UvA-DARE (Digital Academic Repository)

Developing a TOD typology for Beijing metro station areas

Lyu, G.; Bertolini, L.; Pfeffer, K.

DOI

[10.1016/j.jtrangeo.2016.07.002](https://doi.org/10.1016/j.jtrangeo.2016.07.002)

Publication date

2016

Document Version

Final published version

Published in

Journal of Transport Geography

[Link to publication](#)

Citation for published version (APA):

Lyu, G., Bertolini, L., & Pfeffer, K. (2016). Developing a TOD typology for Beijing metro station areas. *Journal of Transport Geography*, 55, 40-50.
<https://doi.org/10.1016/j.jtrangeo.2016.07.002>

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <https://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

Developing a TOD typology for Beijing metro station areas

Guowei Lyu ^{*}, Luca Bertolini, Karin Pfeffer

University of Amsterdam, Department of Geography, Planning and International Development Studies, Amsterdam Institute of Social Science Research, PO Box 15629, 1001 NC Amsterdam, The Netherlands

ARTICLE INFO

Article history:

Received 19 April 2016

Received in revised form 3 July 2016

Accepted 5 July 2016

Available online 17 July 2016

Keywords:

Transit Oriented Development

Typology

Metro station areas

Node-place model

Beijing

ABSTRACT

Across the world, Transit Oriented Development (TOD) offers a strategy to integrate land use and transport systems by clustering urban developments around public transport nodes in functionally dense and diverse, pedestrian- and cycling-friendly areas. Even though the basic philosophy of TOD seems to be the same in all contexts, its specific applications greatly differ in form, function and impacts, calling for context-based TOD typologies that can help map these local specificities and better focus policy interventions. In recent years, TOD has also been widely advocated and applied in China; however, so far no study has systematically developed a TOD typology in a Chinese context. This paper fills this gap for the case of the Beijing metropolitan area. The approach is based on the node-place model, introduced by Bertolini (1996, 1999) to chart 'Transit' and 'Development' components, expanding it with a third, 'Oriented', dimension to quantify the degree of orientation of transit and development components towards each other. The paper reviewed the main TOD indicators in the international literature, selected those appropriate for the Beijing context, and classified the metro station areas into TOD types through a cluster analysis. The six identified types of metro station areas in Beijing demonstrate how the context-specific typology can support local urban and transport planners, designers and policymakers when considering future interventions.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Growing concern about the effects of rapid urban growth and increasing mobility has fueled a debate about planning strategies that can help manage development. One focus is on effective integration of land use and the transport system (Banister, 2008; Pan et al., 2011; Suzuki et al., 2013), with Transit Oriented Development (TOD) as a commonly followed approach. TOD advocates the clustering of urban developments around public transport nodes as well as creating areas with high urban density, diverse land use, and pedestrian- and cycling-friendly environments (Bertolini and Spit, 1998; Cervero, 1998; Cervero, 2004; Dittmar and Ohland, 2004). Even though the basic philosophy of TOD seems to be the same in all contexts, studies show large differences in the applications of TOD principles. For instance, in North America and Australia, the focus seems mostly on re-centering suburban sprawl around transit stops and networks (Cervero, 1998, 2004; Dittmar and Ohland, 2004; Hemsley, 2009); in Europe it seems rather on the redevelopment of existing station areas (Bertolini and Spit, 1998); in Asia, TOD seems to be seen above all as a strategy of channeling mega-city growth in mass rapid transit corridors (Zhang and Liu, 2007; Yang and Lew, 2009); in South America it seems

more often considered as a way of re-connecting and re-focusing around transit already dense urban developments (Lindau et al., 2010).

Context-based TOD typologies – aiming to both account for local differences and support policymakers, planners, developers and designers – have been developed based on the following assumptions. First, the similarities within one type could allow urban and transport planners and policymakers to develop more targeted sets of strategies to promote TOD (Renne and Wells, 2005; Reusser et al., 2008). Second, each type of station areas possesses a set of morphological characteristics (e.g. number of metro directions from metro station, street density within station area) and functional characteristics (e.g. functional composition/diversity of economic entities in a station area), which can help to answer planning and design operational questions (Belzer et al., 2002; Kamruzzaman et al., 2014). These might include questions such as how many commuters the area can support, whether jobs and residences should be relocated to make best use of the station, or whether the walkability of the area should be improved. Third, a classification enables local governments and developers to invest in each type of TOD to achieve a better overall leverage of benefits across the region (Center for Transit-Oriented Development, 2011). Fourth, a context-based typology might give policymakers a better understanding of the relationships between TOD and the area's urban problems, by analyzing the impacts of different types of TOD (Xie, 2012).

China is undergoing rapid and sustained urbanization, reaching 51.3% in 2011 (Pan and Xu, 2014). According to predictions, nearly 70% of the population will live in urban areas by 2035 (Heilig, 2012).

^{*} Corresponding author.

E-mail addresses: g.lyu@uva.nl (G. Lyu), l.bertolini@uva.nl (L. Bertolini), k.pfeffer@uva.nl (K. Pfeffer).

This growth is accompanied by many challenges that TOD can address, according to its advocates, such as increasing scarcity of available urban land (Xie, 2012; Suzuki et al., 2013), long commuting time (Wang and Chai, 2009; Clower et al., 2011), air pollution and increasing greenhouse gas emissions (Xie, 2012; Pan et al., 2013), and inequality of spatial accessibility (Cervero and Day, 2008). According to a number of studies (see Yang and Li, 2004; Wang et al., 2007; Zhang and Liu, 2007; Lu and Zhao, 2008), the implementation of TOD in the metropolises of China has been considered a potential solution for several years; however, no study has developed a systematic TOD typology in a Chinese context.

To address this important knowledge gap, the paper develops a TOD typology for the Chinese metropolitan context of Beijing. The capital region is one of the four main metropolises of China, with 21.5 million residents and 1385.6 km² urban built areas in 2014 (National Bureau of Statistics of China, 2015). Concerning the mode of transport, we focus on the metro system, the backbone of the public transport system. In 2014, the metro, with 18 lines, 268 stations and 527 km of track in operation, served 10 million passengers each workday in 11 of Beijing's 16 districts (Beijing Mass Transit Railway Operation Corporation Limited, 2015; Beijing Infrastructure Investment Corporation Limited, 2015). While Beijing is used as the case of application, the methodology – as discussed below – is innovative in several respects and of more general value, and is meant to be applicable also in other contexts, both in China and beyond.

The paper is structured as follows. Section 2 discusses the theoretical basis, namely the node-place model introduced by Bertolini (1996, 1999), and our interpretations and modifications. Section 3 presents a systematic approach to classifying metro station areas in Beijing, detailing the TOD indicators and their selection, the data used, and the classification methods. Section 4 discusses the classification results, in particular the six TOD types. In Section 5, we draw conclusions, reflect on the limitations of the study, and provide direction for future research efforts.

2. Theoretical background

The essence of a TOD classification is the grouping of station areas that have a common set of morphological and functional characteristics. One approach is to qualitatively label and describe types of TOD. For example, in his pioneering book Calthorpe (1993: p57) distinguishes between 'urban TOD' and 'neighbourhood TOD', based on the main spatial orientation of the functions in the area. However, quantitative approaches are increasingly preferred by planners and researchers alike, because they provide testable expressions and support more systematic analyses and comparisons (Bertolini, 1999; Reusser et al., 2008; Cervero and Murakami, 2009; Shastry, 2010; Zemp et al., 2011; Atkinson-Palombo and Kuby, 2011; Center for Transit-Oriented Development, 2011, 2013; Ivan et al., 2012; Song and Deguchi, 2013; Pollack et al., 2014; Kamruzzaman et al., 2014; Singh et al., 2014; Monajem and Nosratan, 2015; Vale, 2015). In this research, we opted for the quantitative approach based on a modified node-place model, introduced by Bertolini (1996, 1999).

2.1. The node-place model

The node-place model is a frequently cited and applied approach in TOD typology studies across the world. The model provides an analytical framework to describe transport ('node') and urban development ('place'), characteristics of a location and their relationships (see Fig. 1). Examples of applications include the original Amsterdam and Utrecht region in the Netherlands (Bertolini, 1999), station areas in Switzerland (Reusser et al., 2008; Zemp et al., 2011), Tokyo in Japan (Chorus and Bertolini, 2011), Ostrava in the Czech Republic (Ivan et al., 2012), Brisbane in Australia (Kamruzzaman et al., 2014), Lisbon in Portugal (Vale, 2015), and Tehran in Iran (Monajem and Nosratan, 2015). While they all share the conceptual basis and original reference,

Fig. 1. The node-place model and five ideal-typical situations for a location. Source: (Bertolini, 1999).

they have all made own adaptations in the operationalization of the variables, depending on specific purpose, data availability, and contextual aspects.

The basic idea underlying the model is that – in line with thinking informing the transport land use feedback cycle – improving transport provision in a location (or its node-value) will, because of improved accessibility, create conditions favorable to the further intensification and diversification of land uses there. In its turn, intensification and diversification of land uses in a location (or increase in its place-value) will, because of growth in the demand for connections, create conditions favorable to the further development of infrastructure there.

[(Bertolini, 2005: p111–p112)]

Bertolini distinguishes five ideal typical situations in the node-place model (Bertolini, 1999, 2005; see Fig. 1). Along the middle diagonal line are areas in 'Balance' where the node and the place values are equally strong, indicating that the development potential of both has been realized. At the upper right corner of the line are areas under 'Stress', which indicates that the potential for land use development is highest (strong node) and that it has been realized (strong place). The same can be said about the potential for transport development. However, competition for scarce space between node and place functions also produces tensions. At the bottom of the middle line are areas characterized by 'Dependency'. There is no tension here, but demand for both land use and transport development is insufficient to generate an autonomous development dynamics. Areas where transportation facilities are more developed than urban activities are labeled 'Unsustained Nodes' (upper left area of Fig. 1). Conversely, in 'Unsustained Places', at the bottom right of Fig. 1, urban activities are much more developed than transportation facilities. The latter two are the situations where the most development dynamics is to be expected, either positive (upgrading) or negative (downgrading).

2.2. Additional dimension 'oriented' and the extended node-place model

The node-place model provides an analytical framework to investigate conditions for transport and urban development in a location, i.e. the interaction between the 'Transit' (T) and the 'Development' (D) components of TOD, but cannot reveal the degree to which transport and urban conditions are functionally and morphologically interrelated. For instance, despite a very high node and place index of a location, the functional interrelation could be weak if the distribution of densities and uses do not gravitate towards the station. Likewise, the morphological interrelation could be weak if the street network does not facilitate walking and cycling connections between the area and

the station. Such a location might be regarded as a 'Transit Adjacent Development' (TAD), where transport and land use features (e.g. a public transport stop and built up density) are consistent, but they are not functionally and morphologically interrelated (Renne, 2009). Thus, one possible enhancement of the node-place model is to add an evaluation of these functional and morphological interrelations.

Vale (2015) has done a pioneer study along such lines by combining the node-place model with a pedestrian shed ratio (highlighting morphological interrelations) to evaluate and classify station areas in Lisbon. With reference to the notion of 'Transit-Oriented-Development' (TOD) and building on the work of Vale (2015), we call these interrelations as the 'Oriented' (O) characteristics of a station area. We assume that the oriented characteristics of a station area do not only directly encourage more transit use and further intensification and diversification of urban development, but also create local conditions favorable to strengthen the realization of the transport land use feedback cycle (Wegener and Fürst, 1999; Wegener, 2004). The 'Oriented' dimension amounts to a third axis orthogonal with the 'Transit' and 'Development' dimensions in an extended node-place model. Concretely, and considering the specific features of the 'Oriented' dimension that can be intervened upon by policymakers, urban planners or designers, this paper focuses on the characteristics of functional proximity of functional entities to the transit node and a pedestrian or cyclist friendly built environment in the station area. Below we discuss how we developed and applied this extended model in the case of Beijing.

3. Methodology

To develop and implement our extended node-place model, we first assembled 'Transit', 'Oriented', and 'Development' indicators from the international TOD literature. Second, based on filtering by means of local knowledge, literature citation, distinctiveness, and public availability of data, we selected a set of indicators. Third, we geographically delineated TOD areas and measured the selected indicators. Fourth, we applied a multi-step procedure to identify distinct types of metro station areas, consisting of the following steps:

- (1) Standardize the indicators with different measurement scales (Suarez-Alvarez et al., 2012);
- (2) Apply principal component analysis (PCA) to generate seven uncorrelated variables. PCA is a multivariate technique that can extract the relevant information from inter-correlated quantitative dependent variables and represent them as a set of new orthogonal variables called principal components (Jolliffe, 2002). Specifically, it has the capacity to separate 'signal' and 'noise'. In our case, the first 7 components (out of a total of 18) encompass 87.1% of all the variance – the 'signal' – while the remaining ones we have considered 'noise' (Jolliffe, 2002; Husson et al., 2010; Song and Deguchi, 2013).
- (3) Apply hierarchical cluster analysis following the Ward method (Ward, 1963) to the scores of the seven principal component in order to build up a cluster tree of cases based on their dissimilarities (the squared Euclidean distances between observations);
- (4) Use the Duda Test to define the optimal number of clusters (Duda and Hart, 1973). This is done because the decision on the optimal number of clusters is a constantly recurring problem that cannot be automatically addressed in a hierarchical cluster analysis.

3.1. TOD indicators and their selection

Numerous studies have proposed or used various indicators to measure TOD characteristics in different geographical contexts (see Bertolini, 1999; Dittmar and Ohland, 2004; Reusser et al., 2008; Cervero and Murakami, 2009; Shastry, 2010; Chorus and Bertolini, 2011; Zemp et al., 2011; Atkinson-Palombo and Kuby, 2011; Center for

Transit-Oriented Development, 2011; Ivan et al., 2012; Center for Transit-Oriented Development, 2013; Song and Deguchi, 2013; Kamruzzaman et al., 2014; Pollack et al., 2014; Singh et al., 2014; Monajem and Nosratian, 2015; Vale, 2015). Based on a systematic review of these studies, we have identified 94 indicators (see Appendix A for the full list and sources), of which 24 focus on the 'Transit' aspect (T_n , n = ID number of indicator), 53 on the 'Development' aspect (D_n), and 17 on the 'Oriented' aspect (O_n).

Next, in order to build a scientifically and locally relevant list of indicators from the original 94, we combined two filters. Through an online survey, we collected the opinions of local experts on the relative importance of the 94 TOD indicators for the case of Beijing. In total, 15 local experts completed the survey: six researchers (two in transport geography, one in economic geography, one in human geography, one in information technology, and one in urban planning), five urban/land use planners, one transport planner, one consultant (on urban planning and design), one property developer and one educator (on urban studies). All of them used to work or still work on TOD-related projects in the Chinese context, either in research or practice, with a relevant work experience ranging from 1 to 32 years, with an average of 10 years. A second filter was provided by ranking the indicators based on the frequency of their occurrence in the international TOD literature. The final indicators were selected based on the following rules:

- (1) For each of the three TOD dimensions, indicators elected in the top five by both local experts and international studies should be selected first.
- (2) The remaining indicators in the top five of both rankings should be selected according to their ranked place.
- (3) When indicators describe similar characteristics of a location, the lower scoring ones should be removed from the final selection (see details below).
- (4) Indicators should be measurable with publicly accessible data (allowing for transparency and applicability in other contexts).
- (5) Each TOD dimension should have the same number of indicators.

Table 1 shows the results of the ranking by local experts and the international studies, data availability, and the final selection. With reference to rule 3, T13 (Geographic distance to CBD) and T15 (Travel times to major employment and activity centres by Metro) were considered measuring a similar characteristic: accessibility to main centre. The same applies to T11 (Number of stations within 45 min of travel by Metro) and T12 (Number of stations within 20 min of travel by metro). T15 and T12 were chosen because of their higher ranking. T8, T6, T21, T16, T20, D30, D2, D19, D12, D36, D25, O3, O4, and O5 (see Appendix A for their definition) were dropped due to lack of publicly available data (T8 and D30 scored in the top five among both local experts and the international literature).

3.2. TOD areas and description of data set for classification

Previous studies delineated TOD precincts according to geographical distances from the transit stop. Specifically, most European researchers (e.g. Bertolini, 1999; Reusser et al., 2008; Zemp et al., 2011; Vale, 2015) proposed a 700 m Euclidian distance from the transit stop as the boundary for TOD precincts, while most American studies used a range between 1/4 mile (400 m) and 1/2 mile (800 m) (e.g. Atkinson-Palombo and Kuby, 2011; Austin et al., 2010; Schlossberg and Brown, 2004). The European and American case studies show that most of the TOD radii use a 10-minute walking distance from the station (assuming walking is the main station access and egress mode, and 10 min is an acceptable walking time). Following a similar logic, we selected a 700 m Euclidian distance from metro stations as the border of TOD precincts in Beijing.

Table 1
Selection of TOD indicators^a, rankings^b, and data availability^c.

Indicator	Rank	Local experts	International studies	Final selection
Transit	1	T1	T5	T1, T5, T12, T2, T15, T19,
	2	T5	T1 , T2, T6	
	3	<u>T15</u>	<u>T19</u>	
	4	T12	T12 , T13, T21	
	5	T8	T8 , <u>T11</u> , T16, T20	
Development	1	D1	D1	D1, D29, D7, D9, D10, D11
	2	D2, D19	D9, D12	
	3	D29	D7 , <u>D10</u> , <u>D11</u>	
	4	D7, D30, D36	D29	
	5	D25	D30	
Oriented	1	O1	O9, O12	O14, O1, O9, O12, O2, O17
	2	<u>O2</u>	O3, O4, O14	
	3	<u>O17</u>	All other indicators	
	4	O5		
	5	O14		

Indicator description^a:

T1: Number of directions served by Metro, T2: Number of directions served by bus, T5: Daily frequency of Metro services, T6: Number of other public transport modes (Bus, Tram) departing on a working day, T8: Number of passengers per day by Metro, T11: Number of stations within 45 min of travel by Metro, T12: Number of stations within 20 min of travel by metro, T13: Geographic distance to CBD, T15: Travel times to major employment and activity centres by Metro, T16: The percentage of private housing, T19: Car parking capacity, T20: Bicycle Parking capacity, T21: Distance to the closest motorway access by car.

D1: Number of residents, D2: Percentage of working-age population, D7: Number of jobs, D9: Number of workers in retail/hotel and catering, D10: Number of workers in education/health/culture, D11: Number of workers in public administration and services, D12: Number of workers in industry, D19: Floor area ratio, D25: Number of public facilities, D29: Degree of functional mix, D30: Land-use Mix, D36: Percentage of TOD-compatible land use.

O1: Average distance from station to jobs, O2: Average distance from station to residents, O3: Percentage of housing units owner-occupied, O4: Percentage of households with access to one or more private vehicles, O5: Percentage workers who use non-automobile commuting, O9: Length of paved foot-path per acre, O12: Intersection density, O14: Average block size, O17: Walk Scores

^a See Appendix A for the descriptions of the TOD indicators and their literature sources.

^b The indicators in bold are those both selected by local experts and the international TOD literature; among them, only **T8** and **D30** (in italics) cannot be measured due to a lack of publicly available data.

^c The indicators that can be measured by publicly available data are underlined.

We identified 268 metro station areas in Beijing based on the metro map (see Table 2 for the indicators and the data sources used). We used two types of data: (1) spatial data, i.e. the street network data downloaded from the OpenStreetMap website (Geofabrik GmbH and OpenStreetMap Contributors, 2015) and the point of interest data grabbed by a web crawler through Baidu Maps Place API (Baidu, Inc., 2015); and (2) quantitative attribute data of each station area, i.e. transit information downloaded from the website of Beijing Mass Transit Railway Operation Corporation Limited (2015), or calculated by Google distance API, or downloaded from Google Route Planner; census data on neighbourhood scale in 2010 in Beijing, and walkability evaluation score of each station area downloaded from the website of Walk Score® (Front Seat Management, 2015). The resultant data matrix consisted of 268 rows, one for each metro station area, and 18 columns, one for each indicator.

3.3. Producing clusters of metro station areas

3.3.1. Reorganization of the dataset

Prior to producing a categorization of metro station areas, a correlation analysis was conducted among the 18 TOD indicators to explore their relationships. The analysis showed that all relationships followed the expected directions according to the logic of the extended node-place model (see Section 2 and Fig. 2). Almost all indicators are positively correlated (with the exception of T15, O1 and O2). T15 describes the temporal proximity to major employment or activity centres: the shorter the travel time, the higher the proximity. O1 and O2 measure the centrality of transit stops relative to the distribution of functions within the TOD precinct: the shorter the distances, the higher the centrality. Therefore, these indicators need to be standardized in a different way than the positively correlated ones. Following Suarez-Alvarez et al. (2012), all indicators beside T15, O1, and O2 were rescaled to have a minimum value of 0 and a maximum of 1 using the formula

$$X_{\text{index}} = (X - \text{Min}(X)) / (\text{Max}(X) - \text{Min}(X)) \quad (1)$$

where X_{index} is the rescaled index of indicator X , $\text{Max}(X)$ is the maximum value of indicator X , and $\text{Min}(X)$ is the minimum value of indicator X .

The inversely correlated T15, O1, and O2 were rescaled to a minimum value of 0 and a maximum of 1 using the formula

$$X_{\text{index}} = (\text{Max}(X) - X) / (\text{Max}(X) - \text{Min}(X)) \quad (2)$$

The correlation analysis also indicated overlap between indicators. In order to extract the main linearly uncorrelated variables of station areas, we performed a principal component analysis. The first seven components, explaining 87.1% (>85%) of the variance of all variables, were used to substitute the original dataset of 18 indicators.

3.3.2. Classification of metro station areas

The new dataset consisted of 268 rows, one for each station area, and seven columns, one for each principal component. To obtain classes of station areas with minimal variance within classes and maximal variance between classes (Ward, 1963), a hierarchical cluster analysis with Ward method was applied. While hierarchical cluster analysis builds a hierarchy of clusters based on dissimilarity (the squared Euclidean distance between samples), it cannot determine how many clusters should be present. Therefore, we used the Duda Test to decide whether or not to split or merge clusters (Duda and Hart, 1973: p45–p47). The criterion index of the Duda Test is calculated as:

$$\text{Duda} = \frac{Je(2)}{Je(1)} = \frac{W_k + W_l}{W_m} \quad (3)$$

where $Je(2)$ is the sum of squared errors ($W_k + W_l$) within clusters when the data are partitioned into two clusters (C_k and C_l),

Table 2
Overview of dataset of metro station area.

Indicator	Measurement	Data source
T1 Number of directions served by Metro	Count on Metro Operational Map	http://www.bjsubway.com/subwaymap/station_map.html - accessed on 21st Aug., 2015
T2 Number of directions served by bus	Count on Metro station area profile	http://www.bjsubway.com/station/xltcx/ - accessed on 21st Aug., 2015
T5 Daily frequency of Metro services	Count on Google Route Planner	https://www.google.nl/maps/@39.9390731,116.1172794,10z?hl=en - accessed on Fri., 21st Aug., 2015
T12 Number of stations within 20 min of travel by metro	Calculate the travel duration between each metro station by metro through Google distance API and then count for each station the number of stations reached within 20 min	https://www.google.nl/maps/@39.9390731,116.1172794,10z?hl=en and Google distance API - accessed on Thu., 13th Aug., 2015
T15 Travel times to major employment and activity centres by Metro (seconds)	Average travel time to Top 10 employment most dense poles in Beijing; these were found by counting the number of jobs within the buffer of 1500 m ^a from the metro station; travel time is calculated by Google distance API	http://map.baidu.com/ and grabbed all the Point of Interest in Beijing City - accessed on 19th Aug., 2015; https://www.google.nl/maps/@39.9390731,116.1172794,10z?hl=en and Google distance API - accessed on Thu., 13th Aug., 2015
T19 Car parking capacity	Count number of car parking lots in a station area	http://map.baidu.com/ and grabbed all the Point of Interest in Beijing City - accessed on 19th Aug., 2015;
D1 Number of residents (Persons)	Count the residents in a station area by calculating the population based on census data and overlapping it with the station area	The census data is as of 2010 at neighbourhood scale in Beijing and the location of station is derived from http://map.baidu.com/ and grabbed all the Point of Interest in Beijing City - accessed on 19th Aug., 2015
D7 Number of jobs	Count the number of employment establishments in a station area	http://map.baidu.com/ and grabbed all the Point of Interest in Beijing City - accessed on 19th Aug., 2015
D9 Number of workers in retail/hotel and catering (Person)	Count the number of establishments in retail/hotel and catering in a station area	http://map.baidu.com/ and grabbed all the Point of Interest in Beijing City - accessed on 19th Aug., 2015
D10 Number of workers in education/health/culture (Persons)	Count the number of establishments in education/health/culture in a station area	http://map.baidu.com/ and grabbed all the Point of Interest in Beijing City - accessed on 19th Aug., 2015
D11 Number of workers in public administration and services (Persons)	Count the number of establishments in public administration and services in a station area	http://map.baidu.com/ and grabbed all the Point of Interest in Beijing City - accessed on 19th Aug., 2015
D29 Degree of functional mix ^b	Calculate on the basis of numbers of establishments in different sectors (D_9 , D_{10} , D_{11}), and housing in a station area; and let $D_{29} = 1 - \frac{(a-b)-(a-b)}{2}$	http://map.baidu.com/ and grabbed all the Point of Interest in Beijing City - accessed on 19th Aug., 2015 with $a = \max(D_9, D_{10}, D_{11}, D_{housing})$ $b = \min(D_9, D_{10}, D_{11}, D_{housing})$ $c = \text{average}(D_9, D_{10}, D_{11}, D_{housing})$ $d = \text{sum}(D_9, D_{10}, D_{11}, D_{housing})$
O1 Average distance from station to jobs (Meters)	Calculate the average distance between station and all entities of economic activity in a buffer area of 1500 m ^a from metro station	http://map.baidu.com/ and grabbed all the Point of Interest in Beijing City - accessed on 19th Aug., 2015
O2 Average distance from station to residents (Meters)	Calculate the average distance between station and housing entities in a buffer area of 1500 m ^a from metro station	http://map.baidu.com/ and grabbed all the Point of Interest in Beijing City - accessed on 19th Aug., 2015
O9 Length of paved foot-path per acre (Meters)	Calculate the total length of sidewalks in a station area based on the open street map of Beijing	Openstreetmap (OSM) data: http://download.geofabrik.de/asia/china - accessed on 8th Sep., 2015
O12 Intersection density (number of points)	Count the total number of intersections in a station area	OSM data: http://download.geofabrik.de/asia/china - accessed on 8th Sep., 2015
O14 Average block size (Meters)	Calculate the total length of the street network in a station area based on the open street map of Beijing	OSM data: http://download.geofabrik.de/asia/china - accessed on 8th Sep., 2015
O17 Walk Scores (It is calculated based on distance to various categories of amenities)	Download the walk score of each station area from the website	https://www.walkscore.com/ - accessed on 14th Sep., 2015

^a In a few cases (10 out of 268) there are no residents/economic entities located in 700 m buffer areas of metro stations. The reason is that these stations are located in the outskirts of urban areas or in as yet undeveloped areas (for example, the metro station of Gonghuacheng is surrounded by a forest). As the result, we cannot compute the average distances from station to jobs (O1) and residents (O2). Therefore, for all the cases, when calculating O1 and O2, we extended the calculating zone to a 1500 m buffer area. A 1500 m buffer area from a station is assumed to be a developmental area that might profit from the transit-connection (Schütz, 1998).

^b For this diversity formula, see also Bertolini, 1999; Reusser et al., 2008.

Fig. 2. Scatter plot of all station areas and the six clusters in the extended node-place model, representing the indexes for the 'Transit', 'Oriented', and 'Development' dimension from both a synthetic and three paired perspectives.

and $Je(1)$ gives the squared errors (W_m) when only one cluster (C_m) is present. It is assumed that clusters C_k and C_l are merged to form C_m (k, l, m are labels). The optimal number of clusters ('the presence of natural groupings' in Duda and Hart, 1973: p46) is the smallest q (number of cluster) such that

$$\text{Duda} \geq 1 - \frac{2}{\pi p} - z \sqrt{\frac{2 \left(1 - \frac{8}{\pi^2 p}\right)}{n_m p}} = \text{critValue_Duda} \quad (4)$$

where p is the number of variables; n_m is the number of objects (station areas) in cluster C_m ; and z is a standard normal score (Gordon, 1999). Several values for the standard score were tested and the best results were obtained when the value was set to 3.2 (Milligan and Cooper, 1985). The smallest number of six was found as the optimum, when $\text{Duda_value} = 0.7489 \geq \text{critValue_Duda} = 0.7195$ (calculated by software package NbClust in R programming, see Charrad et al., 2014). The values for the six resulting clusters of metro station areas are presented in Table 3 and Fig. 2.

4. Results and discussion

4.1. Six types of metro station areas

Of the six clusters (see Table 3, Figs. 2, and 3), C2 ($N = 23$), located in the periphery of the urban area and on the fingers of the metro system (see Fig. 3), comprises the station areas with the lowest scores on the T, O, and D aspects. Compared to C2, C1 ($N = 72$) scores higher on distance to jobs and residences (closer to the station), functional density and diversity (higher).

The station areas in C4 ($N = 55$) are located in the periphery of the core urban districts or on the outer palm of the metro system. The scores of their TOD indicators are slightly lower than average, but functional mix is on the highest level. The station areas in C3 ($N = 22$) have similar 'Transit' characteristic as those in C4, but higher values on the 'Development' dimension, their jobs and residence are located closer to the stations, and they have higher walk scores.

The station areas in C5 ($N = 33$) and C6 ($N = 63$) are located in the core urban districts and on the inner palm of the metro system. Although both score high on all TOD indicators, there are some notable differences. The 'Oriented' scores in C6 are highest among all clusters

suggesting that these areas are the most walkable, with the highest clustering of jobs and residences around stations. Furthermore, the urban development density in C6 is much higher than in C5. On the other hand, station areas in C5 show higher 'Transit' scores, also visualized in Fig. 3 by most of them being transfer stations.

4.2. Some potential uses of the TOD typology

The TOD typology of station areas in Beijing can be useful in several ways. The internally similar but externally distinctive characteristics of station areas in a cluster may allow urban planners, designers and policymakers to develop a set of targeted strategies for that cluster. For instance, the station areas in C4 are characterized by average levels of urban density and walkability, but show the highest level of urban function mix. For station areas in C4, strategies to promote TOD could therefore focus on increasing density and improving walkability to match their already high mix. The characteristics of station areas in C3 suggest a different set of strategies. Their urban density is relatively high, but their transportation supply is relatively low, suggesting that improving the transit dimension is a more logical strategy to promote TOD there. A similar reasoning could be applied to other clusters. The TOD scores of individual station areas can help further fine-tune strategies to local specificities.

The TOD typology can also help understand how focusing investment in particular clusters might help achieve higher overall cost-to-benefit ratios. For example, investing in C5 instead of C6 areas may deliver more effective and efficient results, because the level of development in C5 is still low relative to its transportation supply (T is higher than D, see Table 3), with arguably much unexploited development potential. In C6 the potential is already exploited or even not matched by transportation supply (D is higher than T). Generally speaking, the logic of the node-place model (see Fig. 1 above and discussion) can help researchers and policymakers understand how cluster and local investments might be related to region- and network-wide opportunities, threats, and impacts.

The same logic applies to addressing other urban development challenges, including those highlighted in the introduction. Rather than only distinguishing between the problem vs. solution tradeoffs of TOD locations relative to non-TOD locations, as found in much of the literature, a more precise distinction between the problem vs. solution tradeoffs between different TOD types can be made. For instance, station areas in some clusters might show a better capacity of addressing the challenge of scarcity of available urban land, of long commutes, of equitable access, suggesting that more of the cluster should be developed. More research is needed prior to drawing any policy implication.

5. Conclusion

The aim of the research was to develop a TOD typology in the metropolitan context of China, and specifically for metro station areas in Beijing. Next to analyzing a hitherto understudied context, we also aimed at building upon and improving existing methodologies with an eye at a wider applicability of the approach. In particular, we extended the node-place model focus on the 'Transit' and 'Development' dimension, adding the third, new dimension 'Oriented' to represent the functional and morphological interrelation between the first two. And indeed we find positive relationships among 'Transit', 'Oriented' and 'Development' dimensions. By assembling indicators from the international TOD literature, selecting a set of indicators for the case-specific context, performing a cluster analysis and determining optimal cluster number, we have developed a flexible and systematic classification methodology that can be adjusted to different geographic contexts. We identified six distinctive types of station areas in Beijing and provided speculative examples of how the classification could support urban planners, designers and policymakers to develop more targeted TOD strategies. This potential value of the TOD typology to support planning is a key area where further research should be concentrated.

Table 3

Cluster description and summary means on rescaled TOD indicators^a and the T, D, and O index^b.

Rescaled	C1 (N = 72)	C2 (N = 23)	C3 (N = 22)	C4 (N = 55)	C5 (N = 33)	C6 (N = 63)	All (N = 268)
T1	0.222	0.217	0.284	0.250	0.750	0.250	0.304
T2	0.136	0.055	0.348	0.191	0.258	0.277	0.206
T5	0.180	0.120	0.280	0.280	0.604	0.249	0.272
T12	0.137	0.067	0.202	0.314	0.591	0.444	0.301
T15	0.553	0.414	0.683	0.842	0.920	0.910	0.740
T19	0.078	0.024	0.258	0.240	0.462	0.463	0.259
D1	0.162	0.058	0.259	0.381	0.518	0.585	0.349
D7	0.189	0.048	0.531	0.266	0.482	0.557	0.343
D9	0.199	0.045	0.572	0.209	0.351	0.434	0.292
D10	0.101	0.015	0.342	0.225	0.408	0.520	0.275
D11	0.156	0.037	0.394	0.273	0.505	0.616	0.340
D29	0.459	0.131	0.564	0.650	0.588	0.560	0.518
O1	0.336	0.172	0.440	0.245	0.274	0.320	0.300
O2	0.586	0.246	0.610	0.498	0.521	0.540	0.522
O9	0.131	0.101	0.229	0.250	0.382	0.450	0.267
O12	0.093	0.056	0.152	0.170	0.311	0.381	0.205
O14	0.249	0.186	0.362	0.357	0.508	0.570	0.382
O17	0.530	0.208	0.769	0.729	0.833	0.861	0.678
T_Index	0.217	0.150	0.343	0.353	0.598	0.432	0.347
D_Index	0.211	0.056	0.444	0.334	0.475	0.545	0.353
O_Index	0.321	0.162	0.427	0.375	0.472	0.520	0.392

^a TOD indicators see Table 2 for descriptions.

^b T_Index, D_Index and O_Index are the average of T, D, and O rescaled indicators.

The study's findings are qualified by several limitations. First, even though local expert input was used to select the TOD indicators, the point of departure was still the set of indicators documented in the international TOD literature. No new, original, context-specific indicator was developed, which might still prove desirable. It might be that other, more open consultation approaches (e.g. Delphi) might produce a different results. Second, due to the lack of publicly available data, we could not measure some relevant indicators (i.e. T8 and D30), selected by both local experts and the international literature. While we have made our methodology as transparent and replicable as possible, the results are, however, dependent on the final selection of indicators, which might have suffered from knowledge (literature), bias (experts) and context (availability of local data) limitations. Awareness of these limitations is important when drawing conclusions. Third, we based our choice of a 700 m Euclidian distance metro station area on the assumption that the Beijing context does not differ significantly from those documented in the international literature in terms of determinants such as station access and egress modes, or acceptable travel times. However, this assumption should be verified. Finally, using a 'as the crow flies' buffer does not take into account physical barriers to walking, such as infrastructure or water, which may influence the effectively 'accessible' station area. These limitations might be addressed in further studies.

As for the next research steps, in order to investigate the context-specific capacity of TOD to address urban problems, the effects of different types of TOD on the built environment, the transportation system, and travel behavior should be examined. This will provide new knowledge on their capabilities of addressing the urgent urban development challenges in Beijing and other Chinese metropolises, such as scarcity of available urban land, inequality of spatial accessibility, or long commutes.

Funding acknowledgement

This work was supported by China Scholarship Council (CSC) [grant numbers 201406040059, year of 2014] and the Department of Geography, Planning and International Development Studies (GPIO)/Amsterdam Institute of Social Science Research (AISSR), University of Amsterdam (UvA).

Fig. 3. The classification of Metro station areas in Beijing City based on the cluster analysis of re-organized dataset for 268 metro station areas. (Source data: OSM data and data from own calculation based on input data in [Table 2](#))

Appendix A. TOD indicators and their sources

TOD indicator	Literature source
T1 Number of directions served by Metro	Bertolini (1999), Reusser et al. (2008), Chorus and Bertolini (2011), Zemp et al. (2011), Song and Deguchi (2013), Vale (2015)
T2 Number of directions served by bus	Bertolini (1999), Reusser et al. (2008), Chorus and Bertolini (2011), Zemp et al. (2011), Song and Deguchi (2013), Vale (2015)
T3 Number of metro stations in one TOD	Song and Deguchi (2013)
T4 Number of bus stops in one TOD	Song and Deguchi (2013)
T5 Daily frequency of Metro services	Bertolini (1999), Dittmar and Ohland (2004), Reusser et al. (2008), Center for Transit-Oriented Development (2011), Zemp et al. (2011), Song and Deguchi (2013), Monajem and Nosratan (2015), Vale (2015)
T6 Number of other public transport modes (Bus, Tram) departing on a working day	Bertolini (1999), Reusser et al. (2008), Center for Transit-Oriented Development (2011), Zemp et al. (2011), Ivan et al. (2012), Vale (2015)
T7 Public Transport Accessibility Level (It is calculated by schedule waiting time of bus and metro, and access (walk) time to stops/stations)	Kamruzzaman et al. (2014)
T8 Number of passengers per day by Metro	Reusser et al. (2008), Monajem and Nosratan (2015)
T9 Ratio of metro passengers on weekends to ones on weekdays	Zemp et al. (2011)
T10 Changing rate of Metro passengers in 10 years	Song and Deguchi (2013)
T11 Number of stations within 45 min of travel by Metro	Bertolini (1999), Monajem and Nosratan (2015)
T12 Number of stations within 20 min of travel by metro	Reusser et al. (2008), Zemp et al. (2011), Vale (2015)
T13 Geographic distance to CBD	Reusser et al. (2008), Chorus and Bertolini (2011), Monajem and Nosratan (2015)
T14 Travel time to CBD by Metro	Center for Transit-Oriented Development (2013)
T15 Travel times to major employment and activity centres by Metro	Center for Transit-Oriented Development (2013)
T16 Type of metro service (e.g. old, new, slow, rapid)	Reusser et al. (2008), Chorus and Bertolini (2011)
T17 Whether station connects to airport directly (no transfer)	Atkinson-Palombo and Kuby (2011)
T18 Whether station is a terminal	Atkinson-Palombo and Kuby (2011)
T19 Car parking capacity	Bertolini (1999), Atkinson-Palombo and Kuby (2011), Ivan et al. (2012), Vale (2015)
T20 Bicycle Parking capacity	Bertolini (1999), Atkinson-Palombo and Kuby (2011)
T21 Distance to the closest motorway access by car	Bertolini (1999), Reusser et al. (2008), Vale (2015)
T22 Number of free-standing bicycle paths (separated bicycle paths)	Bertolini (1999)
T23 Total bike path length within 2 km around metro station	Reusser et al. (2008)
T24 Number of staff in the station	Reusser et al. (2008)
D1 Number of residents	Bertolini (1999), Reusser et al. (2008), Shastry (2010), Atkinson-Palombo and Kuby (2011), Chorus and Bertolini (2011), Center for Transit-Oriented Development (2011), Zemp et al. (2011), Ivan et al. (2012), Center for Transit-Oriented Development (2013), Song and Deguchi (2013), Kamruzzaman et al. (2014), Singh et al. (2014), Monajem and Nosratan (2015), Vale (2015)
D2 Percentage of working-age population	Center for Transit-Oriented Development (2011), Center for Transit-Oriented Development (2013)
D3 Percentage of elderly population (above 65)	Song and Deguchi (2013)
D4 Changing rate of residential population in 10 years	Song and Deguchi (2013)
D5 Changing rate of working-age population in 10 years	Song and Deguchi (2013)
D6 Changing rate of elderly population (above 65) in 10 years	Song and Deguchi (2013)
D7 Number of jobs	Shastry (2010), Atkinson-Palombo and Kuby (2011), Zemp et al. (2011), Kamruzzaman et al. (2014), Pollack et al. (2014), Singh et al. (2014)
D8 Number of jobs per resident	Shastry (2010)
D9 Number of workers in retail/hotel and catering	Bertolini (1999), Reusser et al. (2008), Chorus and Bertolini (2011), Ivan et al. (2012), Singh et al. (2014), Monajem and Nosratan (2015), Vale (2015)
D10 Number of workers in education/health/culture	Bertolini (1999), Reusser et al. (2008), Chorus and Bertolini (2011), Ivan et al. (2012), Monajem and Nosratan (2015), Vale (2015)
D11 Number of workers in public administration and services	Bertolini (1999), Reusser et al. (2008), Chorus and Bertolini (2011), Ivan et al. (2012), Monajem and Nosratan (2015), Vale (2015)
D12 Number of workers in industry	Bertolini (1999), Reusser et al. (2008), Chorus and Bertolini (2011), Ivan et al. (2012), Singh et al. (2014), Monajem and Nosratan (2015), Vale (2015)
D13 Housing density (units/acre)	Dittmar and Ohland (2004), Pollack et al. (2014)
D14 Number of flats	Ivan et al. (2012)
D15 The percentage of public housing above 6 floor	Song and Deguchi (2013)
D16 The percentage of private housing	Song and Deguchi (2013)
D17 Total gross floor area of development	Cervero and Murakami (2009)
D18 Building floor area by use (residential, office, retail shopping, hotel/service apartments and other)	Cervero and Murakami (2009), Ivan et al. (2012)
D19 Floor area ratio	Cervero and Murakami (2009), Song and Deguchi (2013)
D20 Height of buildings	Cervero and Murakami (2009)
D21 The number of neighbourhood retail and service establishments	Center for Transit-Oriented Development (2011)
D22 The size of built-up area for housing and services	Ivan et al. (2012)
D23 Areas with commercial urban amenities	Shastry (2010), Center for Transit-Oriented Development (2013)
D24 Number of massive commercial facilities (above 1000 square meter in areas)	Song and Deguchi (2013)
D25 Number of public facilities	Reusser et al. (2008), Song and Deguchi (2013)
D26 Average real estate sales per square foot	Center for Transit-Oriented Development (2011), Center for Transit-Oriented Development (2013)
D27 Land prices per square meter	Ivan et al. (2012)
D28 Average residential rents	Center for Transit-Oriented Development (2013)
D29 Degree of functional mix (Calculated by numbers of workers from different economic sections and residents)	Bertolini (1999), Reusser et al. (2008), Chorus and Bertolini (2011), Monajem and Nosratan (2015), Vale (2015)
D30 Land-use Mix	Dittmar and Ohland (2004), Kamruzzaman et al. (2014), Singh et al. (2014)
D31 The proportion of similar adjacent land use types	Shastry (2010)
D32 Mixed-use attributes (Building floor area Mix)	Cervero and Murakami (2009)

Appendix A (continued)

TOD indicator	Literature source
D33 Housing types (e.g. multifamily, single family, loft, town-home)	Dittmar and Ohland (2004)
D34 Statistical dispersion of different income groups	Shastry (2010)
D35 Geographic position of station area (e.g. urban downtown, urban neighbourhood, suburban centre, suburban neighbourhood, commuter town centre)	Dittmar and Ohland (2004)
D36 Percentage of TOD-compatible land use (A parcel was defined as being TOD-compatible if it is neither residential nor vacant and its property use code would be allowed for future development in the overlay zoning ordinances)	Atkinson-Palombo and Kuby (2011)
D37 Percentage of TOD-incompatible land use (see the definition above (D36))	Atkinson-Palombo and Kuby (2011)
D38 Percentage of vacant land use	Atkinson-Palombo and Kuby (2011), Center for Transit-Oriented Development (2013)
D39 Areas of green or open space	Shastry (2010)
D40 Changing rate of public facility in 15 years	Song and Deguchi (2013)
D41 Changing rate of floor area ratio in 10 years	Song and Deguchi (2013)
D42 Changing rate of office jobs in 10 years	Song and Deguchi (2013)
D43 Qualitative rating of planning initiatives (e.g. station area planning or zoning)	Center for Transit-Oriented Development (2013)
D44 The Presence of a redevelopment authority	Center for Transit-Oriented Development (2013)
D45 Qualitative rating of recent development activity	Center for Transit-Oriented Development (2013)
D46 Qualitative rating of securing funding and financing for projects	Center for Transit-Oriented Development (2013)
D47 Private investment in the area	Singh et al. (2014)
D48 Percentage of people with bachelor's degree	Atkinson-Palombo and Kuby (2011)
D49 Household income	Atkinson-Palombo and Kuby (2011)
D50 Unemployment levels	Singh et al. (2014)
D51 Rate of unemployed with basic education	Ivan et al. (2012)
D52 Tax earnings of district	Singh et al. (2014)
D53 Arriving tourists per 1000 residents of the district	Zemp et al. (2011)
O1 Average distance from station to jobs	Zemp et al. (2011)
O2 Average distance from station to residents	Zemp et al. (2011)
O3 Percentage of housing units owner-occupied	Atkinson-Palombo and Kuby (2011), Pollack et al. (2014)
O4 Percentage of households with access to one or more private vehicles	Center for Transit-Oriented Development (2013), Pollack et al. (2014)
O5 Percentage workers who use non-automobile commuting	Pollack et al. (2014)
O6 Percentage of households with low income	Pollack et al. (2014)
O7 Percentage of income spent on transportation	Pollack et al. (2014)
O8 Walking time to a Metro Station from the centre of each block	Shastry (2010)
O9 Length of paved foot-path per acre	Shastry (2010), Pollack et al. (2014), Singh et al. (2014)
O10 Length of sidewalks and low-stress bike ways	Center for Transit-Oriented Development (2011)
O11 Number of cul-de-sac (dead end road)	Kamruzzaman et al. (2014)
O12 Intersection density	Shastry (2010), Kamruzzaman et al. (2014), Singh et al. (2014)
O13 Number of entry points into the neighbourhood	Shastry (2010)
O14 Average block size	Center for Transit-Oriented Development (2011), Center for Transit-Oriented Development (2013)
O15 Closeness index of urban street networks (space-syntax, network structure index)	Monajem and Nosrati (2015)
O16 Betweenness index of urban street networks (space-syntax, network structure index)	Monajem and Nosrati (2015)
O17 Walk Scores (It is calculated based on distance to various categories of amenities (e.g., schools, stores, parks and libraries) that are weighted equally and summed)	Pollack et al. (2014)

References

- Atkinson-Palombo, C., Kuby, M.J., 2011. The geography of advance transit-oriented development in metropolitan Phoenix, Arizona, 2000–2007. *J. Transp. Geogr.* 19 (2), 189–199.
- Austin, M., Belzer, D., Benedict, A., Esling, P., Haas, P., Miknaitis, G., Zimbabwe, S., 2010. *Performance-Based Transit-Oriented Development Typology Guidebook*.
- Baidu, Inc., 2015. Place API of Web Service API. <http://developer.baidu.com/map/index.php?title=webapi/guide/webservice-placeapi> (Accessed on Thu, 13th Aug 2015).
- Banister, D., 2008. The sustainable mobility paradigm. *Transp. Policy* 15 (2), 73–80.
- Beijing Infrastructure Investment Corporation Limited, 2015. The number daily metro passengers exceeds 10 million on workday in 2014 in Beijing. <http://www.bii.com.cn/705-2063-5114.aspx> (Accessed on 4th Feb, 2016).
- Beijing Mass Transit Railway Operation Corporation Limited, 2015. The profile of metro stations in Beijing. <http://www.bjsubway.com/station/xltcx/> (Accessed on 21st Aug, 2015).
- Belzer, D., Autler, G., Economics, S., 2002. *Transit Oriented Development: Moving From Rhetoric to Reality* (pp. 06–15). Brookings Institution Center on Urban and Metropolitan Policy, Washington, DC.
- Bertolini, L., 1996. Nodes and places: complexities of railway station redevelopment. *Eur. Plan. Stud.* 4 (3), 331–345.
- Bertolini, L., 1999. Spatial development patterns and public transport: the application of an analytical model in the Netherlands. *Plan. Pract. Res.* 14 (2), 199–210.
- Bertolini, L., 2005. Sustainable urban mobility, an evolutionary approach. *Eur. Spat. Res. Policy* 12 (1), 109–125.
- Bertolini, L., Spit, T., 1998. *Cities on Rails: The Redevelopment of Railway Station Areas*. Spon Press, London.
- Calthorpe, P., 1993. *Next American Metropolis*. Princeton Architectural Press, Princeton, p. p57.
- Center for Transit-Oriented Development, 2011. *Portland Metro TOD Program and TOD Strategic Plan Case Study*.
- Center for Transit-Oriented Development, 2013. *Transit-Oriented Development Typology Strategy for Allegheny County*.
- Cervero, R., 1998. *Transit Villages in California: Progress, Prospects, and Policy Reforms*. Institute of Urban and Regional Development, University of California, Berkeley.
- Cervero, R., 2004. *Transit-Oriented Development in the United States: Experiences, Challenges, and Prospects* (Vol. 102). Transportation Research Board.
- Cervero, R., Day, J., 2008. Suburbanization and transit-oriented development in China. *Transp. Policy* 15 (5), 315–323.
- Cervero, R., Murakami, J., 2009. Rail and property development in Hong Kong: experiences and extensions. *Urban Stud.* 46 (10), 2019–2043.
- Charrad, M., Ghazzali, N., Boiteau, V., Niknafs, A., 2014. NbClust: an R package for determining the relevant number of clusters in a data set. *J. Stat. Softw.* 61 (6), 1–36.
- Chorus, P., Bertolini, L., 2011. An application of the node place model to explore the spatial development dynamics of station areas in Tokyo. *J. Trans. Land Use* 4 (1), 45–58.
- Clower, T.L., Ruggiere, P., Bomba, M., Arndt, J.C., Li, J., Edrington, S., Hendershot, P., 2011. *Evaluating the Impact of Transit-Oriented Development* (No. FHWA/TX-10/0-6511-1).
- Dittmar, H., Ohland, G. (Eds.), 2004. *The New Transit Town: Best Practices in Transit-Oriented Development*. Island Press.
- Duda, R.O., Hart, P.E., 1973. *Pattern Classification and Scene Analysis*. J. Wiley and Sons, pp. 45–47.
- Front Seat Management, 2015. Walk score®. <https://www.walkscore.com> (Accessed on 14th Sep, 2015).
- Geofabrik GmbH, OpenStreetMap Contributors, 2015. Download OpenStreetMap data for this region: China. <http://download.geofabrik.de/asia/china.html> (Accessed on 8th Sep, 2015).
- Gordon, A.D., 1999. *Classification*. second ed. Chapman & Hall/CRC, London.
- Heilig, G.K., 2012. *World Urbanization Prospects the 2011 Revision*. United Nations, Department of Economic and Social Affairs (DESA), Population Division, Population Estimates and Projections Section, New York.

- Hemsley, W., 2009. The commercial reality of TOD in Australia. In: Curtis, C., Renne, J.L., Bertolini, L. (Eds.), *Transit Oriented Development: Making it Happen*. Ashgate Publishing, Ltd, pp. 201–208.
- Husson, F., Josse, J., Pages, J., 2010. Principal Component Methods-Hierarchical Clustering-Partitional Clustering: Why Would We Need to Choose for Visualizing Data. Applied Mathematics Department.
- Ivan, I., Boruta, T., Horák, J., 2012. Evaluation of railway surrounding areas: the case of Ostrava city. *Urban Transport XVIII-Urban Transport and the Environment in the 21st Century*, pp. 141–152.
- Jolliffe, I., 2002. *Principal Component Analysis*. John Wiley & Sons, Ltd.
- Kamruzzaman, M., Baker, D., Washington, S., Turrell, G., 2014. Advance transit oriented development typology: case study in Brisbane, Australia. *J. Transp. Geogr.* 34, 54–70.
- Lindau, L.A., Hidalgo, D., Facchini, D., 2010. Curitiba, the cradle of bus rapid transit. *Built Environ.* 36 (3), 274–282.
- Lu, H.P., Zhao, J., 2008. Study on TOD planning methodology for Chinese cities. *Highw. Eng.* 33 (6), 64–68 (陆化普, 赵晶, 2008. 适合中国城市的 TOD 规划方法研究. 公路工程, 33(6): 64–68).
- Milligan, G.W., Cooper, M.C., 1985. An examination of procedures for determining the number of clusters in a data set. *Psychometrika* 50 (2), 159–179.
- Monajem, S., Nosrati, F.E., 2015. The evaluation of the spatial integration of station areas via the node place model; an application to subway station areas in Tehran. *Transp. Res. Part D: Transp. Environ.* 40, 14–27.
- National Bureau of Statistics of China, 2015. *China Statistical Yearbook*. China Statistics Press, Beijing.
- Pan, H., Shen, Q., Liu, C., 2011. Transit oriented development at urban periphery: insights from a case study in Shanghai, China. *Transp. Res. Rec.* 224, 95–102.
- Pan, H., Shen, Q., Zhao, T., 2013. Travel and car ownership of residents near new suburban metro stations in Shanghai, China. *Transp. Res. Rec.: J. Transp. Res. Board* 2394 (1), 63–69.
- Pan, H., Xu, R.F., 2014. An empirical study on the factors of Chinese urbanization process and policy proposals about the “new-type” urbanization. *Open J. Soc. Sci.* 2, 12–17.
- Pollack, S., Gartsman, A., Boston, M., Benedict, A., Wood, J., 2014. Rating the performance of station areas for effective and equitable transit oriented development. *Transportation Research Board 93rd Annual Meeting* (No. 14-0392).
- Renne, J.L., Wells, J.S., 2005. *Transit-Oriented Development: Developing a Strategy to Measure Success* (No. 294). Transportation Research Board.
- Renne, J.L., 2009. From transit-adjacent to transit-oriented development. *Local Environ.* 14 (1), 1–15.
- Reusser, D.E., Loukopoulou, P., Stauffacher, M., Scholz, R.W., 2008. Classifying railway stations for sustainable transitions—balancing node and place functions. *J. Transp. Geogr.* 16 (3), 191–202.
- Schlossberg, M., Brown, N., 2004. Comparing transit-oriented development sites by walkability indicators. *Transp. Res. Rec.: J. Transp. Res. Board* 1887 (1), 34–42.
- Schütz, E., 1998. *Stadtentwicklung durch Hochgeschwindigkeitsverkehr* (Urban development by high-speed traffic). Heft 6, 369–383.
- Shastri, S., 2010. *Spatial Assessment of Transit Oriented Development in Ahmedabad, India* (Master Thesis) University of Twente.
- Singh, Y.J., Fard, P., Zuidgeest, M., Brussel, M., van Maarseveen, M., 2014. Measuring transit oriented development: a spatial multi criteria assessment approach for the City Region Arnhem and Nijmegen. *J. Transp. Geogr.* 35, 130–143.
- Song, J., Deguchi, A., 2013. Evaluation and typology of railway station areas in a 30 km circumference surrounding Central Tokyo from view of transit-oriented development. *J. Archit. Plann. (Trans. AIJ)* 78 (684), 413–420 (宋俊煥, & 出口敦, (2013). TOD の観点からみた東京 30 km 圏の鉄道駅周辺地区の評価と類型. 日本建築学会計画系論文集, 78(684), 413–420.).
- Suarez-Alvarez, M.M., Pham, D.T., Prostov, M.Y., Prostov, Y.I., 2012. Statistical approach to normalization of feature vectors and clustering of mixed datasets. *Proc. R. Soc. A* 468, 2630–2651.
- Suzuki, H., Cervero, R., Iuchi, K., 2013. *Transforming Cities with Transit: Transit and Land-Use Integration for Sustainable Urban Development*. World Bank Publications.
- Vale, D.S., 2015. Transit-oriented development, integration of land use and transport, and pedestrian accessibility: combining node-place model with pedestrian shed ratio to evaluate and classify station areas in Lisbon. *J. Transp. Geogr.* 45, 70–80.
- Wang, D., Chai, Y., 2009. The jobs–housing relationship and commuting in Beijing, China: the legacy of Danwei. *J. Transp. Geogr.* 17 (1), 30–38.
- Wang, J.E., Jin, F.J., Mo, H.H., et al., 2007. Analysis and review of transit oriented development. *Traffic Transp.* 12, 19–22 (王姣娥, 金凤君, 莫辉辉, 等, (2007). TOD 开发模式解析及研究述评, 交通与运输, 12, 19–22.).
- Ward Jr., J.H., 1963. Hierarchical grouping to optimize an objective function. *J. Am. Stat. Assoc.* 58 (301), 236–244.
- Wegener, M., 2004. Overview of land-use transport models. In: Hensher, D.A., Button, K. (Eds.), *Transport Geography and Spatial Systems*. Pergamon/Elsevier Science, Kidlington, UK.
- Wegener, M., Fürst, F., 1999. Land-use transport interaction: State of the art. Deliverable D2a of the project TRANSLAND (Integration of Transport and Land use Planning). *Berichte Aus Den Institut für Raumplanung*, p. q.
- Xie, L., 2012. Sustainability Implications of Mass Rapid Transit on the Built Environment and Human Travel Behavior in Suburban Neighborhoods: The Beijing Case. Arizona State University.
- Yang, P.P.-J., Lew, S.H., 2009. An Asian model of TOD: the planning integration in Singapore. In: Curtis, C., Renne, J.L., Bertolini, L. (Eds.), *Transit Oriented Development: Making it Happen*. Ashgate Publishing, Ltd, pp. 91–106.
- Yang, Z.Z., Li, D.Z., 2004. Study on TOD and its application in China. *Urban Transp. China* 2 (2), 15–18 (杨忠振, 李大洲, (2004). 公交导向发展策略及其在中国城市的应用研究. 城市交通, 2(2), 15–18.).
- Zemp, S., Stauffacher, M., Lang, D.J., Scholz, R.W., 2011. Classifying railway stations for strategic transport and land use planning: context matters! *J. Transp. Geogr.* 19 (4), 670–679.
- Zhang, M., Liu, J., 2007. The Chinese edition of TOD. *Urban Plann. Forum* 1, 91–96 (张明, 刘菁, 2007. 适合中国城市特征的 TOD 规划设计原则. 城市规划学刊, 1, 91–96.).