) as an example, this study assesses HSR station area urban vitality (SAUV). It constructs an indicator system comprised of concentration, accessibility, liveability, and diversity of physical facilities and socioeconomic activities. It compares the rank-size distribution of urban vitality in different station types: conventional rail (CR), upgraded-HSR, and newly built HSR stations. The spatial differentiation and influence factors of SAUV in the YRD are further examined among cities and provinces of different station types and HSR lines. The results show that station areas with high urban vitality are mainly distributed along major economic corridors. Only a few newly built HSR stations could attract vibrant urban activities. More vibrant economic activities could be clustered in HSR station areas in provincial-level cities and along the Shanghai-Nanjing HSR line. Although the SAUV value is strongly associated with local socioeconomic contexts, it is significantly influenced by the administrative rank of cities, station-city transit connectivity, and frequency of train services. This study suggests that integrating multilevel spatial planning with vitality-led urban development is necessary for the sustainability of the HSR economy.

Keywords: High-speed rail station, station area, station types, urban vitality, HSR new town

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1 Introduction

In 2020, China developed 35,000 km of high-speed rail (HSR) lines, and most of these lines were developed in the past decade. This accounts for over two-thirds of the total length of the world's HSR (UIC, 2018). HSR development in China is an integrated state project within the country's urbanization and regional economic development strategies (Li et al., 2014). Governments at various levels have embraced HSR-led urban development, coupled with China's transformation toward a more consumer-based economy (Zheng & Kahn, 2013). Consequently, many new towns and commercial centers with shopping malls have been planned and developed in HSR station areas. From a global perspective, the objective of HSR development in many countries is to support broader economic projects (Vickerman, 2015). For example, the European Commission regards the development of the HSR network as an important project that promotes regional integration (Mohíno et al., 2018). HSR development in France, for example, has been embedded in its regional economic coordination strategy (Ryder, 2012). Elsewhere, the proposal to develop HSR in the UK was justified by the need to reduce the long-standing north-south economic disparity in England (Chen & Hall, 2013). Although the wide economic return is difficult to prove, the potential economic benefits have been widely used to justify HSR plans worldwide (Garmendia et al., 2012; Givoni & Dobruszkes, 2013).

According to Banister and Givoni (2013), the quantity, locations, and the connection of HSR stations with other transport networks are critical issues for it to exert its role in improving regional access and for wide economic impacts. Indeed, the two HSR station types, i.e., HSR stations upgraded from conventional rail (CR) stations and newly built HSR stations, have different patterns of spatial impact. Upgraded HSR stations, located in city centers, provide better access to markets and can reinforce economic development in the areas contiguous to the stations. In the UK, France, and the Netherlands, this development model is part of the city center's urban regeneration strategy (Hall, 2009; Harman, 2006; Trip, 2007). However, newly built HSR stations are usually located far from the city center (e.g., in Spain and China) and start from a blank slate station area. Apart from technical issues, this development model also considers the construction costs. Given its unequal political-economic context, China's approach to HSR station development is very different from that of the Western European countries that pioneered HSR (Chen & Wei, 2013; Wang et al., 2013). Most Chinese HSR stations are newly built in suburban areas with an airport-like waiting hall inside the station and a large square outside. Given that China is still in the rapid urbanization process, this type of over-demand station design and selecting suburban areas for newly built stations is expected to spur new town development and guide urban expansion (Wang & Duan, 2018).

Various studies have explored the impact of HSR development on regional economic development and changes in land use, housing prices, and employment structures (Geng et al., 2015; Wang, Wang, et al. 2019; Zheng & Kahn, 2013; Zhu et al., 2019). A few other studies have examined how urban development has been formed in HSR station areas, where the opening of HSR services has directly impacted local development from the perspective of megaregions (Ribalaygua & Perez-Del-Caño, 2019). Banister and Thurstain-Goodwin (2011) opined that wide economic impacts of HSR development should be examined under different spatial scales that focus on various dimensions of economic development. The study of station areas' economic development and restructuring is not new. However, due to the constrained availability of valid data at such a fine scale, most studies have been qualitative case analyses (Chen & Wei, 2013; Wang et al., 2017). Thanks to the progress of big data technologies, such as location-based social media datasets, mobile phone recording datasets, and online maps' points of interest (POI) datasets, the limitation on small-scale research is easing, and studies are increasingly focusing on these emerging big data solutions (Xia et al., 2020; Ye et al., 2018).

Among the various methods employed to examine urban development around HSR stations, urban vitality is a practical approach that captures physical and socioeconomic features. Despite many studies on the HSR influence on accessibility and urban development, little research has been conducted on the influence of HSR on urban vitality in station areas across different cities in megaregions. Some studies have made vitally relevant discussions on increased trips and improved economic activities around HSR stations (Kim et al., 2018; Mohíno et al., 2018). However, most arguments are qualitative and lack spatial perspectives on the regional scale.

Due to these reasons, this paper takes a big data analytical approach to examine urban vitality of HSR station areas in one of China's most developed megaregions—the Yangtze River Delta (YRD), and to provide a spatial analysis on variations of urban vitality surrounding different HSR station types. A systematic understanding of the association between HSR stations and urban vitality would provide important insights for policy-making. Furthermore, previous studies have mainly examined newly built HSR stations while ignoring the impact of the upgrading CR stations to HSR stations on urban development and what other opportunities, if any, this has provided. Considering the relatively short period (about ten years) of HSR development in China, the examination of upgraded HSR stations can also reference the station area development of newly built HSR stations.

Following this introduction, this paper reviews relevant literature on HSR station development and its impacts in China and elsewhere. It then provides research methodology and data sources, followed by the spatial variation of station area urban vitality (SAUV) in the YRD and its underlying factors. The final section comprises discussions on policy implications and conclusions.

2 Literature review

There is a plethora of evidence that rail investment can powerfully reshape cities and regions (Cervero, 2009). The HSR system, which lies at the forefront of advanced transportation systems, is considered the engine for improving accessibility and regional development (Kim et al., 2018). To appreciate the effects of HSR stations on urban vitality, this section provides a brief review of previous research on the impact of HSR on urban development.

From a regional perspective, rail transit investment can enhance accessibility, energise regional economic development, and reshape city-region relationships and intercity relationships (Hall, 2009). Reduced travel time between HSR-served cities directly influences HSR development (Yin et al., 2015). When Spiekermann and Wegener (1994) demonstrated the effects of the evolving European HSR network with time-space maps, they showed the compressed time-space as a "shrinking continent." In some cases, however, the improved inter-city connectivity may not be achieved after accounting for the prolonged intracity travel and interchanges within rail hubs (Diao et al., 2017). For example, the establishment of Hangzhou East Rail Station was found to have had a slight improvement in inter-city accessibility due to the distance between the station and the city center, as well as the increased interchange time in the large HSR station hall (Chen & Wei, 2013).

Furthermore, the improved accessibility is not equally geographically distributed. Many studies have investigated changed accessibility and spatial variations in accessibility (Martínez & Givoni, 2012; Monzón et al., 2013; Wang, Zhang, et al. 2019). In the example of Spain, a rise in the distance can be observed with higher accessibility concentrated in the surroundings of HSR stations such as Madrid, Valencia, and Barcelona (Monzón et al., 2013). This phenomenon is expressed as the "tunnel effect" in which the presence of HSR stations produces "islands" with improved accessibility while isolated places become shadow areas (Monzón et al., 2013; He et al., 2021). Increased accessibility, in turn, influences regional economic development (Banister & Thurstain-Goodwin, 2011). A considerable amount of research has corroborated the positive impact of HSR on regional economic growth (Jia et al., 2017;

Sands, 1993). Again, impacts also vary from one location to the other. Imbalanced regional economic growth has been observed, with various effects on core and periphery areas (Givoni, 2006). The findings correspond to Hall's assumption (2009) that HSR benefits the large central areas they connect while posing threats to peripheral cities.

HSR development provides opportunities for cities connected to the rail line to expand the local economy, transform their structure, and alter their image (Ureña et al., 2009). Regarding economic growth, however, mixed findings have been drawn from different studies. A city with HSR does not necessarily benefit from an HSR station in the area (Ampe, 2003). Transport infrastructure does not automatically exert transformative power on the economy (Vickerman, 2018). Many other factors determine whether the introduction of HSR stations will generate the expected socioeconomic impacts. One crucial factor is the location of the HSR station. In Todorovich et al. (2011) study, three types of HSR station locations were identified: (1) center-of-city stations, (2) edge-of-city stations, and (3) suburban and exurban stations. Center-of-city stations have the potential to strengthen concentrations of development. Edge-of-city stations may change the center of gravity of a city's core and stimulate redevelopment of underutilised areas at the edge of the city. Suburban and exurban stations may help produce new centers around the station area. Generally, stations that are well-connected to the city's center, coupled with other investments, present the highest potential for urban regeneration (Ribalaygua & Garcia, 2010). Ureña et al. (2009) have argued that HSR at the local level acts more like a catalyst for establishing new city images and urban projects. To spur the development of HSR station surroundings and even the whole city, strategies must be developed to maximise the opportunities proffered by the enhanced connectivity and generated trips (Ampe, 2003; Trip, 2007).

Among various studies on the effects of HSR on urban development, very few have examined how it influences urban vitality in station areas across different cities in megaregions. Looking into urban vitality in HSR station areas can, however, provide a novel and effective perspective to unveil the influences of HSR on urban development. The discussion on urban vitality can be traced back to Jacobs (1961), as read by Delclòs-Alió, et al. (2019), emphasised that the vitality of cities is dependent upon their diversity, street life, and human scale. Urban vitality is closely related to diversity, which involves four primary conditions—land use mix, short blocks, the mixture of buildings with different characteristics and ages, and sufficient developmental density. These are then complemented by two secondary conditions, accessibility to public facilities and the reduction of border constrains, as interpreted by Sung et al. (2013). Montgomery (1998) also emphasised that vitality was closely related to pedestrian flows across different periods, the active use of different facilities, cultural events, and celebrations over the year, as well as active street activities. It is argued that urban vitality is a fundamental element for the quality of life in a city (Lopes & Camanho, 2013) and a critical feature that can distinguish prosperous urban areas from debilitated ones (Montgomery, 1998). It is worth mentioning that urban vitality is understood differently and associated with local economic, cultural and social contexts (Pugalis, 2009). In developing countries like China, where urbanization is still undergoing rapid change, urban development and vitality are highly dynamic processes. It subsequently needs to decide a time frame and spatial scale to identify the form of urban vitality.

Many empirical studies have measured urban vitality from different perspectives, despite the ambiguous meaning and similar concepts of vibrancy and liveability (Markusen, 2013). For example, efforts have been made to establish indicators representing built environment variables for urban vitality, such as land use mix, building density, and accessibility (Delclòs-Alió et al., 2019; Sung & Lee, 2015), while some other studies emphasise social and economic vitality. The former usually considers pedestrian flows, walking activities, and human activities as the proxies of urban vitality (Sulis et al.; 2018; Kim, 2018). On the other hand, indicators reflecting economic vitality in the scholarship involve those relating to economic activities and attractiveness, such as property yields (Ribalaygua & Garcia, 2010), housing prices (He et al., 2018), and small business activities (Ye et al., 2018).

With the development of novel technologies and accessibility to "big data," an increasing number of studies use these data to provide insights into micro-level human activities. Various studies have widely applied location trace data, smart card records, social media data, and geo-tagged data for such insights. For example, Jin et al. (2017) used POI and location-based service data to assess the urban vitality of residential development, which further facilitated the identification of ghost cities. Smart card data from public transport and Twitter data were employed to establish the relationship between diversity and vitality in London (Sulis et al., 2018). The association between urban expansion types and urban vitality in China was examined by employing POI and location check-in data (Fang et al., 2021; He et al., 2018). Despite the increased usage of these data, there have remained several concerns, including data representativeness, reliability, and associated analytics (Thakuriah et al., 2020). This calls for integrating multiple data sources and cross-validation of different data and methods results.

3 Methods

3.1 Measuring urban vitality in station areas

Previous studies have tested changes in housing, land prices, and land use in station areas vis-à-vis HSR development (Chen & Haynes, 2015; Ribalaygua & Garcia, 2010; Wang & Duan, 2018). Considering the high population density and increasing mobility in the context of rapid urbanization, China's HSR stations have been designed to accommodate more passengers than there are. Based on previous studies (Shen et al., 2014; Zhao et al., 2018), we used a unified radius to test urban vitality in the station areas in the YRD. A unified scale of station area makes the HSR impact on cities at different levels comparable. Nevertheless, it ignores the fact that stations also have different scales in the hierarchical railway system. We controlled the test by adding some other station attributes. A 3 km radius was taken to be an appropriate area for testing urban vitality, as the vitality attributes of different station areas in the megaregion, such as the population of this area in the YRD, were in a normal distribution. Diao (2015) employed one-half mile (0.8 km) to define the catchment area of a metro station because the distance relatively corresponded to the traveller's comfortable walking distance. For the intercity railway system, the radius used to define HSR station area, for purposes of examining HSR's impact on land-use patterns and firm locations varied from 1 km to 3 km. (Chen & Wei, 2013; Shen et al., 2014; Wang & Gu, 2019; Xu et al., 2017). Our study employed a relatively large buffer area—a 3 km radius to cover the station and its surrounding areas as the distance relatively corresponded to the traveller's comfortable cycling distance. The effect of station area size on urban vitality was further controlled using a station's daily train service frequency indicator.

Based on previous studies (Xia et al., 2020; Ye et al., 2018) conceptualizing urban vitality and data availability, we developed a comprehensive method of assessing the station area's urban vitality. Their study areas were large, with high spatial functional heterogeneity, and they had to find unified sample factors to measure urban vitality. Therefore, they defined urban vitality from a narrow perspective, based on the number of small catering businesses within individual buildings. While this was a good method of capturing specific information on urban vitality, the authors acknowledged that it could not reflect all aspects of urban vitality. In contrast, therefore, while the function of our study areas was very similar to theirs, it also varied, based on different levels of urban development.

Consequently, we measured urban vitality from various dimensions to capture the variety of vitality of station areas in the YRD. We measured urban vitality using a big open data approach and collected the data in 2018. Four dimensions were covered to evaluate SAUV, i.e., concentration, accessibility, liveability, and diversity.

(1) Concentration

The concentration dimension was characterised by POI density (POID), population density (POPD), road junction density (RD), and building density (BD). These indicators have been used in previous studies (Xia et al., 2020; Ye et al., 2018). POPD reveals physical density while POID can reflect human activities in different places. Both have been widely used as proxies for sufficiently dense concentrations of people, necessary for flourishing city diversity (Jacobs, 2016). The concentration of the built environment is another useful proxy for urban vitality measurements. RD represents the spatial coverage of the transportation network (Tu et al., 2019), while BD refers to the building coverage ratio to reflect the relationship between built-up and undeveloped areas. The formulas used were as follows:

$$POID = \frac{N_{poi}}{A} \quad (1)$$

$$POPD = \frac{N_{pop}}{A} \quad (2)$$

$$RD = \frac{N_{rj}}{A} \quad (3)$$

$$BD = \frac{BA}{A} \quad (4)$$

N_{poi} is the number of POIs in a high-speed railway station area, N_{pop} is the number of residents in a high-speed railway station area, *N_rj* represents the number of road junctions in a high-speed railway station area, *BA* denotes the gross building footprint of a high-speed railway station area, and *A* denotes the size of the HSR station area.

(2) Accessibility

Accessibility is the average distance to the nearby commercial areas (DC). Commercial uses include large-scale retail sites, such as supermarkets and convenience stores and retails, such as Lawson, and restaurants like McDonald's. We first used the Network Analysis tool in ESRI ArcGIS to obtain the existing road distances from commercial uses to the rest of the space, respectively.

(3) Liveability

Liveability was analysed through the indicators of the mean construction time calculated by month (BM) and the average housing prices (HP). In China, comparing with the old neighbourhood with inadequate facilities, newly built housing, and high housing prices suggest a good living environment in the community (He et al., 2020). The formulas used were as follows:

$$BM = \frac{\Sigma_l^m M_l}{m} \quad (5)$$

$$HP = \frac{\Sigma_l^m P_l}{m} \quad (6)$$

M_l represents the construction time (month) of the l-th residential quarter, P_l represents the housing price of the l-th residential quarter, and m is the total number of residential quarters within the same high-speed railway station area.

(4) Diversity

POI data were used to identify the functional mixing of land uses. The dimension of diversity was addressed by the Shannon entropy, the most widely used diversity indicator to quantify the mix of land use types (Christian et al., 2011; Manaugh & Kreider, 2013; Yue et al., 2017). The diversity index is usually constructed by POI and by land use mix (Guan & Rowe, 2016), and the two generally capture similar information. Their difference lies in spatial resolution. The resolution of land use mix interpreted from satellite images is relatively low, but it is widely used in large scale research (it mainly captures horizontal information). In contrast, POI data is usually used in small scale research such as building block level (it also contains the vertical information). The diversity in this study is constructed as follows:

$$MIX = -\sum_{i=1}^{n} (P_i \times \ln P_i) \tag{7}$$

P_i is the proportion of the i-th POI type for the total POI records, and n is the total number of POI types.

(5) SAUV and its influence factors

To compare the indicators with different units, we normalised each indicator via the Min-Max normalisation approach. The weights of the indicators for each dimension (W_i) were determined by the information entropy method to capture the largest variation. A conventional linear regression was employed to evaluate the extent to which the dependent variables were associated with the SAUV in the YRD. As we have documented, the SAUV is normally distributed, which satisfies the assumption of the linear regression model.

The steps to calculate the SAUV and weight W_j of each indicator X_j are demonstrated are as follows:

$$\text{SAUV} = \sum_{j=1}^{m} W_j \times X_j \tag{8}$$

$$W_j = \frac{1 - ej}{\sum_{j=1}^{m} (1-ej)} \tag{9}$$

$$e_j = -\frac{1}{\ln m} * X_j \log (X_j) \tag{10}$$

Where m is the number of indicators, here m is equal to 8; X_j is the value of the jth indicator; e_j is the entropy of the j^{th} indicator.

3.2 Data sources

Four primary datasets were used and synthesised in this study from various sources in 2018. First, the POI dataset obtained from the Baidu open platform[1] was used as the primary dataset for calculating urban vitality. We selected frequently used POI types regarding restaurants, hotels, shopping malls, education and training centers, transport facilities, buildings and shop fronts of finance, real estate,

[1] http://lbsyun.baidu.com/index.php?title=webapi/guide/webservice-placeapi

corporates, governments, automobile services, and life services. Second, the neighbourhood datasets were used and crawled from the Anjuke website [2], a popular online platform that publishes real-estate information for more than 640 cities in China. Finally, we collected relevant housing attributes of all the residential quarters within the HSR station area in the YRD in 2018, including identity number, building area, built time, and housing price. Any false records were then excluded, such as those with abnormal housing prices. The locations of all residential quarters were obtained through Baidu Maps by searching their names. Third, the road network was derived from OpenstreetMap (OSM)[3], one of the most widely used data sources of crowdsourced Volunteered Geographic Information with more than five million registered contributors (Bshouty et al., 2020). Fourth, different road networks (railway, motorway, primary way, and secondary way) of the YRD cities were gathered. Fifth, the population data were shared by Worldpop website [4], which provided current data on human population distributions in 100 m spatial resolutions of the entire country from 2000 to 2020. The database proffered a fine-scale pattern of population distribution for China. Demographic maps in the Yangtze River Delta were gathered and extracted within the high-speed railway station area. Lastly, dependent variables, such as train frequency and years of station operation, were collected from the online booking system of the China Railway[5] and China Railway Statistical Yearbooks, while the YRD cities' socioeconomic variables were collected from relevant statistical yearbooks.

3.3 Study area

Located in eastern China (Figure 1), the YRD megaregion is one of the most developed megaregions (Wang et al., 2016). Economically centered by Shanghai, it covers the three other provincial-level administrations of Jiangsu, Zhejiang, and Anhui. The region accommodates 42 cities at the prefecture level or above, 54 county-level cities, and 117 rural counties. Economically, the megaregion is unevenly developed, with more developed coastal areas than others. The YRD is ahead of the country's HSR expansion in both speed and scale. By 2018, 191 passenger rail stations were serving 122 cities at different levels. Among these, 121 stations operated HSR services, of which 86 were newly built in the past decade, and 38 were upgraded from conventional rail stations. Besides, there were 68 conventional rail stations. With the developed CR and the HSR networks, the YRD was typical for studying the SAUV. Figure 2 shows that the main indicators of the SAUV are highly heterogeneous in the YRD.

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[2] https://www.anjuke.com/sy-city.html
[3] https://www.openstreetmap.org/
[4] https://www.worldpop.org/
[5] https://www.12306.cn/index/

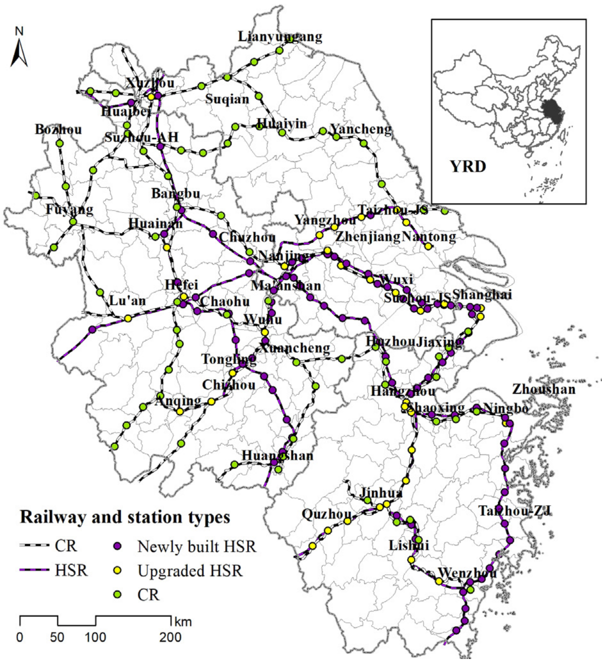

Figure 1. YRD location and distribution of HSR and CR stations

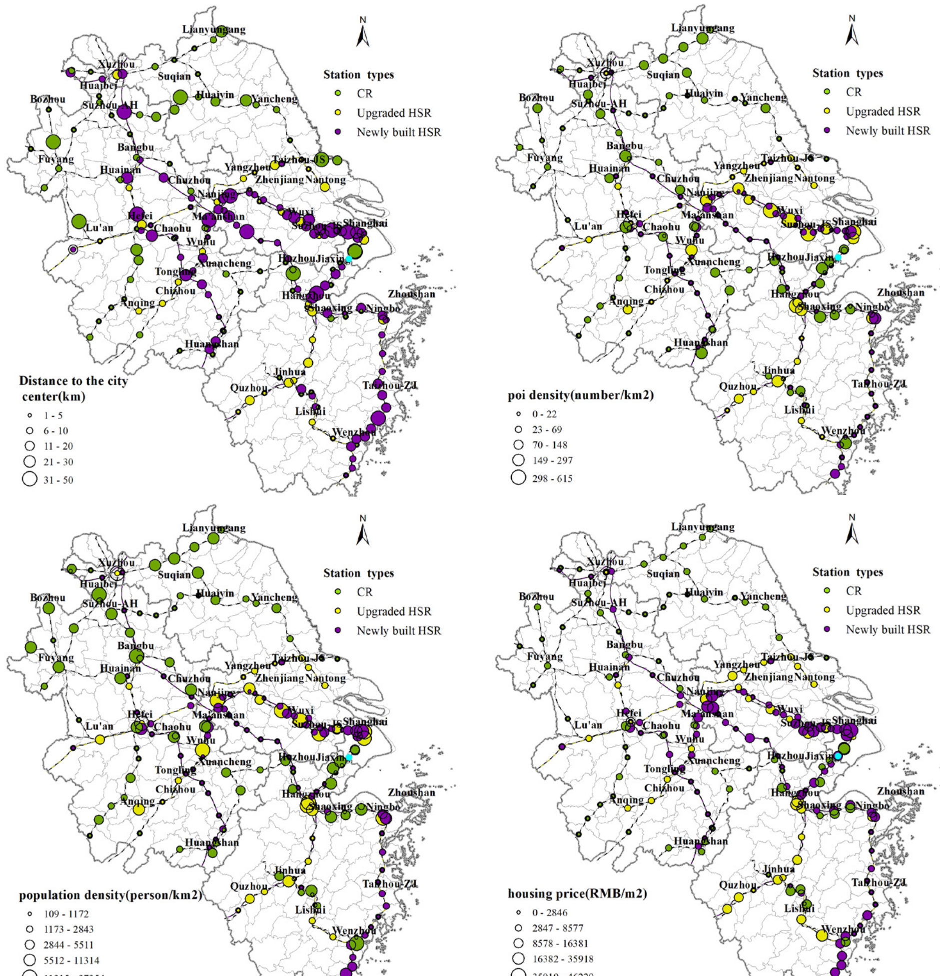

Figure 2. The distribution of main indicators of SAUV in the YRD

4 Results

4.1 The rank-size distribution of urban vitality in HSR and CR station areas

Figure 3 shows the global pattern for SAUV values in the YRD. SAUV was not related to whether it was in CR or HSR network because the station areas served by HSR and CR had high and low urban vitality values. SAUV appeared to have a closer association with the cities' administrative ranking. In general, higher values of SAUV were mainly found in central economic cities, i.e., Shanghai, Nanjing, Hangzhou, Suzhou, and Hefei, and in cities within the two traditional economic corridors of Nanjing-Shanghai and Shanghai-Hangzhou. It is worth mentioning that most central cities developed more than one station with high SAUV. In contrast, those with lower values of SAUV were mainly located in cities in periphery areas, such as the western part of Anhui Province and the south-western part of Zhejiang Province, and intermediate cities with newly built HSR lines, such as cities along the Ningbo-Taizhou and Nanjing-Hangzhou HSR lines.

The Shanghai upgraded HSR station had the highest SAUV value (0.876), followed by Hefei (0.59) and Hangzhou (0.581) upgraded stations. Among newly built HSR stations, Shanghai South (0.483) ranked first, followed by Ningbo East (0.354) and Hangzhou South (0.313). In contrast, newly built HSR stations of Dingyuan (0.0021), Tongling North (0.0039), and Huai Nan East (0.0045) ranked the bottom three. Except for the station halls, there are rare facilities and buildings in the station areas. The statistics of the three station types provide a clear understanding of the SAUV pattern in the YRD. The average SAUV of upgraded HSR stations was 0.241, followed by CR stations (0.105) and newly built HSR stations (0.09). It makes sense that station areas of upgraded HSR stations and CR stations have been in development for decades. Most have become city centers, or are encompassed by various built-up areas. In contrast, the opening of the earliest newly built HSR station was in 2009 for the Ningbo-Taizhou HSR. The short development time and distance from the city center are the possible reasons why most newly built HSR station areas present relatively lower SAUV.

Figure 4 presents the rank-SAUV and its four dimensions plot. The y-axis represents the urban vitality of different station types, and the x-axis represents the corresponding ranks of SAUV. The distribution of SAUV for the upgraded HSR stations was the flattest among the three types of HSR stations. According to Table 1, Zipf's two-parameter model fits the three station types. The absolute slope for the newly built HSR station type was the largest, and the upgraded HSR station type had a relatively smaller slope. The result suggests that only a few newly built HSR stations could attract vibrant urban activities in their surrounding areas, and most of them were far from well developed. However, upgraded HSR stations had better foundations than CR stations because they were located in cities with relatively good economic performance. It is evidenced that, at the average level, upgraded HSR stations had much higher values than CR stations and newly built HSR stations in the concentration and liveability dimension of urban vitality. Comparatively, the three station types had a relatively low difference in accessibility and diversity of urban vitality.

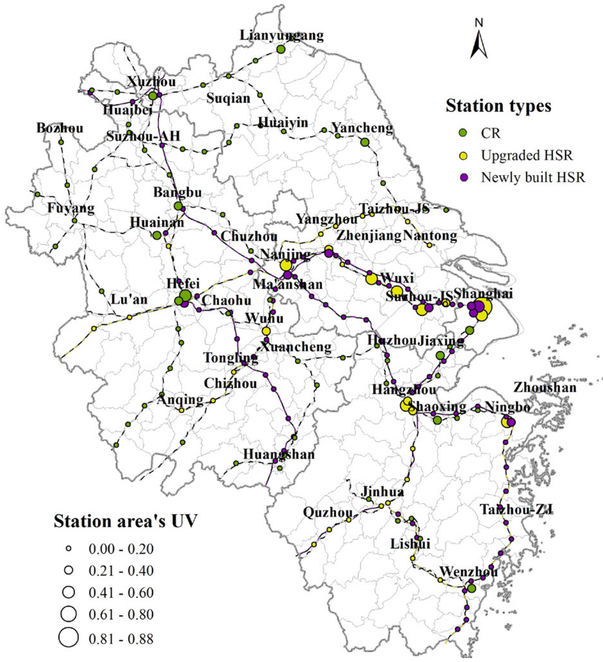

Figure 3. The pattern for rail station area's urban vitality in the YRD

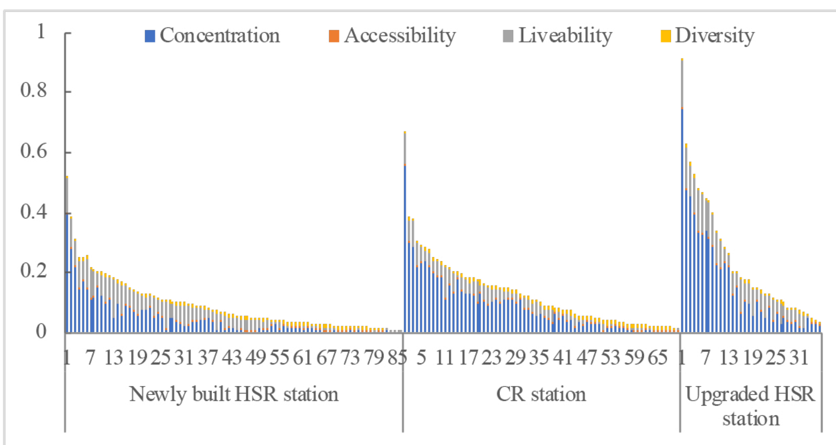

Figure 4. The comparison of SAUV and its dimensions for different station types

Table 1. Results of the Zipf's two-parameter model

Type	Formula	q	R^2
Newly built HSR Stations	$LnY = -1.01 LnX + 0.66$	1.01	0.74
Upgraded HSR Stations	$LnY = -0.85\ LnX + 0.48$	0.85	0.86
CR Stations	$LnY = -0.94\ LnX + 0.52$	0.94	0.76

4.2 Spatial differentiation of HSR station areas' urban vitality across cities/counties, provinces, and HSR lines

4.2.1 SAUV's variation in different city administrative levels

Figure 5 shows that the decrease in the three respective station types' average SAUV was in line with the decline of cities' administrative rank in the YRD. Provincial cities had the highest average SAUV, regardless of station type, while rural counties had the lowest average SAUV. Among the three station types in the same city-level, upgraded HSR stations had the highest value of SAUV, followed by CR stations and newly built HSR stations. For the group of provincial-level cities, the absolute average SAUV gap between upgraded and newly built HSR stations was the largest at 0.265. This was more than double the average for the group of prefecture-level cities. Cities at the county level and counties had very low SAUV, while the gap between upgraded HSR stations and newly built HSR stations was also small.

However, represented by the coefficient of variation, in the statistics of disparity, generally, the higher the city ranking levels were, the lower were the values of SAUV's coefficient of variation (CV) within the same city group. This pattern was particularly significant for newly built HSR stations. This corresponds to the pattern of economic development at different city levels in which the lower the city level, the greater the economic divergence among them (Ma, 2005; Wei et al., 2017). However, the upgraded HSR station type showed some variations from the general pattern. Prefectural-level cities had the highest SAUV disparity. Perhaps, this is because prefecture cities' upgraded HSR stations brought different levels of economic potential and urban regeneration to station areas. Using upgraded HSR stations and CR stations as benchmarks, the results suggest that the potential for urban growth that is driven by HSR is very limited in county-level units. In contrast, HSR stations can increase SAUV in cities to a higher level over time.

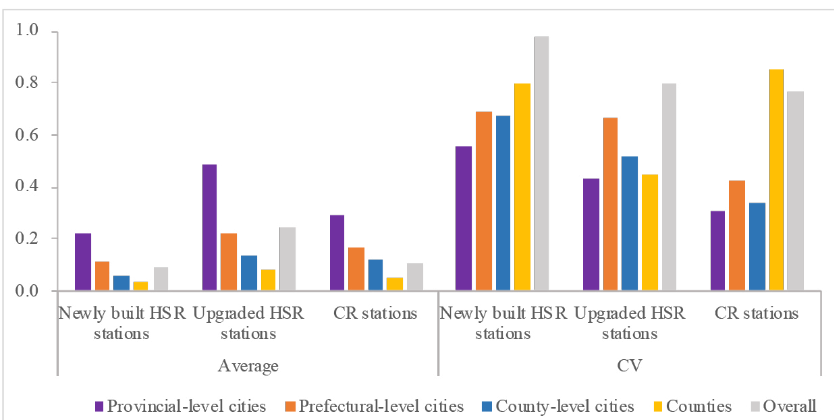

Figure 5. The pattern of SAUV for different city administrative levels in the YRD

4.2.2 SAUV variation in different provincial administrative regions

Figure 6 shows a very high spatial disparity of average SAUV among the four provincial-level units in the YRD. Shanghai had the highest value regarding the average SAUV, followed by Jiangsu, Zhejiang, and Anhui. The average SAUV pattern of different station types for the four provincial-level administrations was similar to that for the four city levels, with the upgraded HSR station type having the highest value and newly built HSR stations possessing relatively lower SAUV. However, the situations in Shanghai and Jiangsu were different, and the average SAUV of their newly built stations was higher than that of their CR stations. On average, newly built HSR station areas in Shanghai and Jiangsu have been more dynamic than those in Zhejiang and Anhui Provinces. Since newly built HSR stations were only developed a few years ago, the values of SAUV have some potential to increase following the urbanization process.

Within the four administrative regions, Shanghai and Jiangsu had similar, relatively lower spatial disparity values for HSR SAUV, while Zhejiang and Anhui had similar, much higher spatial disparity values. Excluding Shanghai, which only had seven HSR stations, the results indicate that SAUV in Jiangsu Province showed a more balanced pattern than Zhejiang and Anhui Provinces. This situation is in line with the disparity levels of the spatial economy within the three provinces of Jiangsu, Zhejiang, and Anhui. Particularly for Anhui Province, the provincial capital—Hefei—plays a dominant role in its economy. Thus, many provincial government-supported funds have been allocated to the city, as evidenced by the five HSR lines passing through it. In Jiangsu, the provincial government only developed HSR lines in its most developed southern part, while its northern cities with poor economic performance were left behind. Jiangsu Province had a relatively lower disparity for newly built and upgraded HSR SAUV due to its HSR network, mainly concentrated in the developed south.

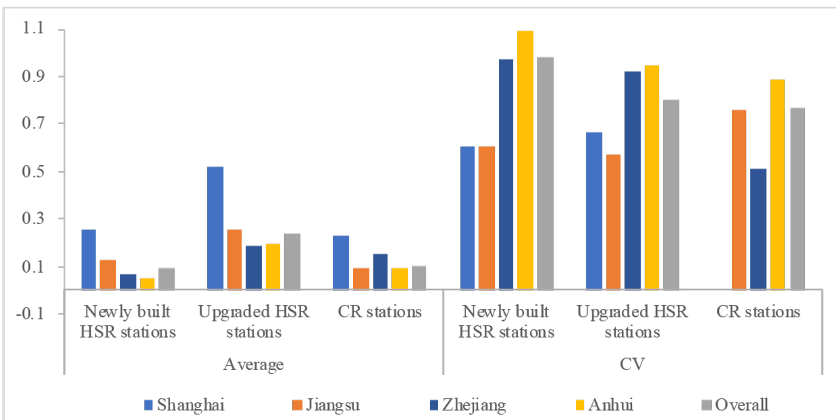

Figure 6. The spatial disparity of HSR SAUV within the four provinces in the YRD

4.2.3 SAUV's variation in different types of HSR lines

Following the analysis of the SAUV variations in different city levels and regions, we analysed its features along with different types of HSR lines. Previous studies have documented the corridor economies generated by HSR development. Since the HSR line has been developed from different types, such as the national backbone link, regional link, and intercity link (Wang et al., 2012), it is helpful to analyse SAUV and its variation along different lines. Figure 7 shows that Shanghai-Nanjing HSR is the most prominent link in the YRD. Operated in 2010, the newly built HSR line was a regional intercity link connecting nine cities. It has 21 stations, most of which were upgraded from CR stations. Therefore, the SAUV is very high, along with the link. Another prominent regional intercity link is Shanghai-Hangzhou HSR, which connects two central cities in the YRD. The two regional HSR lines connect the most developed cities, reinforcing the traditional economic corridors of the YRD.

Paralleling the Shanghai-Nanjing HSR line is a national backbone link—the Beijing–Shanghai HSR line—which connects the YRD and the capital megaregion. This newly built HSR line is another critical link in the YRD. However, most of its stations are newly built and located in suburban areas.

Therefore, its UV rank-size distribution was relatively flat. Hefei-Fuzhou and Hangzhou-Changsha HSR lines belong to a national backbone link that also possessed the flat distribution pattern for the UV rank-size. Lastly, some metropolitan links such as the Nanjing-Anqing and Hefei-Bengbu HSR lines have been developed to connect the central city and its hinterlands to promote regional economic integration. Therefore, the UV slope for this type of HSR line is very steep. Worse is that many HSR stations in small cities are newly built and located far from the city center, thereby restricting their ability to attract economic activities in station areas.

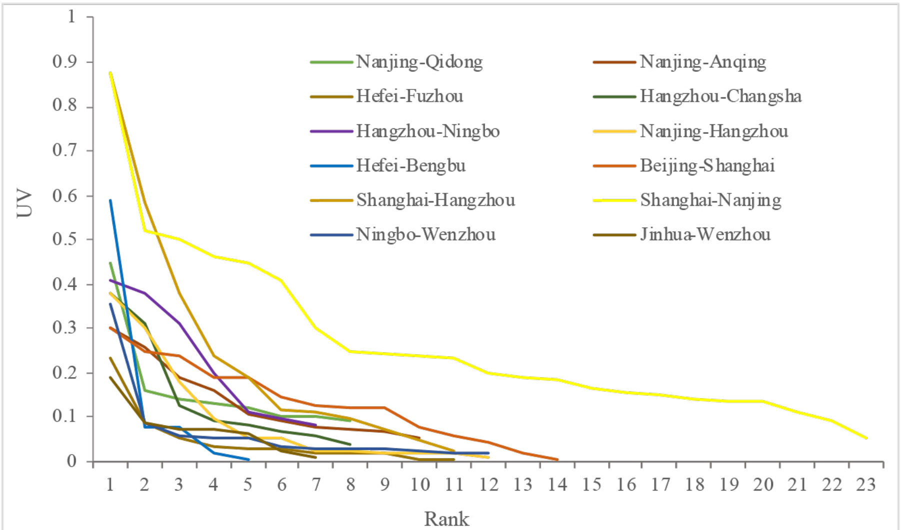

Figure 7. The rank-size distribution of HSR SAUV among different HSR lines in the YRD

4.3 Determinants of HSR station areas' urban vitality in the YRD

The developed HSR network provides an important underpinning infrastructure for urban development. The place quality of HSR station area is understood from spatial, economic, and experiential dimensions (Du et al., 2021). Similarly, previous case studies (Chen, 2020; Yin et al., 2015) argued that the dynamics of urban development in HSR station areas were associated with three dimensions at both station and city levels—the characteristics of infrastructure, urban economic performance, and institutions. Diao et al. (2017) argued that the station location played a vital role in HSR impact on urban development. They stated that the connectivity of HSR stations to the city center was a crucial indicator of the development in HSR station areas. Thus, to represent the characteristics of station factors, we selected the indicators of train frequency, years of station operation, road distance to the city center, whether the station had a subway connection, and years of being built. To represent the city's institutional and socioeconomic factors, the indicators of the city's administrative level, population density, industrial structure, and GDP were chosen as the scale and structure factors. It is noteworthy that parts of these indicators have been discussed in previous case studies on urban development in station areas (Geng et al., 2015; Vale, 2015; Wang & Duan, 2018). Here, we applied a multiple regression model to account for the patterns of SAUV and attempted to ascertain which factors were more relevant to the urban vitality of rail station areas in the YRD.

To reduce potential heteroscedasticities, the value of variables, such as the station's train frequency and distance to the city center and the city's population density and GDP, were transformed into logarithmic form. The variance inflation factors (VIFs) were tested, and no value higher than four was found. This met the rule of thumb against multicollinearity. The F-test from the multi regression analysis indicates that each listed model is significant at the 99% confidence level (Table 2). The variables at the station level are all significant predictors, accounting for 24.5% of SAUV's variation. The results suggest that new station areas were less vibrant than their old counterparts, ceteris paribus, and the station's distance to its city center was negatively related to SAUV. By adding variables at the city level, the model's explanatory power was increased significantly to 78.2%. This result echoes previous studies (Shen et al., 2014; Wang & Gu, 2019) that a city's socioeconomic performance significantly impacts urban development in station areas.

We further conducted a regression analysis, particularly on HSR stations, to examine whether there was any difference from the above analysis that included both HSR and CR stations. The results presented a similar pattern of the effects from different factors, except that the station's train frequency was an insignificant predictor. However, compared to the total sample, the station factors doubled the accountability for explaining the SAUV's variation in the group of HSR stations. This suggests that SAUV is very sensitive to years of station operation. Interestingly, a station's distance from the city center became significant when control variables were added at the city level. It was demonstrated that there was an interactive effect between distance and city-scale factors. Large cities had a higher probability of developing a vibrant station area economy, even though the station was far from the city center, but this was a problem for small cities.

Table 2. Multi regression results for SAUV of all rail stations in the YRD

	Variables	(1)	(2)	(3)	(4)	(5)
Station level	Constant	-0.080** (0.036)	-0.091** (0.038)	0.003 (0.031)	0.313*** (0.06)	-0.101 (0.067)
	Ln (Train service frequency)	0.042*** (0.006)	0.043*** (0.006)	0.023*** (0.005)	0.012** (0.005)	0.005 (0.004)
	Whether the station is newly built (yes = 1)	-0.076*** (0.016)	-0.080*** (0.016)	-0.078*** (0.013)	-0.065*** (0.012)	-0.067*** (0.01)
	Road distance to its city center/m		0.0006 (0.0008)	-0.0006 (0.0006)	-0.0007 (0.0005)	-0.003*** (0.0005)
	Whether a connected metro (yes = 1)			0.212*** (0.018)	0.142*** (0.021)	0.064*** (0.019)
	Administrative ranks				-0.067*** (0.011)	-0.045*** (0.01)
City level	Ln (population density)					0.05*** (0.007)
	Ln (gross domestic product)					0.041*** (0.009)
F		31.81	21.37	61.53	64.86	79.01
Adjust R^2		0.245	0.255	0.56	0.627	0.742
N		191	191	191	191	191

Notes: *, **, and *** denote significance levels of 0.1, 0.05, and 0.01, respectively.

Table 3. Multi regression results for SAUV of HSR stations in the YRD

Variables	(1)	(2)	(3)	(4)	(5)	(6)
Constant	0.098 (0.072)	0.082 (0.075)	0.153*** (0.056)	14.67** (7.481)	0.506*** (0.081)	0.075 (0.102)
Ln (Train service frequency)	0.019* (0.01)	0.02* (0.01)	0.002 (0.008)	-0.0007 (0.0008)	-0.016* (0.007)	-0.009 (0.006)
Whether the station is newly built (yes = 1)	-0.122*** (0.026)	-0.125*** (0.026)	-0.107*** (0.021)	-0.118*** (0.021)	-0.111*** (0.018)	-0.087*** (0.016)
Road distance to its city center (m)		0.0008 (0.0001)	-0.0007 (0.0008)	-0.0009 (0.0008)	-0.001 (0.0007)	-0.003*** (0.007)
Whether a connected metro (yes =1)			0.208*** (0.021)	0.197*** (0.021)	0.114*** (0.024)	0.052** (0.023)
Years of being developed				0.007** (0.004)	0.009*** (0.003)	0.005* (0.003)
Administrative ranks					-0.078*** (0.013)	-0.051*** (0.013)
Ln (population density)						0.051*** (0.009)
Ln (gross domestic product)						0.026** (0.013)
F	18.52	12.47	40.89	34.25	41.65	46.81
Adjust R^2	0.226	0.222	0.571	0.581	0.67	0.753
N	121	121	121	121	121	121

Notes: *, **, and *** denote significance levels of 0.1, 0.05, and 0.01, respectively.

5 Discussion and conclusion

The rapid expansion of China's HSR network has significantly impacted the country's urban development. This is particularly evidenced in developed megaregions, where various levels of government have invested heavily in HSR development over the past decade. This study evaluated urban vitality in rail station areas and its impacting factors in the context of rapid HSR expansion in the YRD megaregion, using the big data approach. Similar to the development of other transport technologies, the newly built HSR network has created both winners and losers, necessitating the restructuring of the already imbalanced economic landscape. Therefore, it needs to contextually analyse the role of HSR development in urban development by integrating different spatial levels of the HSR station, the city, and the regional network. This paper highlights the varied impacts of HSR network development on station areas' urban vitality across different city ranks, HSR lines, and sub-regions.

The general pattern of SAUV demonstrates that high HSR SAUV is mainly located along major economic corridors, which have been partly formed in tandem with the conventional rail network for decades. The pattern of SAUV is significantly associated with the city's administrative rankings and socioeconomic development levels, as proven by the regression analysis on SAUV determinants. The findings echo those of the recent research by Chen (2020) that the hierarchical urban system significantly mediates the HSR impact on urban development. In China, the higher the administrative ranking of a city is, the stronger and larger is the city's economy. This conclusion makes sense because high-ranking cities have high inward and outward travel demands that facilitate the concentration of economic activities in station areas to serve travellers. However, transforming a transport hub into an economic place requires local development context and time to consolidate.

Along with China's HSR expansion, many cities have planned new towns and commercial complexes in the station areas. The aim is to use HSR-related initiatives to promote local economic growth and property development. The planning is ambitious for many cities, while the reality varies. To this end, the SAUV values can be further used to evaluate the implementation of urban plans and inform future planning policy interventions. Given that China is still in the process of rapid urbanization and population is concentrating in big cities, urban expansion would eventually give access to peripheral HSR stations in many big cities. For example, the Nanjing South Station is built on farmland. Ten years ago, travellers complained that the station was far away from the city center, while at the time of this study, the station was enclosed in urbanised space and had become one of the city's sub-centers. In contrast, taking Suzhou East Station in Anhui Province as an opposite example, a new 48 km2 HSR town was planned in 2013, but very few housing property companies wanted to invest in it. The new HSR town had only finished the road network and a few government-supported residential buildings.

Our analysis corroborates earlier perspectives that the longer a newly built HSR station has been in operation, the higher its development level of SAUV. The variation in SAUV of newly built HSR stations was higher than that of CR stations and upgraded HSR stations. The results suggest that since the newly built HSR stations have only existed for a few years, the SAUV in high-ranking cities can grow from rapid urbanization. In the context of rapid HSR network expansion in China, many new HSR towns have been planned and developed under the assumption that the operation of HSR stations will bring economic opportunities to cities and station areas (Wang & Duan, 2018). This assumption is seemingly supported by the TOD model of urban development and European experiences of integrating HSR development and urban regeneration. However, based on our evaluation of urban vitality in HSR station areas, the reality is that HSR-led urban development varies significantly across different cities and regions. There are no uniform benefits for the cities with HSR stations.

Furthermore, if an HSR station is far from the city center, it negatively impacts the development of UV in the YRD. This negative effect is particularly significant for low-ranking cities with low HSR service frequency. Combined with a suburban location for an HSR station, the low train frequency makes travellers shift to other modes of transport for intercity travel. On the other hand, low-ranking cities may face financial constraints with regard to funding facilities and infrastructures for HSR-led development. In this case, physical and economic connections cannot be well developed between the city center and the newly built HSR station area. In contrast, high-ranking cities are more capable of addressing the potential adverse effects of the suburban location of newly built HSR stations. This is because they have more resources to support HSR-led development and are still in the rapid urbanization process. There is a reinforcing cycle of economic activities' concentration and rail development in large cities.

The political fragmentation of transport planning and urban planning in China creates uneven capacities for cities with different ranks to integrate two types of plans for local development. Technologically, although HSR development needs a flat and straight trajectory, HSR routes and station locations in different cities have also resulted from the negotiations between urban governments and the Ministry of Transport (Wang & Duan, 2018). Rail planning is a very top-down process under China's hierarchical administrative system. Economically, the Ministry of Transport prefers to develop new HSR stations in suburban areas to reduce development costs and construction cycles. High-ranking cities can lobby the ministry and invest in HSR development in line with their urban plans, while low-ranking cities must follow the rail development plan from the upper levels. To integrate urban planning and HSR network planning, a fast link (through public transport) is recommended to overcome the long distance between a newly built HSR station and the city center. Such a link could then facilitate urban area expansion toward HSR stations. These are critical issues for future urban and regional development in China.

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