How does transit-oriented development contribute to station area accessibility? A study in Beijing

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ABSTRACT
Theoretically, transit-oriented development (TOD) can enhance accessibility by providing a relatively high level of transport connections and high-density, mixed-use, cycling- and pedestrian-friendly land use around transit stations. Empirically, there is a noted positive relationship between the transport component of TOD and accessibility, but the evidence is more mixed with respect to components other than transport (e.g., high urban density and diversity, or proximity of land uses to the transport node). In order to examine how the specific components of TOD are related to accessibility and the relative importance of each component to enhance accessibility, the paper develops a methodology to explore the relationship between each TOD component and accessibility, and applies it to Beijing, China. First, the paper assesses the accessibility of metro station areas in Beijing. Second, it studies how TOD components are related to accessibility at the one-hour travel time catchment level. The results highlight that, in the Beijing context, both a station area’s location relative to the city center and the land use pattern (e.g., a relatively lower average residential density; a relatively higher average all-job density; a relatively lower average job density in the sector of retail, accommodation, and catering; a relatively higher average job density in the sector of education, health, and culture; and a relatively lower average degree of functional mixes) around all the stations within the targeted station’s one-hour travel catchment are relatively more important to enhance the area’s accessibility than improving the area’s transit performance. This outcome provides insights for developing area-specific and targeted strategies to enhance the accessibility of a given metro station area in Beijing.

1. Introduction
A shift from mobility-centered to accessibility-centered transport and land use planning has been advocated for over two decades (Bertolini & le Clerq, 2003; Cervero, 1997; Curtis & Scheurer, 2010; Levine & Garb, 2002; Levine, Merlin, & Grengs, 2017; Martens, 2016; Papa, Silva, Te Brümmelstroet, & Hull, 2015). This argument starts from the idea that transport demand is largely derived from people’s need to reach their desired destinations rather than for the sake of movement per se. It suggests that enhancing accessibility to desired destinations is what really counts for users of the transport system (Martens, 2016). Furthermore, enhancing accessibility may reduce automobile use and greenhouse gas emission, foster economic development and improve the quality of urban life. A currently popular accessibility-centered planning approach is transit-oriented development (TOD) (Curtis & Scheurer, 2010; Handy, 2002; Papa & Bertolini, 2015). Under favorable conditions, TOD is expected to enhance accessibility by providing a relatively high level of transport connections and a relatively high-density, mixed-use, cycling- and pedestrian-friendly land use around transit stations (Bertolini & Spit, 1998; Calthorpe, Yang, & Zhang, 2014; Cervero, 1998; Cervero et al., 2004; Curtis, Renne, & Bertolini, 2009; Xu, Guthrie, Fan, & Li, 2017). While this claim is theoretically well grounded, it does raise the two empirical questions investigated in this paper: How is each component of TOD related to accessibility, and what is the relative importance of each component for enhancing accessibility? Furthermore, this topic has also important policy implications. Namely, in order to enhance accessibility, which component of TOD should be emphasized? However, there are only a few empirical studies on this topic, and their conclusions provide a mixed assessment. On the one hand, some studies advocate that the transport components of TOD are more important for enhancing accessibility. For instance, Papa and Bertolini (2015) investigated the relationship between the degree of TOD of a metropolitan area and rail-based accessibility to jobs and inhabitants. They found that cumulative rail-based accessibility is higher in cities with a higher TOD degree (in their research defined as the match between the distribution of land use densities and of network connectivity). Their analysis also showed high correlations between overall network connectivity levels (transport component) and accessibility.
However, they did not find significant correlations between average land use density and accessibility. Their findings echo the statements by Mees (2009), who argued that urban density shows little or no relationship to transport modes share, which seems more related to the quality of transport networks. On the other hand, other studies (Chatman, 2013; Levine, Grengs, Shen, & Shen, 2012) show that urban densities or land use around transit stations are relatively more important for enhancing accessibility than connection to transit. For example, Levine et al. (2012) found that denser metropolitan areas are more accessible. Chatman (2013) found that rail access does little to lower automobile ownership or use of an area, while other factors—such as housing type and tenure, local and sub-regional density, bus service, and particularly off- and on-street parking availability—play a much more important role. In the context of discussions about TOD, it is interesting to further examine how each TOD component (e.g., connection to transit, land use density and diversity, proximity of land uses to the transport node, and cycling- and pedestrian-friendly development) relate to accessibility, as well as its relative importance for enhancing accessibility.

This paper aims to address these knowledge gaps by analyzing how different components of TOD contribute to accessibility. We empirically investigate these relationships with a focus on the accessibility of station areas in the city of Beijing, China. Beijing is home to 21.5 million residents, with an urban population share of 86.4% and 1385.6 km² of urban built-up environment in 2014 (Beijing Municipal Statistics Bureau, 2015; Ministry of Housing and Urban-Rural Development of China, 2014). In 2014, the metro served 10 million passengers each workday, with 18 lines, 268 stations and 527 km of track in operation (Beijing Infrastructure Investment Corporation Limited, 2015; Beijing Mass Transit Railway Operation Corporation Limited, 2015). Beijing is an interesting case because of the following reasons. First, TOD strategies centered on the metro system have been proposed and applied for many years. Specifically, in Beijing’s Urban Master Plan 2004–2020, TOD strategies were proposed as commute metro corridors, aimed at connecting Beijing’s central area to the former satellite towns (now practically integrated in Beijing’s continuous built-up area), in order to improve accessibility and better meet the inhabitants’ housing and job needs (Beijing Municipal Government, 2003). Since then, metro-based TOD is one of the key policy tools used to respond to the challenges faced by the highly congested and polluted, fast-growing Beijing (Beijing Municipal Commission of Transport, 2012, 2016). Second, while the Urban Master Plan 2016–2030 (Beijing Municipal Commission of Planning and Land Resource Management, 2017) emphasized TOD as a strategy to connect jobs and housing, it did not provide the specific strategies how to achieve this planning goal. Third, although some studies have looked at TOD guidelines for the Chinese context (e.g., Calthorpe et al., 2014; Zhang & Liu, 2007), the relationships between the specific TOD components and effects (e.g., especially accessibility as its primary effect) are less studied. Therefore, it seems timely to empirically investigate the relationship between TOD and accessibility in Beijing and develop policy-relevant insights to support its TOD strategy development.

The paper is organized into six sections. Following this introduction, Section 2 discusses the theoretical background of the relationship between TOD and accessibility. In Section 3 and Section 4, we develop a methodology to empirically assess this relationship for the case of Beijing and differentiate the contribution of each TOD component. Section 5 discusses potential policy implications, while Section 6 draws conclusions, reflects on the limits of the study, and identifies future research directions.

2. Theoretical background

According to classic conceptualizations, accessibility can be defined as the 'potential of opportunities for interaction' (Hansen, 1959) or 'the ease with which any land use activity can be reached from a location using a particular transport system' (Burns & Golob, 1976). Geurs and Van Wee (2004) identified four types of components from the different definitions and practical measures of accessibility (related studies are Cheng & Bertolini, 2013; Handy & Niemeier, 1997; Kwan & Weber, 2003; Lau & Chiu, 2003; Miller, 2005; Niemeier, 1997; Papa & Bertolini, 2015; Pirie, 1979; Recker, Chen, & McNally, 2001). These components include land use (e.g., the number, quality, and spatial distribution of activity opportunities and individual needs); transportation (i.e., the infrastructure available for covering the distance between origin and destination using a specific transport mode); temporal constraints (i.e., the availability of opportunities at different times of the day); and people-related components (e.g., individual physical condition, availability of adequate travel modes, monetary and time travel budgets). TOD strategies can have substantial effects on the transportation and land use components of accessibility. In the following sections, we first measure the accessibility of station areas in Beijing and their TOD components theoretically related to accessibility (Section 3). We then conduct spatial regression models to weigh the importance of each TOD component for enhancing accessibility of station areas (Section 4). The results help identify which components of TOD should be emphasized to enhance the accessibility of a given metro station area in the context of Beijing (Section 5).

3. Measuring accessibility and TOD components of station areas

In this section, we first measure accessibility to jobs and inhabitants of a given metro station area. Next, we measure the specific TOD components related to accessibility for the given metro stations.

3.1. Measuring accessibility of station areas

Based on the literature discussed in the theoretical section, we measure accessibility as the cumulative number of inhabitants and jobs in the built-up area of Beijing that can be

1We define TOD strategies as planning or policy strategies that follow Transit Oriented Development principles and that affect the transport and/or land use characteristics of a station area or a city.
reached from a given place, by traveling a certain time by one or a combination of transport modes during a certain time period. Although this type of measurement does not take into account some of the aspects discussed in the literature — for example, people-related factors (e.g., an individual’s physical condition, the availability of adequate travel modes, or monetary and time travel budgets), distance decay or, importantly, competition effects (e.g., between workers for jobs or jobs for workers) — (Cheng & Bertolini, 2013; Shen, 1998; Weibull, 1976), it is considered a relatively sound, transparent and easily communicable measurement in a planning context (for a similar measurement and argument see Papa & Bertolini, 2015; also see Bertolini, le Clercq, & Kapoen, 2005).

Similar to Papa and Bertolini (2015), we focus on access to potential opportunities for jobs (relevant for workers), employees and consumers (relevant for firms), and social contacts (relevant for residents), as captured by the number of jobs and inhabitants within reach. With respect to travel mode, our focus is on public transport modes (bus, tram, metro — or their combinations with walking) for two reasons. First, public transport is the main transport mode that underpins TOD strategies in Beijing. Second, public transport is an affordable and frequently used transport mode in Beijing. According to Beijing’s 2014 annual transport report, 48% of all trips (all types of transport modes, not including walking) were made by public transport (Beijing Transportation Research Centre, 2015). We set a travel time of one hour because the average commute time of all passengers by public transport in Beijing during peak hours (7:00–8:00 in the morning and 17:00–18:00 in the afternoon) is about one hour (Beijing Transportation Research Centre, 2015). With respect to our specific study context, we measure accessibility as the cumulative number of jobs and inhabitants that can be reached by traveling one hour by public transport in the morning peak hours in the built-up area of Beijing from a given origin point.

In this study, we set the entire built-up area of Beijing as the study area (using open access data from Yang, He, Zhang, Han, & Du, 2013), divided into 1651 regular grid cells (1 km by 1 km) (for a visual representation see Figure 1, red grid). Given the modifiable areal unit problem (Openshaw, 1984), the choice of spatial scale may influence the results of the analysis. The 1 km² scale was selected because this size of grid cell (1) can sufficiently distinguish between each metro station area (right hand of Figure 2, colored cells) and (2) is approximately equal to the average size of the spatial units of the original economic census dataset (Figure 1, light gray boundary). Using this grid system, metro station cells were identified by selecting those grid cells that overlapped with one or more centroid(s) of metro stations (right hand of Figure 2, colored cells). Since
a few centroids of metro stations are located in the same grid cells, there is a slightly smaller number of metro station cells (261) than the number of metro stations (268).

Accessibility ($ACC_{\text{hour}}$) of a given metro station cell is measured as the cumulative number of jobs and inhabitants in the built-up area that can be reached by traveling one hour with public transport in the morning peak hours from a metro station cell’s centroid, as measured by Equation (1):

$$ACC_{\text{hour}} = \sum_{\text{Time}(MS_i, Cell_k) \leq 1 \text{ hour}} (\text{Job}_{N_k} + \text{Inhabitant}_{N_k}).$$

($MS_i$ is a given metro station cell ($i = 1, 2, 3, \ldots, 261$) as an origin; $Cell_k$ is any grid cell ($k = 1, 2, 3, \ldots, 1651$) within the built-up area as a destination; $Cell_k$ includes $MS_i$. Time ($MS_i, Cell_k$) is the shortest travel time by public transport from the centroid of $MS_i$ to the centroid of $Cell_k$, which can be retrieved by using Google Maps Distance Matrix API (see below). $Job_{N_k}$ is the number of jobs in $Cell_k$, which can be retrieved by spatially overlaying the economic census data and the grid cell. $Inhabitant_{N_k}$ is the number of inhabitants in $Cell_k$, which can be retrieved by spatially overlaying the population census data and the grid cell.

With regard to travel times (see Equation (2) below), we retrieved the dataset by using Google Maps Distance Matrix API (Google Inc., 2016), which returns the travel times of the shortest travel route from multiple given places to other multiple places by a given transport mode for a given departure time. We selected the 261 centroids of TOD cells (which do not necessarily coincide with the centroids of metro stations) as trip origins ($MS_i$), while the trip destinations were the centroids of all the grid cells for the entire built-up area, 1651 in total ($Cell_k$). The departure time was set at 7:00 in the morning Beijing local time on Wednesday, 9 November 2016, by using a timestamp code (departure_time = ‘1478646000’). Due to the focus on TOD, the transport mode was set as ‘transit’ (Google Inc., 2016), i.e., public transport (metro, bus, tram – or their combinations with walking). The computed travel time dataset is a table displaying total travel times between pairs of origin and destination points – 261 rows (origins) x 1651 columns (destinations) and 430,911 table cells (261*1651). This travel time includes walking time from origin (the centroid of the TOD cell) to the first public transit stop ($\text{aWalk}_{Tik}$), waiting time for public transport mode ($\text{bWalk}_{Tik}$), riding time in public transport ($\text{Ride}_{Tik}$), and walking time from the last transit stop to destination ($\text{cWalk}_{Tik}$). If one or several transfers are required, the transfer times ($\text{Transfer}_{Tik}$) are also accounted for by the travel time returned by this API. The left map of Figure 2 shows an example of accessible areas (colored green) for a one-hour travel time from a given TOD cell (marked by a red star).

$$\text{Time}(MT_{i}, Cell_k) = (a + b)\text{aWalk}_{Tik} + \text{bWalk}_{Tik} + \text{Ride}_{Tik} + \text{Transfer}_{Tik}.$$
two census datasets: the economic census data of 2014, which contains numbers of employed workers (jobs) in each census zone in Beijing (Beijing Municipal Statistics Bureau, 2016) and the population census data of 2010, which contains the numbers of inhabitants in each town of Beijing (Beijing Municipal Statistics Bureau, 2012). The boundaries of the economic census zones and the number of employed workers in each economic census zone were retrieved from Beijing’s web application depicting the third economic census of 2014 (also see Figure 1). The boundaries of the population census zones were derived by aggregating the respective zone boundaries of the economic census zones to the level of population census zones, while the number of inhabitants in each population census zone was retrieved from the 2010 Population Census of Beijing Municipality Town and Sub-district Volume (Beijing Municipal Statistics Bureau, 2012). These data are the most disaggregated and publicly accessible census data. In the built-up areas of Beijing, there are 3045 economic census zones, which have an average surface area of 0.71 km² and are thus smaller than the area of a grid cell. While the population census data is distributed at the town level, in 169 towns with an average surface area of 16.8 km².

In the ArcGIS 10.3.1 desktop platform, we calculated the number of jobs and of inhabitants (Job_Nk + Inhabitant_Nk) in each grid cell (Cell_k) in the following manner. First, we calculated the job density of economic census zones as well as the population density of population census zones. Second, we created (1) the spatial overlaps between ‘economic census zones’ and ‘grid cells’ as well as (2) the spatial overlaps between ‘population census zones’ and ‘grid cells’. This resulted into (1) new sub-areas including attribute information on their surface areas as well as their job densities calculated in the first step and (2) new sub-areas including attribute information on their surface areas as well as their inhabitant densities calculated in the first step. Third, the number of jobs within a new sub-area was calculated through multiplying the job density by the surface area of the sub-area. The same procedure was applied to calculate the inhabitants of a new sub-area. Fourth, the number of jobs and number of inhabitants were separately aggregated to the level of the grid cell. Finally, the number of jobs and inhabitants (Job_Nk + Inhabitant_Nk) of a grid cell was summed up.

Based on the processes and datasets above, accessibilities to jobs and inhabitants from all metro station cells (261) were calculated (visualized in the right map of Figure 2). In order to show their spatial distribution pattern, we categorized their values into four classes using the standard deviation method in ArcGIS (Esri, 2012).

3.2. Identifying and measuring specific TOD components related to accessibility

Based on the measurement of accessibility to jobs and inhabitants in Section 3.1, accessibility of a metro station area depends on (1) the surface area of the area’s catchment² (including both TOD and non-TOD cells, see map in Figure 2, left) and (2) how many jobs and inhabitants are contained in this catchment (which depends on the overall density of jobs and inhabitants in the catchment).

Some components of TOD can affect the level of travel impedance within the catchment. A lower level of travel impedance results in a larger catchment surface area and, all things being equal, in a higher accessibility of an area. For instance, the characteristics of transit performance (e.g., metro speed or frequency), local transport connection (e.g., the number of bus directions/stops around the transit station), and pedestrian-friendly urban design (e.g., the density of pedestrian lanes around the transit station) can affect the level of travel impedance from an area by public transport and walking.

Other components of TOD can indicate the density of jobs and inhabitants within a catchment. For instance, the geographic or travel time distance of a TOD area to city center(s) can indicate the overall density of jobs and inhabitants within a catchment. In most cases, the closer it is to the city center(s), the higher the level of job and inhabitant density of the catchment (McDonald, 1985; Mills, 1970). Similarly, the average job and inhabitant density of the station areas within a catchment is expected to be positively related to the average job and inhabitant density of the catchment. For other TOD components, however, the relationship might not be as straightforward. For instance, the correlation direction between the average urban diversity of station areas within a catchment and the level of the average job and inhabitant density of the catchment varies in the different contexts. In some contexts, diversity has been found to positively correlate with density (e.g., Bramley, Dempsey, Power, Brown, & Watkins, 2009), while in others it had a negative correlation (e.g., Yi, Yang, & Yu, 2017). Complex relationships between diversity, specialization and density underline these ambivalent findings.

With respect to the study area of Beijing, our measurements of the specific components of TOD are based on the work of Lyu, Bertolini, & Pfeffer (2016). Their TOD indicators were generated based on a TOD literature review and opinions of local TOD experts, providing contextualization of the TOD indicators identified in the international literature. Additionally, we set the following selection and adaptation rules: selected and adapted indicators should be theoretically relevant to the area’s accessibility to jobs and inhabitants along the lines discussed in Section 3.2 above. See Table 1 for all selections, adaptations and the corresponding reasons.

4. Relating the specific components of TOD to station area accessibility

In order to explore the relationships between the specific TOD components and station area accessibility (ACC), we first conducted a regression analysis using the ordinary least square (OLS) method, with the TOD components (Table 1) as explanatory variables and station area accessibility to jobs and inhabitants as the dependent variable. As we found that the residuals of the regression are spatially autocorrelated, we applied a spatial error regression model (SERM) to
The analysis platform used in this study is Geoda (Anselin, 2004). We found that the residuals of the OLS models are mostly autocorrelated at the Euclidean distance of 2000 m (indicated by the highest Global Moran’s I value, through an incremental spatial autocorrelation analysis on the residuals (Esri, 2018)). Thus, we set 2000 m as a distance threshold: if the Euclidean distance between residuals was up to and including 2000 m, the weight was set as one; otherwise it was set as zero. Next, we ran the spatial error regression model based on the defined weight matrix. The results and diagnostics of SERM show that the spatial autocorrelation of residuals of OLS models has been corrected (compare Global Moran’s I statistics between OLS and SERM).

correct the bias. Next, in order to identify the relative importance of each TOD component to accessibility, we standardized the explanatory and dependent variables (by first subtracting the mean and then dividing by the standard deviation) and conducted a spatial error regression analysis with the standardized variables. Akaike information criterion (AIC) was used to further identify TOD components significantly related to accessibility. In this paper, we report the results of (1) the regression analyses with all TOD components as explanatory variables (Table 2, left) and (2) the regression analyses with the stepwise selected TOD components by means of AIC, as explanatory variables (Table 2, right).

### Table 1. Selections and adaptations of TOD indicators according to their theoretical relevance to station area accessibility.

<table>
<thead>
<tr>
<th>Original indicators based on the work of (Lyu et al., 2016)</th>
<th>Select, drop or adapt (indicator abbreviation)</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of directions served by metro</td>
<td>Select (NDM)</td>
<td>Relevant to the travel impedance to destination areas</td>
</tr>
<tr>
<td>Number of directions served by bus</td>
<td>Adapted as the average number of directions served by bus for all station areas within a catchment (ADB)</td>
<td>Relevant to the travel impedance from last metro station to destination areas</td>
</tr>
<tr>
<td>Daily frequency of metro services</td>
<td>Select (DFM)</td>
<td>Relevant to the travel impedance (through travelers’ waiting times) to destination areas</td>
</tr>
<tr>
<td>Number of stations within 20-minutes travel by metro</td>
<td>Select (NSM)</td>
<td>Relevant to the travel impedance to destination areas</td>
</tr>
<tr>
<td>Travel times to major employment and activity centers by metro*</td>
<td>Select (TCM)</td>
<td>Irrelevant to public transport accessibility</td>
</tr>
<tr>
<td>Car parking capacity</td>
<td>Drop</td>
<td>Marginally relevant to the job accessibility of a station area (reducing both travel impedance to and number of jobs within reach)</td>
</tr>
<tr>
<td>Average distance from station to jobs in the station area</td>
<td>Adapted as the averaged value of average distances from station to jobs of all station areas within a catchment (ADJ)</td>
<td>Marginally relevant to the job accessibility of a station area (reducing both travel impedance to and number of inhabitants within reach)</td>
</tr>
<tr>
<td>Average distance from station to residents in the station area</td>
<td>Adapted as the averaged value of average distances from station to residents for all station areas within a catchment (ADR)</td>
<td>Relevant to the travel impedance to destination areas</td>
</tr>
<tr>
<td>Length of paved footpaths of a station area</td>
<td>Select (LFS)</td>
<td>Same as LFS</td>
</tr>
<tr>
<td>Intersection density (number of intersections in a station area)</td>
<td>Select (NIS)</td>
<td>Same as LFS</td>
</tr>
<tr>
<td>Average block size* of a station area</td>
<td>Select (BSS)</td>
<td>Relevant to the average inhabitant density of the catchment</td>
</tr>
<tr>
<td>Walk Scores* of a station area</td>
<td>Select (WSS)</td>
<td>Relevant to the average job density of the catchment</td>
</tr>
<tr>
<td>Number of residents of a station area</td>
<td>Adapted as the average number of residents for all station areas within a catchment (ANR)</td>
<td>Relevant to the average job density of the catchment (the relationship between this indicator and accessibility could show the relative importance of this specific economic sector on overall accessibility)</td>
</tr>
<tr>
<td>Number of jobs*</td>
<td>Adapted as the average number of jobs for all station areas within a catchment (ANJ)</td>
<td>Relevant to overall accessibility (the relationship unknown)</td>
</tr>
<tr>
<td>Number of workers in retail, hotel, and catering</td>
<td>Adapted as the average number of workers in retail, hotel, and catering for all station areas within a catchment (AWR)</td>
<td>Same as AWR</td>
</tr>
<tr>
<td>Number of workers in education, health, culture</td>
<td>Adapted as the average number of workers in education, health, and culture for all station areas within a catchment (AWE)</td>
<td>Same as AWR</td>
</tr>
<tr>
<td>Number of workers in public administration and services</td>
<td>Adapted as the average number of workers in public administration and services for all station areas within a catchment (AWP)</td>
<td>Same as AWR</td>
</tr>
<tr>
<td>Degree of functional mix*</td>
<td>Adapted as the average degree of functional mixes for all station areas within a catchment (ADM)</td>
<td>Relevant to inhabitant and job density of all station areas within the catchment (but direction of the relationship unknown)</td>
</tr>
</tbody>
</table>

*Measured as the average travel time by metro (in minutes) to the top ten most dense station areas by employment in Beijing (by counting the number of economic establishments per station area, see more in Lyu et al., 2016).  
*The total length of the street network in a station area (in kilometres).  
*Walk Score is a number between 0 and 100 that measures the walkability of a location. The score is available from www.walkscore.com.  
*The calculation was based on all the economic establishments. Calculations of the number of workers in retail; hotel and catering; education, health, culture; and public administration and services are based on the numbers of their corresponding types of economic establishments.  
*The calculation is based on the number of establishments in the three sectors (number of establishments in retail, hotel and catering; education, health, culture; and public administration and services) and the number of housing units in a station area; where Degree of functional mix = 1−{(a−b)/d−(a−c)/d}/2, with a=max(the three types of establishments and housing), b=min (the three types of establishments and housing), c=average (the three types of establishments and housing), and d=sum (the three types of establishments + housing).  
Data source: Adapted from Lyu et al. (2016).
The results of the regression models show that certain TOD components can significantly explain the variance of a station area’s accessibility. As expected, transit performance (i.e., number of stations within 20-minutes travel time by metro), the area’s location relative to city centers (e.g., travel times to major employment and activity centers by metro), walkability of the area (e.g., length of paved footpaths and Walk Scores) and average job density for all station areas within the catchment (e.g., average number of jobs and average number of workers in education, health, and culture for all station areas within a catchment) can significantly explain the station area’s spatial difference in terms of accessibility (see Section 3.2). Interestingly, the Beta values on variables of average number of residents for all station areas within a catchment (ANR); average number of workers in retail, hotel, and catering for all station areas within a catchment (AWR); and average degree of functional mixes for all station areas within a catchment (ADM) are negative, even though each of these three variables is separately positively correlated to the dependant variable (Pearson’s correlation coefficients: 0.74** between ANR and ACC; 0.63** between AWR and ACC; and 0.53** between ADM and ACC). The results show that when controlling for the effect of the other TOD variables, ANR, AWR, and ADM contribute negatively to accessibility. For instance, a station area with a lower average degree of functional mixes for all station areas within the area’s catchment (ADM) has a higher accessibility than the compared station area with a higher ADM, when the other TOD components of these two station areas are the same or similar.

The results of the regression models also show the relative importance of the specific TOD components in enhancing a station area’s accessibility. Based on the results of the AIC stepwise SERM on the standardized variables, we find that a station area’s location relative to the city center (TCM: −0.35**) and the land use pattern around all the stations within the targeted station’s catchment (e.g., ANR: −0.30**, ANJ: 0.41**, AWR: −0.36**, AWE: 0.59**, ADM: −0.14**) are relatively more important for enhancing the area’s accessibility than the area’s transit performance (NSM: 0.11**). The walkability of a station area does contribute to the area’s accessibility, but the relative importance is small (e.g., LFS: 0.06** and WSS: 0.07**).

5. Potential policy implications

The findings regarding the relationships between the specific TOD components and the accessibility of station areas...
deliver some useful insights for policy- and strategy making. First, assessing accessibility of a given metro station area provides information on which metro station area scores relatively low or high in accessibility (Figure 2). Since more accessibility is inherently preferred (Martens, 2016), this assessment helps planning professionals develop area-targeted strategies to enhance the area’s accessibility.

Second, the results identified which specific TOD components are related to the spatial difference in accessibility of a metro station area and to what extent (Table 2). In order to enhance the accessibility of a given metro station area, a dedicated mix of TOD policies should be advocated in the Beijing context. In particular, focusing on the land use pattern around all stations within the targeted station area’s one-hour travel catchment is relatively more important than improving the targeted station’s transit performance in the Beijing context. Unlike the calls by many TOD advocates (see Calthorpe et al., 2014; Cervero et al., 2004) for a generic increase of urban density and diversity around stations, this study suggests that to enhance a station area’s accessibility in Beijing the following land use patterns around all stations within a station’s one-hour travel catchment are favored: (1) a relatively lower average residence density; (2) a relatively higher average all-job density; (3) a relatively lower average job density in the sector of retail, accommodation, and catering; (4) a relatively higher average job density in the sector of education, health, and culture; and (5) a relatively lower average degree of functional mixes. In the context of Beijing, the policies or strategies that foster such land use should be advocated, in order to enhance metro station area’s accessibility to jobs and inhabitants.

Furthermore, this study suggests that pedestrian-friendly urban design around metro stations in Beijing can significantly enhance the station area’s accessibility. Its relative importance is just slightly smaller than improving transit performance, and larger and more significant than the effect of bus transport connection to destination locations. It implies that walking is the most important access or egress from a metro station in Beijing. The short distance between stations (in the inner city often less than 700 m) might explain this finding. This result suggests that providing a pedestrian-friendly environment around metro stations is more important than bus connections in the Beijing context.

An important nuance here is that, because TOD components are in practice interrelated, changing one of them might affect others. For instance, increasing the density of one type of function will directly affect the degree of functional mix in the area; more indirectly, increasing land use densities or changing the land use mix might affect the walkability of an area; and there might be conflicts and the need of trade-offs between the intensification of land uses, or the improvement of walkability, and the enhancement of transport connectivity in an area (Bertolini & Spit, 1998). When applying the findings of the paper in policy, these interrelations should be acknowledged.

6. Conclusion and discussion

This research explored the relationships between specific TOD components and station area accessibility in the case of Beijing. The study has identified that some TOD components are more significant than others for enhancing a station area’s accessibility. These insights could help develop a dedicated mix of TOD strategies for enhancing a targeted station area’s accessibility to jobs and inhabitants. Our finding is different from much of the recent literature on transport and land use planning, which has made the point that running a fast, time-competitive transit is relatively more important for enhancing accessibility than land use management (e.g., Mees, 2009; Papa & Bertolini, 2015). Aligning with the works of e.g., Chatman, 2013; Levine, Grengs, Shen, & Shen, 2012, our work shows that, in order to enhance a station area’s accessibility to jobs and inhabitants in the Beijing context, land use management around all the stations within the targeted station’s one-hour travel catchment is relatively more important than increasing the targeted station’s transit performance. Another issue highlighted by recent studies is related to the effects of urban diversity around transit stations. For Beijing – differently from the claims of many TOD advocates (see Calthorpe et al., 2014; Cervero et al., 2004) – our study found that a lower average degree of functional mixes for all station areas within a targeted station’s one-hour travel catchment is correlated with a higher level of the targeted station area’s accessibility, after controlling for the effects of the other TOD components. This result indicates that despite the seemingly apparent positive correlation between urban diversity and urban density, after controlling for the effect of urban density, lower urban diversity contributes to higher accessibility (perhaps following the logic of positively linking specialization and density, see Yi et al., 2017 or because of the particular accessibility measure used in this study). The study also pointed out that in order to enhance station area accessibility, enhancing the urban density of specific functions should be favored. In the context of Beijing, urban density around metro stations on aspects of all-jobs and jobs in the sector of education, health, and culture positively contributes to a targeted station area’s accessibility. The opposite is true for density of inhabitants and job density in the sector of retail, accommodation, and catering. The reason might be that the former allow (or could drive) higher overall urban densities for the catchment than the latter. Of course, a different conclusion could be reached if other kinds of accessibility are the desired goal (e.g., accessibility to local stores and daily services) or if altogether different policy goals are pursued.

Taken together these outcomes provide insights for developing area-specific and targeted strategies to improve the accessibility of existing metro station areas in Beijing. What is true in Beijing might not be true in other contexts, for instance because of a different distribution of land uses and/or a different configuration of the transport network (even in Beijing conditions might change in the future). Understanding which land use and transport conditions are related to which outcomes is in itself a fascinating research question. Further exploring this issue might also help make sense of some of the apparent contradiction in the findings in the literature. Simply put, context is very important. With
this in mind, a further contribution of our research is that it offers a methodology with application potential in other geographic contexts, with both analytical and planning support value. This contribution might even be more important than any attempt at and insights from generalizing findings in a single context. In particular, we suggest that the adoption of the catchment area as the spatial unit of analysis is a key innovation relative to previous studies and, we contend, necessary in order to acknowledge the systemic nature of the determinants of a station (or any other local) area’s accessibility.

The study’s methodology and findings are qualified by several limitations. First, the regression analysis ignores the long-term interactions between the transport and land use components of TOD, i.e., the transport and land use feedback cycle (Bertolini, 2012; Wegener & Fürst, 1999). As a consequence, policy implications cannot be simply extended to the long term. This limitation suggests a future research direction aimed at documenting and analyzing the interaction or causality between the changes in different TOD characteristics (as a result of TOD strategies) and accessibility over time via a longitudinal study. Second, the analysis only shows the relative contributions (i.e., benefits) of the specific TOD components to accessibility but does not consider the relative costs of strategies aimed at improving each TOD component. This limitation suggests the following future research direction: developing a costs and benefits analysis of policy interventions, which can reveal trade-offs and possibly also synergies – between components. Third, since the results were based on publicly available datasets – TOD dataset of Lyu et al. (2016), Google Maps Distance Matrix API, and Beijing’s census data on population (2010) and economy (2014) – the level of detail or bias of these datasets also influences the result. Fourth, the analysis is based on the assumption that more accessibility is inherently preferred (Martens, 2016) and the belief that urban form determines the content (e.g., criticized by Harvey, 1997). The relationship between TOD and the anticipated effects to people and firms might, however, not be that straightforward. Therefore, future research could aim to quantify the link between TOD and its effects other than accessibility, e.g., reduced greenhouse gas emission, lower air pollution and energy consumption (Kimball, Chester, Gino, & Reyna, 2013; Nahlik & Chester, 2014), spatial (in)equity (Fernandez & Creutzig, 2017; Jang, An, Yi, & Lee, 2017; Sun & Fan, 2018) or increased land and property rent/values (Cervero & Murakami, 2009; Duncan, 2011). Fifth, several aspects of accessibility have not been taken into consideration, including the key distance decay and competition effects (e.g., Cheng & Bertolini, 2013; Shen, 1998; Weibull, 1976) but also accessibility at other than morning-peak hours as well as the more qualitative aspects of accessibility (e.g., comfort, safety, and cleanliness of travel, types of jobs and inhabitants). Thus, our results cannot reflect the relationship between TOD components and accessibility with respect to these factors. Sixth, the analysis is limited by the modifiable areal unit problem. We took strong efforts to minimize its possible and what conditions and mechanisms explain variations. The methodology developed and applied in this study provides a useful tool for such research endeavors.

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