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Assessing the Relationship of Transit-oriented Development with Urban Vitality in China

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Abstract. Transit-oriented development (TOD) is regarded as urban planning concept of integrating urban land use and transportation networks. Previous studies on TOD indicators and their impacts on shifting trip modes have been enriched, while quantitative analysis of the relationships between specific indicators of TOD principles and urban vitality remains limited. Therefore, we proposed a three-step framework to conduct a nationally large-scale analysis assessing the relationship of TOD with urban vitality, which was applied in 35 cities with 3,273 subway stations in China. The results show that (1) TOD principles are significantly relevant to urban vitality, (2) stations closer to the city CBD, with dense roads, buildings, parks, and walkability are more vibrant, and (3) more complexity of functionalities will be detrimental to offline consumption activities. The results and suggestions may serve as references for enhancing urban planning and policies in China and other developing nations, thereby promoting worldwide sustainable development.

Keywords: Transit-oriented Development, Urban Vitality, Indicator Assessment, Multisource Data.

1 Introduction

Transit-oriented development (TOD) is regarded as the result of integrating urban land use and transportation systems. It has become an effective urban planning concept due to its pedestrian-friendliness, diversified land use, and transportation network accessibility [1-3]. This concept was initially proposed in Peter Calthorpe's research, where a TOD area is described as "a mixed-use community within an average 2000-foot walking distance of a transit stop and core commercial area". The TOD area will "mix residential, retail, office, open space, and public uses in a walkable environment" [1]. Based on this concept, Cervero and Kockelman introduced density, diversity, and design ("3Ds") as fundamental principles of TOD [4]. In their view, high-density construction

along the transit line can meet the convenience of more people and promote public transportation; a mixed-use development allows individuals to meet as many demands as feasible in a compact area; suitable pedestrian space can increase the use of public transportation. Subsequently, Ewing and Cervero added distance to transit and destination accessibility to these principles ("5Ds") [5]. The following studies summarized TOD indicators and proposed their assessment standards according to TOD principles to measure the TOD level considering local conditions [6-8].

Urban vitality is the measure of the quality of urban spaces that have the ability to attract a diverse range of individuals for various activities across different time periods [9]. High-vitality areas within a city are commonly perceived as lively, vibrant, and bustling, drawing individuals to engage in activities, take leisurely walks, or simply spend time there. On the other hand, areas with low vitality tend to deter people and can be perceived as unsafe [10]. Previous studies have often characterized urban vitality using number of population, through data such as Baidu heat maps, population grids from mobile signaling data, etc. In addition to passenger flow data, factors such as the total amount of recreational activities among residents, commercial consumption, and cycling volume also partially reflect urban vitality. These factors not only emphasize population counts but also highlight the commercial activities and level of physical activity in the area.

Previous studies have admitted that TOD is effective in promoting low-emission transportation and improving urban vitality [11]. Higher urban vitality can drive the sustainable development of cities [12]. Since this concept originated, studies on TOD indicators and their effects on shifting trip modes have enriched many studies. However, the quantitative assessment of the relations between specific indicators of TOD principles and urban vitality is still limited [8]. Some researchers explored associations between subway access and land use but mainly focused on the density dimension, lacking adequate insights into the importance of the diversity dimension [13]. Meanwhile, a single population density indicator is typically used in assessing urban vitality in existing research, which is limited for measurement [12]. As the largest developing country in the world, China has been experiencing vast-scale urbanization and infrastructure construction, including subways over the past decades. Chinese cities are facing challenges like urban sprawl and limited available land resource. However, existing research mainly stems from the issue of the rapid increase of private cars squeezing urban space in cities of western developed countries, while urban development in Chinese cities started much earlier than subway construction, resulting in very different conditions of development and urban vitality between stations [8, 13].

Therefore, this study aims to answer three questions: (1) How to conduct nationally large-scale analysis for assessing the application conditions of multiple TOD principles? (2) How to comprehensively assess urban vitality at different urban scales? (3) How to quantitatively assess the relationship of transit-oriented development with urban vitality? To answer these questions, this paper proposed a framework for systematically conducting nationally large-scale analysis assessing the relationship of transit-oriented development with urban vitality. Meanwhile, the findings and recommendations of this study may provide a reference for improving urban planning and policies

for China and other developing countries experiencing rapid urbanization to facilitate global sustainable development.

2 Data and methodology

2.1 General framework

In this study, we proposed a three-step framework to conduct a nationally large-scale analysis assessing the relationship of transit-oriented development with urban vitality (Fig. 1.). First, a hierarchical indicator system was established, and indicators were calculated using multisource data to reveal the current development condition of TODs in China. Then, four indicators were selected to conduct the integrated analysis of urban vitality, which was comprehensive and representative, compared with the urban single vitality indicator as the dependent variable. The comprehensive urban vitality was estimated from two urban scales (i.e., station scale and city scale). A four-quadrant classification was adopted to classify the urban vitality of TODs in various cities. Third, the relationship of TODs with urban vitality was assessed through a multivariable linear regression model. Thus, practical implications and insights for urban planners and policymakers across cities were provided based on the assessment results.

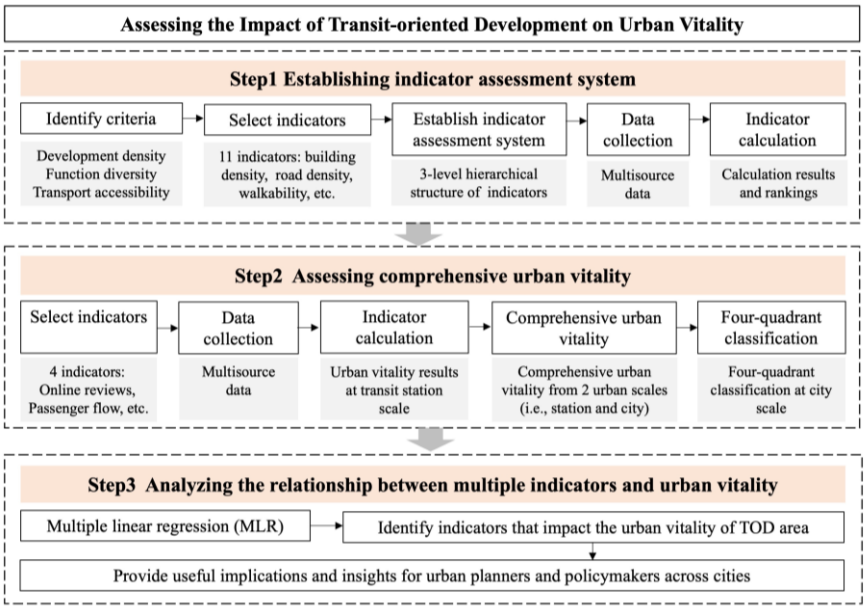

Fig. 1. Three-step framework for assessing the relationship of transit-oriented development with comprehensive urban vitality.

2.2 Study Area

This study selected 35 cities with transit systems in China to study the nationally large-scale assessment of the relationship of transit-oriented development with comprehensive urban vitality. There are 3,273 subway stations in the study cities (Fig. 2.). A 500-meter subway station buffer is performed to conduct analyses. These study cities are distributed in diverse provinces throughout the country, illustrating the urbanization of those regions and the total transit-oriented development of China.

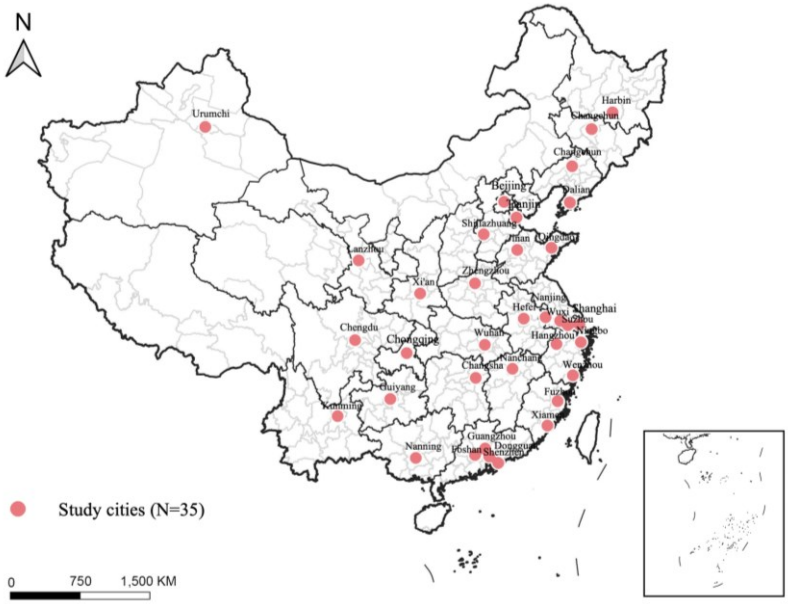

Fig. 2. Distribution of 35 study cities in China.

2.3 Data and Variables

Based on previous studies [11, 13], this study summarized widely recognized variables for the assessment, as shown in Table 1. The spatial extent of all the variables is within the 500-meter buffer of a station, which is regarded as the surrounding land of a subway station.

The independent variables are used for assessing TOD principles, including three categories: development density, function diversity, and transport accessibility. It is noted that points of interest (POI) include four categories: dining, shopping, business, and residence. The dependent variable is urban vitality, including four indicators, that is, sports records, online reviews, cycling records, and population flow volume. Compared to other studies that solely rely on population flow to characterize urban vitality, the use of sports records can represent the physical activity vitality of the population in the area, while online reviews can reflect the commercial vitality. Additionally, as people commonly use shared bicycles for their last-mile connectivity to subway stations,

shared cycling records data also partially represents the urban vitality in the vicinity of subway stations. By combining population flow, cycling flow, commercial activity, and physical activity, a more comprehensive representation of urban vitality related to TOD can be achieved.

Table 1. Variable definition and data source.

Variable Name	Variable Description	Data Source
Development density		
Building density	Total area of building bases / area of the surrounding land (m^2/m^2)	Dataset of buildings in 2017 provided by Beijing City Lab [14]
Plot ratio	Total floor area / area of the surrounding land (m^2/m^2)	Dataset of buildings in 2017 provided by Beijing City Lab [14]
Road density	Road length / area of the surrounding land (km/km^2)	Gaode Map in 2019 [15]
Density of points of interest (POI)	Total amount of POI / area of the surrounding land (number/$100m^2$)	Gaode Map in 2016 [15]
Function diversity		
Function mix	$\sqrt{\frac{-\sum(P_i \times \ln P_i)}{n}}$, P_i = Amount of POI of type i / Amount of POI of all types, n = Quantity of POI types	Gaode Map in 2016 [15]
Housing-employment mix	1- abs (Housing population - employment population) / (Housing population + employment population)	Website of Baidu Huiyan in December 2019 [16]
Green land density	Total area of green space / area of the surrounding land (m^2/m^2)	Dataset of green land in 2017 provided by Beijing City Lab [17]
Transport accessibility		
Walkability	Length-weighted average walk score of all the streets	Related research of Beijing City Lab [14]
Transferability in the station	Total amount of subway lines transferable in the station	Gaode Map in 2019 [15]
Transferability to transit buses	Total amount of bus stops	Gaode Map in 2016 [15]
Distance to the city center	Straight line distance from the station center to the city center (km)	Dataset of buildings in 2017 provided by Beijing City Lab [17]
Urban vitality		

Sports records	Total amount of sports records in a mobile sports app on average for a day	Records in the Chinese mobile sports app Gudong in the first half of the year in 2018 [18]
Online reviews	Total amount of comments on a review website	Website of Meituan Dianping (Chinese TripAdvisor) in 2019 [19]
Cycling records	Total amount of cycling records in a bike-sharing app	Records in the Chinese bike-sharing app Mobike in a week in September 2017 [20]
Population flow volume	Average daily population flow volume within a month on a map website	Website of Baidu Huiyan in December 2019 [16]

2.4 Analysis Approaches

After evaluating the overall vitality of each station, the overall vitality of the city may be determined by totaling the ratings of stations in each city. Then, study cities are divided into four categories: Starting, Upgrading One, Upgrading Two, and Mature. For cities classified as Starting, TOD construction is in its first stages. For cities in the category of Upgrading One, the urban scale is relatively small. There are fewer constructed subway stations, and both usage efficiency and vitality are high. For Upgrading Two cities, the pace of subway station construction is quicker than that of land growth, awaiting holistic development and boosting vitality. For cities in the category of Mature, subway systems were constructed early, and stations are in a large amount with high average vitality.

To further analyze the relationship between indicators of TOD principles in different dimensions and urban vitality at the station level, this study used the multivariable linear regression model to find out the impact factors of independent variables that influence multiple indicators of the dependent variable. The formula is shown below.

$$Y=\beta_0+\beta_1X_1+\beta_2X_2+\ldots+\beta_kX_k+e \quad (1)$$

where Y is the dependent variable (i.e., indicators of urban vitality); β_0 is the constant; e is the error; X_k is the independent variable k (i.e., indicators of development density, function diversity, and transport accessibility); β_k is the coefficient of X_k.

3 Results

3.1 Indicator system establishment and assessment of TOD principles

A three-level indicator assessment system of TOD principles is established, as shown in Table 2. The calculation results of the 11 indicators of 3,273 stations from three dimensions, including development density, function diversity, and transport accessibility, are shown from the mean, standard deviation, etc.

The study has derived the top-ranked stations for each dimension, where each dimension is ranked by the subordinate indicators, and equal weights are applied to obtain

the total ranking (Table 3). From the point of development density, most top-ranked stations are distributed in southern China, where they are characterized as surrounded by popular business districts, office areas, etc. Liji North Road Station is the top-ranked station in terms of high-density development. It is located in the central region of Wuhan city, with large commercial and public facilities such as Wuhan Plaza, Xiehe Hospital, and Wuhan International Exhibition Center. As for function diversity, most top-ranked stations are positioned in the outer urban area, mainly in large public facilities, such as terminals, train stations, etc. In the dimension of transport accessibility, higher-ranked stations prefer to have better street walkability and convenient access to public transit.

Table 2. Statistical results of multiple TOD principles assessment (N=3,273).

Target Level	Criteria Level	Indicator Level	Mean	St. Dev.	Med	Min	Max
Multiple TOD principles assessment	**Development density**	A_1 Building density (m^2/m^2)	0.18	0.11	0.20	0.00	0.90
		A_2 Plot ratio (m^2/m^2)	1.27	0.94	1.20	0.00	12.48
		A_3 Road density (km/km^2)	27.49	12.53	27.81	0.00	86.34
		A_4 Density of points of interest (POI) (number/$100m^2$)	0.08	0.12	0.04	0.00	1.40
	Function diversity	B_1 Function mix (/)	0.32	0.23	0.30	0.00	1.00
		B_2 Housing-employment balance (/)	0.60	0.22	0.60	0.00	1.00
		B_3 Green land density (m^2/m^2)	0.09	0.26	0.00	0.00	2.68
	Transport accessibility	C_1 Walkability (/)	69.73	23.12	80.22	0.00	98.88
		C_2 Transferability in the station (number)	1.19	0.46	1.00	1.00	4.00
		C_3 Transferability to transit buses (number)	6.65	5.30	6.00	0.00	36.00
		C_4 Distance to the city center (km)	11.18	9.10	8.64	0.10	78.49

Table 3. Top 1 station in each dimension.

		A_1 (m^2/m^2)	A_2 (m^2/m^2)	A_3 (km/km^2)	A_4 (#/100 m^2)	B_1 (-)	B_2 (-)	B_3 (m^2/m^2)	C_1 (-)	C_2 (#)	C_3 (#)	C_4 (km)
Top 1 station of development density	Liji North Road Station, Wuhan	0.38	3.49	50.64	0.55	0.20	0.93	0.03	92.70	2	7	3.49
	Mean of Wuhan City	0.20	1.42	33.15	0.08	0.28	0.60	0.06	65.68	1.19	4.55	11.43
Top 1 station of function diversity	National Art Museum of China Station, Beijing	0.14	0.45	4.13	0.02	0.93	0.98	0.38	74.26	1	3	2.82
	Mean of Beijing City	0.19	1.27	12.95	0.08	0.45	0.64	0.09	72.10	1.21	6.25	13.57
Top 1 station of transport accessibility	People's Square Station, Shanghai	0.31	3.28	45.93	1.09	0.50	0.74	0.21	97.35	3.00	20.00	1.21
	Mean of Shanghai City	0.20	1.38	36.99	0.11	0.32	0.60	0.08	73.52	1.35	8.04	12.59

3.2 Integrated analysis of urban vitality

This research presents the integrated urban vitality of all subway stations based on the four indicators (i.e., sports records, online reviews, cycling records, and population flow volume) of urban vitality. General statistical results are in Table 4.

Table 4. Statistical results of urban vitality.

Indicator	Mean	St. Dev.	Med	Min	Max
Sports records	2844.94	3523.54	1808.54	0	$6.60*10^4$
Online reviews	3110.67	$1.79*10^4$	15	0	$6.67*10^5$
Cycling records	$6.08*10^4$	$9.09*10^4$	$1.61*10^4$	0	$8.34*10^5$
Population flow volume	$6.74*10^4$	$4.94*10^4$	$5.72*10^4$	97	$3.41*10^5$

To analyze the vitality difference between subway stations, this study made an equal-weighted calculation of the indicators to obtain the stations at the highest vitality level (top 100), which were then summarized to the city level, as shown in Fig. 3. Subway stations at the highest level are mainly distributed in three cities: Shenzhen, Guangzhou, and Beijing (Fig. 4.). These cities are megacities in the first tier of cities in China.

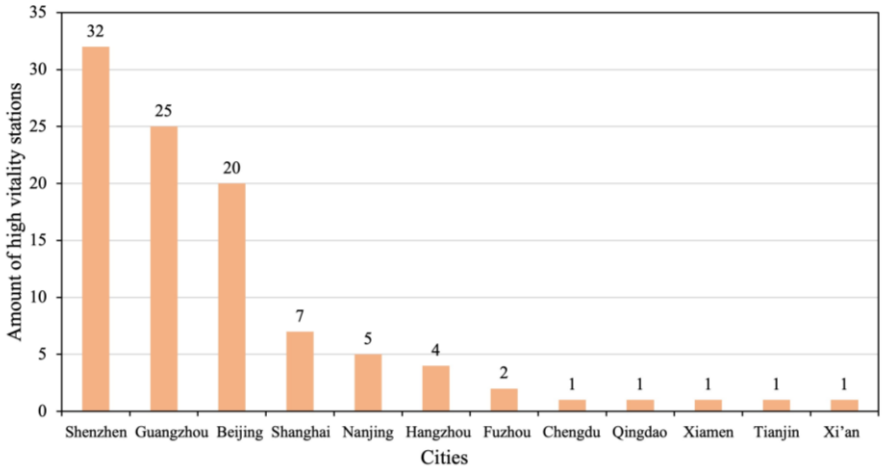

Fig. 3. Cities with subway stations at the highest level.

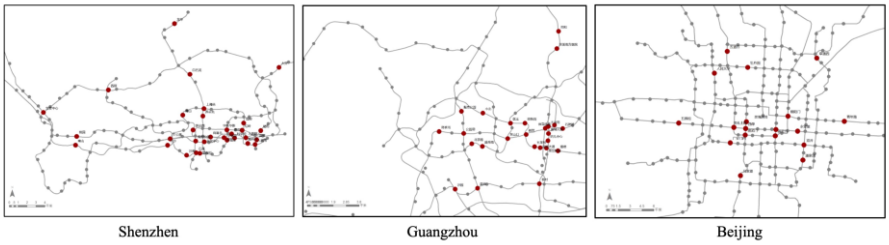

Fig. 4. High urban vitality subway stations in the top 3 cities.

To compare the general development characteristics of subway stations between cities, this study classified all the analyzed cities into four TOD categories, as mentioned above. As displayed in Fig. 5., the results show that the comprehensive development level of TOD does not present regional characteristics. For example, urban agglomerations such as the Yangtze River Delta and the Pearl River Delta differ significantly in vitality and TOD level. There is no obvious positive relationship with the size of the city. For example, the TOD development level in the provincial city of Chongqing is lower than that in sub-provincial cities such as Chengdu and Wuhan. The Mature category mainly consists of first-tier megacities. Upgrading One and Upgrading Two mainly consist of advanced provincial capitals and sub-provincial cities. Most cities belong to the Starting category.

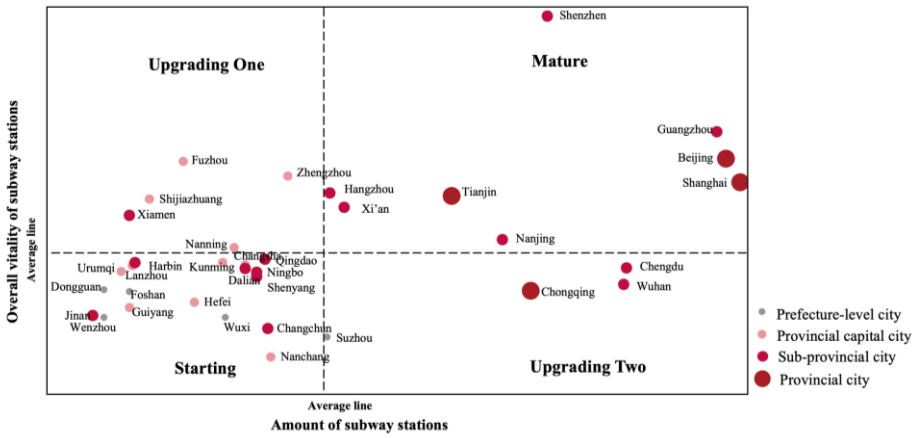

Fig. 5. TOD categories of different cities in China.

3.3 Relationship of transit-oriented development (TOD) with urban vitality

Based on the results of measuring TOD principles and urban vitality, this study comprehensively assessed the relationship of TOD with urban vitality to find the spatial characteristics that affect urban vitality at the subway station. The impact factors of multiple independent variables on the indicators of the dependent variables were found out by the multivariable linear regression model.

The correlation test was done first. As shown in Table 5, almost all the TOD indicators (except for green land density and housing-employment mix) have a correlation with sports records, online reviews, and population flow volume. Green land density has a correlation with sports records and online reviews. Transferability to transit buses, transferability in the station, and housing-employment mix have a correlation with cycling records.

The distribution patterns of data were first analyzed to prepare for regression analysis. Data like road density were subject to a normal distribution, which could be directly imported into regression analysis. Data like distance to CBD belonged to long-tail distribution, and their logarithmic forms were imported into regression analysis. Meanwhile, this study constructed four regression models to analyze the relationship of TOD with the four indicators of urban vitality, respectively.

The results of significant independent variables are shown in Table 6. Model 1 is the regression model for sports records, which shows that walkability has a positive impact on sports activities. In contrast, the distance to CBD and the density of POI have negative impacts. Model 2 is the regression model for online reviews, which shows that road density, walkability, and building density have positive impacts on attracting people to visit and review, while function mix and distance to CBD have negative impacts. Model 3 is the regression model for cycling records, which shows that the density of POI and function mix have positive impacts on cycling activities, while transferability to transit buses, plot ratio, and housing-employment mix have negative impacts. Model 4 is the

regression model for population flow volume, which shows that road density, walkability, and building density have positive impacts on population flows, while the distance to CBD has a negative impact. In general, more complexity of functionalities will be detrimental to offline consumption activities.

Table 5. Pearson correlation between TOD and urban vitality.

			Urban vitality			
			Sports records	Online reviews	Cycling records	Population flow volume
TOD	Building density	Pearson Correlation	.282**	.093**	.491**	.614**
		Sig. (2-tailed)	.000	.000	.000	.000
	Plot ratio	Pearson Correlation	.411**	.131**	.554**	.746**
		Sig. (2-tailed)	.000	.000	.000	.000
	Road density	Pearson Correlation	.160**	.050**	.265**	.414**
		Sig. (2-tailed)	.000	.004	.000	.000
	Density of points of interest (POI)	Pearson Correlation	.375**	.207**	.644**	.774**
		Sig. (2-tailed)	.000	.000	.000	.000
	Function mix	Pearson Correlation	.139**	-.066**	.089**	.116**
		Sig. (2-tailed)	.000	.000	.000	.000
	Housing-employment mix	Pearson Correlation	.136**	.075**	.199**	.252**
		Sig. (2-tailed)	.000	.000	.000	.000
	Green land density	Pearson Correlation	.174**	-.012	.023	.022
		Sig. (2-tailed)	.000	.483	.185	.217
	Walkability	Pearson Correlation	.422**	.116**	.522**	.650**
		Sig. (2-tailed)	.000	.000	.000	.000
	Transferability in the station	Pearson Correlation	.197**	.026	.310**	.440**
		Sig. (2-tailed)	.000	.146	.000	.000
	Transferability to transit buses	Pearson Correlation	.297**	.099**	.391**	.589**
		Sig. (2-tailed)	.000	.000	.000	.000
	Distance to CBD	Pearson Correlation	-.260**	-.094**	-.368**	-.494**
		Sig. (2-tailed)	.000	.000	.000	.000

Note: **: Correlation is significant at the 0.01 level (2-tailed); *: Correlation is significant at the 0.05 level (2-tailed).

Table 6. Results of significant independent variables.

Regression model	Significant TOD Indicator	Standardized coefficient	T	Sig.
Model 1 (Y= Sports records)	Building density	-0.207	-8.05	0
	Plot ratio	0.305	11.552	0
	Road density	-0.086	-4.981	0
	Density of points of interest (POI)	0.11	5.081	0
	Function mix	0.077	4.812	0
	Housing-employment mix	0.043	2.709	0.007
	Green land density	0.137	8.967	0
	Walkability	0.286	11.694	0
	Transferability in the station	0.063	3.942	0
Model 2 (Y= Online reviews)	Density of points of interest (POI)	0.212	8535	0
	Function mix	-0.076	-4.160	0
Model 3 (Y= Cycling records)	Building density	0.065	2.985	0.003
	Plot ratio	0.113	5.045	0
	Road density	-0.04	-2.716	0.007
	Density of points of interest (POI)	0.422	22.917	0
	Housing-employment mix	0.035	2.598	0.009
	Walkability	0.172	8.283	0
	Transferability in the station	0.096	7.052	0
Model 4 (Y= Population flow volume)	Plot ratio	0.285	19.178	0
	Road density	0.029	3.022	0.003
	Density of points of interest (POI)	0.352	28.772	0
	Housing-employment mix	0.057	6.49	0
	Walkability	0.116	8.439	0
	Transferability in the station	0.175	19.244	0
	Transferability to transit buses	0.12	11.099	0
	Distance to CBD	-0.087	-8.022	0

4 Conclusion and Policy Recommendations

The main contributions of this paper are (1) proposing a framework for systematically assessing the relationship of transit-oriented development with urban vitality, (2) utilizing various vitality indicators to examine the connection between TOD application conditions and urban vitality, which is more comprehensive than using only a single indicator in existing research, and (3) conducting nationally large-scale analysis including multiple cities and a considerable number of stations, which are analyzed from both station level and city level. Thus, the relationship of transit-oriented development with urban vitality is revealed comprehensively and quantitatively. The results show that (1) TOD principles are significantly relevant to urban vitality in China, (2) stations closer to the city CBD, with denser roads, buildings, parks, and better walkability, are more vibrant, and (3) more complexity of functionalities will be detrimental to offline consumption activities.

The Center for Transit-Oriented Development [21] has proposed development principles for several forms of TOD and established related targets, such as the minimum and maximum thresholds for density and housing mix. The exploration of the relationship of the TOD principles application with urban vitality offers empirical evidence for the formulation of essential planning principles. Planners may utilize factors like the share of office area, restaurant density, and entertainment density to achieve the desired level of urban vitality throughout the day. Therefore, the results of this study can provide guidance for community planning and implications for cities seeking transit investment, transit-oriented development, and high urban vitality.

Acknowledgements

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