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Does yesterday's accessibility shape today's TOD-nesses in metro station areas? A tale of Shenzhen, China

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Abstract: As an overarching policy and development model, transit-oriented development (TOD) is widely used to promote the integration of land use and transit services, which arguably brings about many benefits. TOD advocates have continuously paid much attention to metro station areas (MSAs), i.e., areas within a reasonable walking distance to a metro station. To TOD advocates, well-planned MSAs should have a sufficient supply of TOD-nesses encapsulating characteristics such as destinations, density, diversity, and design. In the existing scholarship, however, little has been done on (a) TOD-nesses' potential "consumers," the population that is only a short metro ride away from an MSA, i.e., the metro-based accessibility (MBA) to the consumers of the MSA; and (b) whether and how TOD-nesses of one MSA and several MSAs in proximity are affected by the MBA. With the help of big and/or open data, we examine whether and to what degree the MBA of an MSA cluster (MSAC), a set of MSAs within t minutes of a metro ride from a metro station is correlated to that MSAC's TOD-nesses in Shenzhen, China. We measure the MBA by the daytime/nighttime population in the same MSAC. We quantify TOD-nesses using the published indices or the averages of the indices in a refereed article. Coefficient of geography association, Gini index, pairwise correlation, and linear regression analyses are carried out. We find that the MBA in one period significantly predicts MSAC-level TOD-nesses in ensuing periods. However, the MBA's prediction power decreases or even disappears over time. Besides, metro station characteristics such as the jurisdiction membership significantly predict the overall TOD-nesses and individual aspects of the TOD-nesses after controlling for the MBA. Our study thus sheds new light on meso- or MSAC-level TOD-nesses and related policy and planning evaluation.

Keywords: Transit-oriented development, metro area cluster, accessibility, TOD-ness, Shenzhen

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1 Introduction

Since Calthorpe (1993) published a seminal book on transit-oriented development (TOD), many related studies have emerged (e.g., Bernick & Cervero, 1996; Cervero et al., 2004; Dittmar & Ohland, 2004; TCRP, 2007). In these studies, authors advocated

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alternative formats of development at the transit station, corridor, and network levels. These "new" developments characterize high-density, diverse, and mixed land uses, pedestrian-friendly and human-scaled design, and identifiable destinations rendering various functions in or around transit station areas. In addition, all the transit station areas should be well served by extensive transit services with frequent headways and "infrequent station stops (one-mile minimums)" (Calthorpe, 1993, p. 27).

In the existing scholarship, authors have coined and frequently used the term "TOD-ness" (e.g., see Singh et al., 2017, p. 96; TCRP, 2007, p. 17-9) to denote the physical characteristics of TOD. TOD-nesses embody the essential guiding and implementation principles for desirable attributes of TOD. On the one hand, dense and mixed land uses that would generate substantial travel/transit demand should be in principal located in or around transit station areas, and these areas should contain lots of TOD-nesses; on the other hand, sufficient and frequent transit services should be provided to effectively link at least the strategically important sites such as urban cores and town centers so that (a) a substantial percentage of daily needs and its subsequent travel demand can be satisfied by transit services, walking, and/or cycling, and (b) different TOD sites are well served and connected by those modes of travel. In short, to achieve good TOD, the relationship between TOD-nesses ("products" or "services") and how people can access them ("consumers") matters. TOD-nesses and the accessibility of their consumers to them are inseparable. They should always be considered simultaneously.

In each city or region, there could be a hierarchy of sites where there are different levels and combinations of TOD-nesses. Calthorpe (1993), notably, recommended two levels of TOD. One is Urban TOD, which is directly served by light rail, heavy rail, and/or express bus stops and has "high commercial intensities, job clusters, and moderate to high residential densities" (p.57). The other is neighborhood TOD, which is only served by a local or feeder bus line within a 10-minute transit travel time (no more than 3 miles) from a trunk line transit stop. Neighborhood TOD has residential, service, retail, entertainment, civic, and recreational land uses of a moderate density. In Calthorpe's eyes, therefore, there should be a strong correlation between different tiers of TOD sites and different kinds of transit services. In other words, there should be a balance between the TOD-ness supply and transit-based accessibility to opportunities, especially population ("TBA" for shorthand hereafter). In his seminar work, however, Calthorpe (1993) did not articulate the sequences of TOD-nesses and transit services. He also did not specify how to conceptualize and evaluate the TBA and its relationships with TOD-nesses. From the theoretical/practical perspectives, there thus exist gaps in this seminal classic concerning (a) who are (potential) consumers for one transit station area (TSA) with different levels and combinations of TOD-nesses? (b) how many of them can potentially come from that TSA and its counterparts that are only a short transit ride apart (e.g., a 30-min transit ride), i.e., how good is the TBA of the TSA? and (c) whether and to what extent the TBA can predict the TOD-nesses of the TSA and its counterparts that are a short transit ride apart? Consumers of TOD-nesses do not necessarily have to go to one specific TSA, rather they can go to a cluster of TSAs that are only a short transit ride apart ("TSAC" for shorthand hereafter).

Taking the above gaps into account, this study aims to examine whether and to what extent TBA can predict TOD-nesses at the TSAC level. The remainder of the text is organized as follows. The next section (Section 2) reviews how existing studies look at the TOD(-ness), accessibility (especially TBA), and their relationships. Section 3 presents an empirical study of the TSA- and TSAC-level TOD-nesses and accessibility. Rather than focusing on all kinds of TSAs, the empirical study looks at metro station areas (MSAs) and metro station area clusters (MSACs) in particular. That is, it focuses on a subset of TSAs and TSACs. Section 4 concludes with some discussion and final remarks.

2 TOD-nesses, accessibility, and their relationships

If we tentatively overlook the complex dynamics (e.g., the bi-directional and constantly changing or chicken-and-egg relationships between TOD[-nesses] and transit services [which create and enhance the TBA]), the TOD ideas by Calthorpe (1993) resonated with the well-established theories in several disciplines. The following text thus first reviews these theories. Then it proceeds to existing TOD literature on accessibility (especially the TBA) and its relationships with TOD-nesses.

2.1 Existing theories related to TOD(-nesses)

Why are there different levels and combinations of TOD-nesses across space? Clues can be found in the existing scholarship other than the classics on TOD such as Calthorpe (1993). In Economics, there have long been concepts of the basic and non-basic functions of a town, city, and region. According to these concepts, the basic function primarily meets the non-local demand whereas the non-basic function caters to the needs of locals (Alexander, 1954). It is because of the basic function that the Urban TOD prescribed by Calthorpe (1993) can have many large-scale commercial facilities and diverse employment opportunities, i.e., a certain level or combination of TOD-nesses concerning density and diversity. These TOD-nesses serve not only residents in the Urban TOD site but also residents who can reach the site within a reasonable travel time by transit and/or non-motorized mode of travel. In this study, one hypothesis that we formulate is based on such economists' ideas on the basic and non-basic functions. In a nutshell, new or improved transit services create or enhance the TBA of different locales. Those locales with better TBA see less travel disutility, attract more people and businesses, and carry out more basic functions (c.f., van Wee, 2011). These basic functions subsequently engender or enhance (new or existing) TOD(-nesses), especially those related to employment and residential diversities, quantities, and densities.

In Geography, Von Thünen proposed the agricultural location theory. In his theory, he argued that distance to the market, which is usually centrally located in a city or region, significantly influences the type and intensity of different land uses therein and around. Roughly speaking, the closer to the market, the higher the land rent, the more profitable and intensive land uses would occur, i.e., certain types of densities and diversity would emerge (Chisholm, 1962; Grotewold, 1959; O'Kelly & Bryan, 1996). This also more or less explains the emergence and dominance of central business districts of cities, which contain many high-rise and multi-purpose buildings and/or building complexes accommodating different profit-driven establishments' offices or stores. In other words, the degree of centrality or good accessibility to (potential) consumers can well predict commercial building/employee densities and related service/occupation diversity.

In Spatial/Urban Economics, Alonso (1964) pointed out that what kind of activities (including buildings and infrastructures in support of them) occur at a locale is not a random event. They are outcomes of trade-offs for accessibility (measured as the average transportation cost to a locale and various amenities, e.g., large lot sizes, desirable school districts, and unique natural landscapes) treasured by residents or firms. Here, again, accessibility predicts people's and firms' location choices and activities, which can be translated into TOD-nesses such as facility and service densities and employment diversity.

2.2 Accessibility, TOD-nesses, and their relationships

At some risk of oversimplifying the complexities concerning accessibility, TOD(-nesses), and their relationships embedded in the existing studies, e.g., one study can touch on several topics simultaneously, we categorize them into three streams as follows.

2.2.1 Accessibility alone: The big picture

Accessibility has been a long-standing topic in the existing scholarship. Levine (2020) showed that it had been examined since at least a century ago given its multidimensional significance. Because of its long history, much has been published on accessibility. Authors such as Geurs and van Wee (2004, 2023), Levine (2020), and Wu and Levinson (2020) have all provided comprehensive reviews of the studies on accessibility up to a time of their respective choices. Based on these reviews and related publications, we can get a big picture of accessibility, especially how it is defined, measured, and applied, and what it might influence, and vice versa in the literature on TOD.

Defining accessibility: In its earliest days, accessibility had been regarded as a goal underlying land-use development, i.e., one of the purposes of land-use development (including provision of supporting road and public transportation facilities and services), is to improve people's access to various services and facilities (Levine, 2020). Hansen (1959) went beyond this and argued that accessibility was "the potential of opportunities for interaction" (p.73). After him, there have been many attempts to define accessibility across disciplines and how heterogeneously defined "accessibility" can be used to serve different purposes. This engendered mixed feelings of "accessibility" by different people: accessibility can mean different things for different people; even for the same people, accessibility's meaning(s) can vary across occasions. According to Wu and Levinson (2020), four types of differences contributed to such situations: intellectual heritage, mathematical formulation, language and words that were used to describe accessibility, and aims concerning why "accessibility" was examined in the first place. In the TOD-related literature, "accessibility" is largely defined in two manners. One is how conveniently or fast one can reach transit services, i.e., accessibility to transit (ATT). The other is how transit services can allow people in different TSAs to reach more opportunities, i.e., "accessibility by transit" (ABT) or the TBA we highlighted above. More examples concerning ATT and ABT are shown in Table A of the Appendix of this manuscript.

Measuring accessibility: According to Geurs and van Wee (2004, 2023), there are four categories of accessibility measures: infrastructure-based, location-based, person-based, and utility-based. Each category of accessibility measures considers four common components to varying degrees: transportation, land-use, temporal, and individual. Taking location-based measures as examples. They care the most about the amount and spatial distribution of the demand for and/or supply of opportunities, which can be measured by indicators such as the amounts of population and land use. But in principle, they can also be refined by further accounting for different travel costs (e.g., travel time and monetary expenditures), temporal resolutions (e.g., hours of the day and days of the week), and subgroups of the population (e.g., the elderly vs. adults). In this study, we use only a series of simplified location-based ABT measures. Specifically, our measures consider the numbers of employees, residents, or both within some travel time by metro and/or walking from a metro station.

Using accessibility: Accessibility measures in place hitherto can be used to serve different purposes. Notably, infrastructure-based accessibility measures are often employed to evaluate which transportation project or plan out of a set of projects or plans is superior. The greater the positive changes would be (e.g., the node-to-node travel speed increases by 10%), the superior an option would be. Location-based accessibility measures allow analysts to simultaneously consider both the transportation and land-use components of accessibility. Person- and utility-based accessibility measures often require individual-level data concerning people's characteristics such as time budget, arrival/departure time constraints, capacities, preferences, price-demand elasticity, and ability/willingness to pay. They allow analysts to conduct more sophisticated assessments concerning socioeconomic affairs/topics such as transportation-related equity, justice, disparities, insufficiencies, and social exclusion. An expanded metro system, for instance, can shorten the average station-to-station travel time, i.e., improve infrastructure- and location-based accessibility but does not necessarily allow more low-income workers to reach more jobs that match their respective expectations or situations. The metro services' fares can be prohibitively expensive for these workers. Quite a few authors have started tackling such complexities (e.g., Martens et al., 2022; Vecchio & Martens, 2021). However, such complexities have rarely been considered in the existing TOD-related literature (please see Appendix–Table A of this manuscript).

What accessibility influences and vice versa: According to Geurs and van Wee (2023), a good accessibility measure should account for three elements simultaneously. These elements are: (a) transportation resistance, (b) locations, and (c) travel needs and desires. Following this line of thinking, accessibility directly influences three important issues faced by the (sub)population in a place of interest, for instance, a TSA or MSA: (1) the average travel cost that they would incur to access opportunities in or around the place; (2) where the (sub)population would perceive to be more centrally located, would be willing to pay more for it, and/or would like to make tradeoffs to access; (3) how likely/costly it would be for the (sub)population to meet or materialize their respective travel and other needs or desires.

In terms of what influences accessibility, Geurs and van Wee (2023) argued that all the four components of accessibility, namely, the land-use, transportation, temporal, and individual components all "have a direct influence on accessibility but also an indirect one through interactions between the components" (p.229). In the same vein, TOD(-nesses) as different forms or levels of land use and public transportation integration also directly impact accessibility. For instance, dense land uses plus frequent public transportation services would result in better ABT than otherwise.

Increasingly, the advent of modern Internet and Communication Technologies (ICTs) has profound impacts on almost every aspect of our world and lives. The four components of accessibility are also not exceptions (Geurs & van Wee, 2023). Therefore, accessibility, especially ABT has greatly been and would continuously be significantly influenced by the existing and emerging ICTs too. Online shopping, for instance, would allow goods and services to be delivered to more people's residences. Neither ATT nor ABT would be as relevant as ever before for those who can afford and conduct online shopping.

Related to the above, new forms of data have increasingly available, for instance, online consumption inventories, smartcard swipe data which records metro riders' entries and departures by station, the General Transit Feed Specification (GTFS) files that store (public transportation schedules and associated geographic information, and online maps' point of interest (POI) data. Because of such data, how we perceive, define, measure, and "use" accessibility can also change profoundly. Using real-time GTFS data, notably, we can estimate more accurately accessibility that transit riders enjoy, and riders can also know better when it is a better time for them to arrive at a transit station/stop to minimize waiting times (c.f., Liu et al., 2023).

2.2.2 How TOD(-nesses) and accessibility are embedded in one another

Regardless of the level at which TOD-nesses are operationalized, they can be measured by indicators concerning 3Ds (Cervero & Kockelman, 1997) or 5Ds (Ewing & Cervero, 2010). Some of these indicators measure accessibility directly whereas others are often highly correlated to it. Employee or employment densities of a TSA, for instance, are positively correlated to destination accessibility to transit and accessibility to jobs for that site as well as neighboring sites (Singh et al., 2017).

Traditionally, accessibility is understood as “the potential of opportunities for interaction” (Hansen, 1959, p. 73) or “the ease with which any land-use activity can be reached from a location using a particular transportation system” (Burns & Golob, 1976, p.175). That being said, accessibility can be a performance measure for, and an outcome of TOD(-nesses) (e.g., Deboosere et al., 2018; Geurs et al., 2006; Pitot et al., 2006). Accessibility can serve as a TOD performance measure at the site (e.g., TSA), cluster (e.g., TSAC), city, and regional levels. Schlossberg and Brown (2004), for instance, assessed eleven TOD sites’ ATT, which was considered as a function of road classification, pedestrian catchment areas, and intersection intensity within a 5-minute and 10-minute walk from a rail station. At the city level, Papa and Bertolini (2015) showed that six European cities’ TOD degrees/performances could be measured and compared based on some ABT indicators, e.g., the numbers of residents and jobs accessible in 30 minutes by public transit. At the TSAC level, Lyu et al. (2019) quantified which dimension of the TOD-nesses contributed the most to the TSAC-level ABT to population and jobs in Beijing, China. They did not, however, explicitly define TSACs. They considered all the TSAs reachable from a given metro station within one hour of travel time by public transportation, i.e., the 60-minute TSACs. They found that the degree of centrality of a metro station and land-use pattern of the TSAC it belonged to contribute the most to the TSAC-level ABT.

2.2.3 TOD-ness and accessibility as separate concepts and variables

Once we treat TOD-ness and accessibility (including both the ATT and ABT) as two distinct concepts and variables, we can better single out their impacts on each other at some risk of simplifying the real-world complexities mentioned above concerning the embeddedness shared by both TOD-ness and accessibility. Many existing studies have already done so. To identify these studies, we adopted the backward/forward methods to search the Web of Science and Google Scholar databases to identify as many relevant refereed publications as possible. Papa and Bertolini (2015) was our starting point, which examined the relationship between TOD-nesses and accessibility (ABT) at the city level in the same year. To make our search manageable, we focused on the literature published between 1993 and 2019 (Appendix–Table A).

We found that TOD-nesses were positively related to accessibility, especially the ABT in the literature. A balance between them can improve the efficacy of TOD projects or TOD-ness supply (e.g., Bertolini, 1999; Geurs et al., 2006; Papa et al., 2013). In terms of TOD-nesses, most of the literature (n=23) dealt with a subset of the 5Ds. Individual Ds’ relationships with the ABT or ATT are heterogeneous. Density, for instance, when measured by the densities of development, population, and jobs, should be or were highly correlated to the ABT or ATT (e.g., Calthorpe, 1993; Farber & Marino, 2017; Pitot et al., 2006). Increasing job accessibility in one TSAC can improve the job densities of TSAs therein (Deboosere et al., 2018). However, a lower TSA-level resident density saw a larger number of residents and jobs reachable by public transit in 60 minutes (Lyu et al., 2019). Diversity, when measured by different land uses, functional mix, and employees at different workplaces, was highly correlated to the ABT and/or ATT (e.g., Atkinson-Palombo & Kuby, 2011; Cervero & Landis, 1997; Shen et al., 2014). Atkinson-Palombo and Kuby (2011) suggested that TSAs with higher ABT, which was measured by the numbers of people and jobs within some transit travel time from a TSA, could expect more mixed development. However, Chorus and Bertolini (2011), Lyu et al. (2019), and Ratner and Goetz (2013) found that diversities in land use or employment cannot always be predicted by ABT. Design (such as walking environment or transit facility provision) and distance to transit were positively correlated to ABT (e.g., Chatman, 2013; Lee et al., 2013; Schlossberg & Brown, 2004). None of the 23 studies investigated the relationships between Destination and the ABT/ATT. The reason might be that ABT/ATT have already (partially) been considered in TSA-level accessibility to destinations. When various Ds were measured by composite indices, such indices were found to be positively correlated to the ABT or some fusion of ABT and ATT (e.g., Bertolini, 1999; Bertolini & le Clercq, 2003; Papa & Bertolini, 2015).

Among the 23 studies, only a few formulated TOD-ness indicators beyond the TSA level. At the city level, the overall ABT to jobs, houses, transit stations, and other cities could positively influence the employee density, building density, and land-use pattern of the whole city (Knowles, 2012). Besides, a composite TOD-ness index, which considers how density is correlated to distance to public transportation across a city, could well predict the average numbers of residents and jobs reachable in 30 minutes by public transportation, i.e., some kind of ABT (Papa & Bertolini, 2015). A study from Shen et al. (2014) was the only one touching on the MSAC-level TOD-nesses. They found that the diversity of a TSA was affected by the population and land uses of its adjacencies. As for accessibility, 17 studies out of the 23 identified studies focused on the ABT. ABT was often considered as the number of opportunities reachable in a given travel time by transit from a transit station, which could be understood as indicators at the TSAC level (Deboosere et al.; 2018; Farber & Marino, 2017; Papa & Bertolini, 2015). However, corresponding indicators had not explicitly accounted for the existence of TSACs. Those indicators were only treated as a predictor of TOD-nesses at the TSA level. Thus, we know little about whether and how accessibility (ABT in particular) and TOD-nesses are correlated at the TSAC level. There are research gaps to be filled, as described below.

2.3 Gaps in the existing scholarship

Based on the above review of the existing literature, we can see that first, even though many have emphasized (a) reasons for the genesis and necessities of various TOD-nesses and (b) the importance of creating or enhancing TOD-nesses at the TSA and TSAC levels, they had rarely considered issues such as (a) (potential) consumers of TOD-nesses and their accessibility (ABT in particular) to a TSA and TSAC; (b) whether and how the ABT of the consumers is correlated to TOD-nesses at the TSAC level.

Second, little has been done empirically on whether and how the accessibility in one period can predict the TOD-nesses in ensuring periods at the TSAC level. But even piecemeal evidence has already indicated that it is likely.

Considering the above gaps in the existing literature, "accessibility" in this study is narrowly defined as the location-based ABT. It is "the catchment area from which people, goods, and information from different locations" can reach a transit station or a cluster of transit stations within a t-minute metro ride (c.f., Dijst et al., 2002; Geurs & van Wee, 2023, p. 227). Due to constraints posed by the empirical data that we collected, we only consider "people" when measuring the ABT in this study. We assume that regular and reliable transit services entice or enable people to consume facilities and services in not only one TSA but also the TSAC it belongs to. For the ABT, we think that it changes over time.

3 Empirical study

In this study, we aim to fill the above-mentioned gaps in the existing scholarship by quantifying the relationship between the TOD-nesses in one period and the ABT in its preceding period at the MSAC level based on empirical data we collected in Shenzhen, a fast-growing Chinese city famous for master-planned developments. We defined MSAC as a subset of metro station areas (MSAs) that are a t-minute (e.g., 15, 30, and 45 minutes) metro ride apart from a given metro station. As a shorthand, an MSAC associated with a t-minute metro ride is written as "t-min MSAC", where t is a preset number. Each MSA is the area within a reasonable walk, e.g., 10 minutes or 800 meters' walk from a metro station.

We hypothesized that:

(a) People from one MSA (e.g., a neighborhood TOD site) are willing to consume other facilities and services, including various TOD-nesses of the other MSAs (e.g., an Urban TOD site) in the same MSAC where metro services make facilities and services in an MSAC more accessible (c.f., Alexander 1954; Calthorpe, 1993; van Wee, 2011).

(b) The TOD-nesses at the MSAC level can be measured by the average of the D indicators or indices of all the MSAs in one MSAC and is correlated to the daytime/nighttime populations of all the MSAs in that MSAC, and these populations are the bulk of the "consumers" of the TOD-nesses in the MSAC.

(c) The correlation between the TOD-nesses and ABT varies across t-min MSACs and across periods. The variations can mean (c1) the (im)balance between the TOD-nesses and ABT across different types of MSACs over time, and (c2) which type of MSAC might see a better match between the TOD-nesses and ABT.

To test those hypotheses, we first defined and extracted different types of MSACs in Shenzhen, China for the Years 2014, 2016, and 2018. We then investigated the correlation between the TOD-nesses and ABT across the MSACs and periods.

Our study supplemented existing studies such as Cervero and Dai (2014), Knowles (2012), and Papa and Bertolini (2015), which examined only the relationship between the TOD-nesses and ABT for a fixed period at the city level. Our study also somewhat did the opposite to Lyu et al. (2019), which studied how the TOD-nesses of the 60-min MSACs contributed to the ABT of these MSACs. We examined how the accessibility of the past might be related to the MSAC-level TOD-nesses of the present—this has not been examined by Lyu et al (2019) and other existing studies. Unlike Papa and Bertolini (2015), which used a single index to measure both the overall level of TOD-nesses and its impacts, we formulated indicators that measure both one dimension of the TOD-nesses (e.g., density) and the overall TOD-ness level across Ds simultaneously. As for the accessibility (ABT) indicators, we considered the MSAC-level ABT to residents, employees, and both (c.f., Deboosere et al., 2018). Finally, we computed/borrowed indicators of the TOD-nesses and accessibility based on big and/or open data, which have rarely been used in the existing TOD scholarship. Thanks to wider spatiotemporal coverage of the big and/or open data, we were able to consider almost every MSA and MSAC in the study site simultaneously. In principle, if we were given full and continued access to the data, we can also monitor all the MSA and MSACs in the site continuously. In this study, we had only two periods' data and thus we actually only partially illustrated the full potential of big and/or open data in facilitating the TOD scholarship and practice.

Given that there can be different time thresholds, i.e., different t's when defining MSACs, our empirical study used 15, 30, 45, and 60 minutes as our t's. Both the minimum/base and increments used to define MSACs were 15 minutes because (a) there exists an emerging trend of 15-minute cities (c.f., EIT Urban Mobility, 2022; Moreno et al., 2021), and (b) Shenzhen's average metro travel time between any station pairs in 2019 was about 40 minutes based on the Baidu map, one the most popular online maps in China. We introduced the 15- to 60-min MSACs to allow us to better understand whether and how the ABT's impacts on TOD-nesses varied as t's change, i.e., across different types of MSACs.

3.1 The site

Shenzhen is one of the first-tier cities in China, with a population of 11.9 million and an administrative area of 1,997 square kilometers as of 2017 (SSB & NBSSOS, 2017). It is China's first Special Economy Zone (SEZ), which only included four administrative districts (Futian, Luohu, Nanshan, and Yantian) in 1980. SEZ was expanded in 2010, allowing the city to have more districts in the outskirts, e.g., Longgang and Baoan (See Figure 1). Shenzhen's metro system has grown significantly in the last few decades. By the end of 2014, the system had 118 stations and a total track length of 178 kilometers. The second half of 2016 saw another round of metro expansion. Districts like Luohu, Futian, Nanshan, and Baoan all welcomed new metro lines. The system ended up with 167 stations and a total track length of 285 kilometers as of 2016. As of 2022, the system had a length of 530 kilometers.

The metro system plays a critical role in (re)shaping land uses in Shenzhen. Building an extensive metro system and intensifying and optimizing land uses along it are city-wide TOD approaches adopted by the Shenzhen Municipal Government. Thus, Shenzhen provides a precious opportunity for one to study the relationships between TOD-nesses and accessibility (especially ABT) at the MSAC level as there have always been conscious and strong public interventions. In theory, there should be a more noticeable relationship between TOD-nesses and accessibility in Shenzhen than elsewhere.

We used the 116 metro stations built before and in 2014 in Shenzhen for the empirical study—two stations in the city were excluded due to the lack of data. We investigated the relationships between the TOD-nesses and ABT among those stations, especially the temporal lag impacts of the ABT on the TOD-nesses.

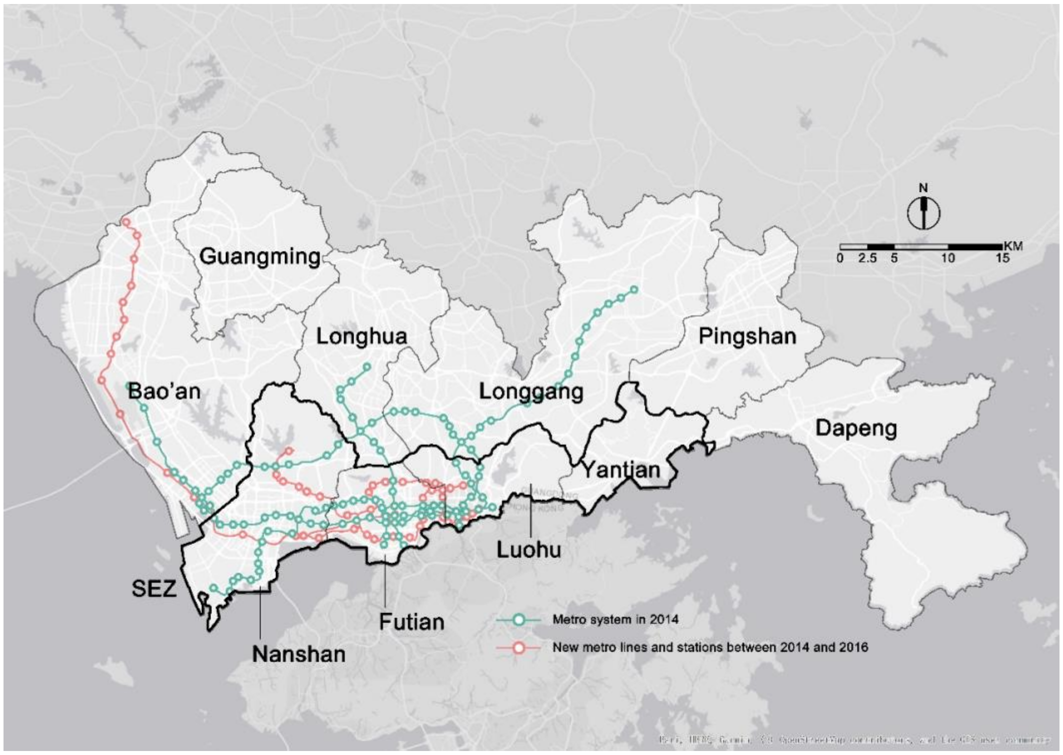


Figure 1. Metro network expansions in Shenzhen: 2014-2016
Sources: Figure created by author

3.2 Units of analysis: MSAs and MSACs

Most existing TOD studies focus on areas within a 10-minute walk (approximately 800 meters) from a metro station, which we call "10-min MSA" or simply "MSA" in this study (c.f., Cervero et al., 2002; Zhou et al., 2019). As mentioned above, we had extended related studies to the MSAC level. An MSAC is a cluster of MSAs within a certain travel time by metro from a given station. Figure 2 provides diagrammatic representations of the MSAs and MSACs in this study. $MSAC_A$ is a cluster of MSAs within *t*-min travel time by metro from station A. Station A is the core station of $MSAC_A$. Unlike MSAs that are often mutually exclusive, MSACs can share some common members, e.g., in Figure 2, $MSAC_A$ and $MSAC_C$ share MSA_A and MSA_C.

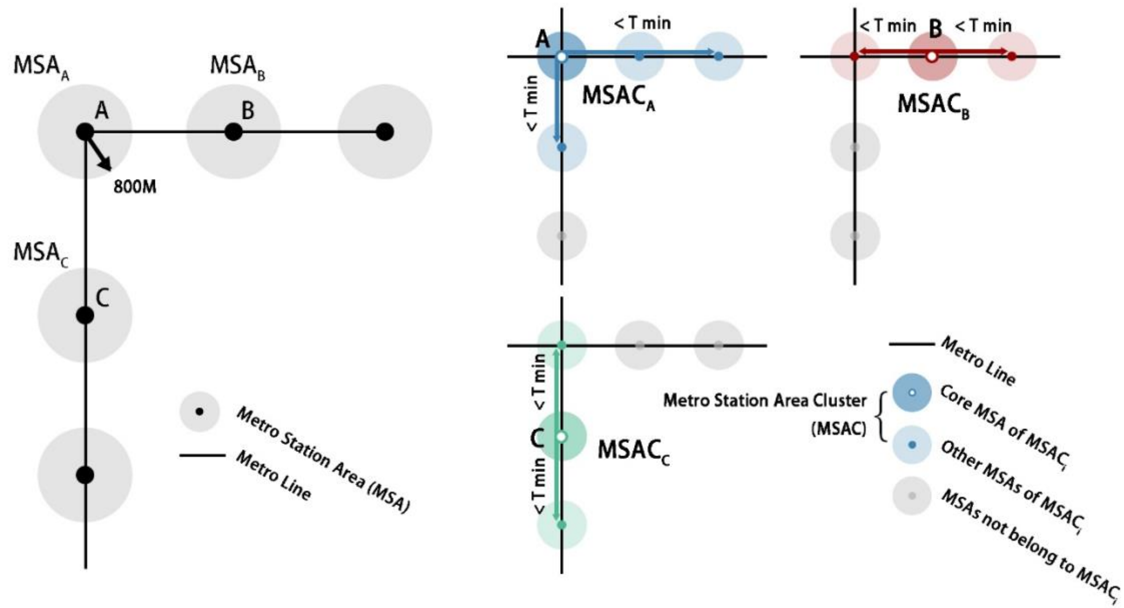


Figure 2. MSAs and MSACs
Sources: Figure created by author

A typical rider's travel time between any two metro stations can be derived by Baidu map services, one of the most popular of its kind in China. Such services allow one to derive the shortest travel time by different modes of travel between any two nodes on an existing multimodal transportation network. Based on such services, a matrix containing the shortest travel time between any station pairs in Shenzhen, or any other city can be created. The matrix for Shenzhen allows us to identify different MSACs, e.g., 15-min and 30-min MSACs in the city.

3.3 The data

Our data for this study came from two sources. Regarding the TOD-nesses, we did not collect our empirical data; instead, we adapted indicators from Gu et al. (2019) and the China TOD Mapping Platform (CityDNA, 2020),[1] which derived four composite indices (the overall TOD-nesses, Density, Diversity, and Design) to measure the overall TOD-nesses and three Ds: Density, Diversity, and Design for each MSA (the 800m-radius buffer of a station) in Shenzhen and other Chinese cities (see Table 1) for both 2016 and 2018. The indices range from 0 to 100, where 100 is the best among all the samples/subjects being evaluated. Like Lyu et al. (2019), the MSAC-level TOD-nesses is the average of corresponding indicators of all the MSAs belonging to the same MSAC.

[1] The details of data from the China TOD Mapping Platform could be referred to as Appendix–Table B.

Table 1. Variable description

Dimension	Variables	Mean (stdev)							
Dependent variables		***2016***				***2018***			
		15-min MSAC#	*30-min MSAC#*	*45-min MSAC#*	*60-min MSAC#*	*15-min MSAC#*	*30-min MSAC#*	*45-min MSAC#*	*60-min MSAC#*
TOD-ness	Overall TOD-ness	81.88 (3.1)	81.78 (1.55)	81.86 (0.6)	81.77 (0.33)	80.31 (2.28)	80.12 (1.37)	80.18 (0.72)	80.16 (0.48)
	Density: Population density; Density gradient; Employ-ment density	74.82 (2.56)	74.66 (1.42)	74.80 (0.64)	74.78 (0.33)	76.29 (2.81)	76.23 (1.57)	76.31 (0.73)	76.25 (0.45)
	Diversity: Ground-floor retail density; Land-use mix; Number of bus lines	75.92 (1.38)	75.88 (0.69)	75.90 (0.47)	75.87 (0.26)	76.62 (2.07)	76.51 (1.50)	76.57 (0.91)	76.53 (0.52)
	Design: Expressway density; Number of parking facilities; Street network density; Number of metro exits	77.37 (3.16)	77.35 (1.55)	77.36 (0.76)	77.23 (0.22)	75.36 (1.29)	75.10 (0.51)	75.10 (0.30)	75.14 (0.15)
Independent Variables									
MSAC*		***2014***				***2016***			
		15-min MSAC#*	*30-min MSAC*#*	*45-min MSAC*#*	*60-min MSAC*#*	*15-min MSAC*#*	*30-min MSAC*#*	*45-min MSAC*#*	*60-min MSAC*#*
Population Accessibility	The number of daytime and nighttime population (million)	0.63 (0.52)	1.39 (0.68)	2.04 (0.5)	2.34 (0.22)	0.93 (0.83)	2.10 (1.00)	2.95 (0.71)	3.33 (0.28)
	The number of daytime population (million)	0.10 (0.08)	0.23 (0.11)	0.32 (0.08)	0.36 (0.03)	0.14 (0.12)	0.32 (0.15)	0.44 (0.1)	0.48 (0.04)
	The number of nighttime population (million)	0.53 (0.44)	1.17 (0.57)	1.71 (0.42)	1.98 (0.18)	0.79 (0.71)	1.78 (0.85)	2.51 (0.61)	2.85 (0.24)
15-min MSAC**									
		2014				***2016***			
		15-min MSAC#*	*30-min MSAC*#*	*45-min MSAC*#*	*60-min MSAC*#*	*15-min MSAC*#*	*30-min MSAC*#*	*45-min MSAC*#*	*60-min MSAC*#*
Station (area) character-istics	Luohu The percentage of stations located in Luohu within an MSAC	0.13 (0.18)	0.13 (0.10)	0.14 (0.06)	0.14 (0.03)	0.14 (0.19)	0.14 (0.15)	0.15 (0.09)	0.15 (0.06)
	Longhua The percentage of stations located in Longhua	0.07 (0.19)	0.07 (0.06)	0.08 (0.03)	0.08 (0.01)	0.07 (0.18)	0.05 (0.06)	0.06 (0.03)	0.06 (0.01)

within an MSAC								
Longgang The percentage of stations located in Longgang within an MSAC	0.18 (0.31)	0.17 (0.23)	0.16 (0.15)	0.16 (0.06)	0.16 (0.30)	0.12 (0.23)	0.11 (0.15)	0.11 (0.07)
Baoan The percentage of stations located in Baoan within an MSAC	0.12 (0.27)	0.09 (0.16)	0.10 (0.07)	0.11 (0.03)	0.11 (0.24)	0.14 (0.24)	0.13 (0.15)	0.13 (0.07)
Longhua & Longgang The percentage of stations located in Longhua & Longgang within an MSAC	0.25 (0.36)	0.24 (0.23)	0.24 (0.14)	0.23 (0.05)	0.23 (0.35)	0.16 (0.24)	0.17 (0.15)	0.17 (0.08)
Terminal The percentage of terminal stations within an MSAC	0.03 (0.05)	0.02 (0.02)	0.02 (0.01)	0.02 (0.00)	0.03 (0.05)	0.03 (0.02)	0.04 (0.01)	0.04 (0.00)

Notes:

* The number of observations is 116. Here, MSA is defined as areas within 10 minutes' or 800 meters' walk from a metro station. Within each MSAC, only daytime and nighttime population within a member MSA are considered. The daytime and nighttime population are calculated using the May 2016 Baidu population heatmaps.

** Station (area) characteristics of other MSACs are available upon request.

The average number of MSAs in different types of MSACs ranges from 24 to 107 and 35 to 149 in 2014 and 2016, respectively.

With respect to the accessibility indicators, we used the station-to-station travel time matrices and estimated population based on the Baidu map services as input to calculate them. The matrices' derivation was quite straightforward and was based on the open-source Baidu map API (https://lbsyun.baidu.com/). It was relatively more complicated to get the estimated population. However, existing studies such as Zhou et al., (2018) have well documented how to do it. We simply followed them in this study. A little more detail about the "how" is as follows.

The Baidu map services offer population heatmaps, which show the number of smartphone users who used any location-based services (LBS) app supported by Baidu, which accounts for 70% share of the LBS market in China (Baidu, 2019). The number of smartphone users by MSA can be derived to represent the hourly population and its spatial distribution in Shenzhen. Specifically, we employed the numbers of smartphone users at 10 am and 11 pm when formulating the accessibility indicators concerning the daytime and nighttime populations in 2014 and 2016. We could not get the 2014 Baidu population heatmaps and thus we had to assume that the daytime and nighttime population for a locale did not change significantly in Shenzhen in two years, i.e., between 2014 and 2016. This is not totally unreasonable—if we had used the local census data, the temporal interval between any two waves of the data would be ten years. There were alternative sources of information for the Baidu population heatmaps such as cellular network data and Gaode Map in the context of Shenzhen. However, we were unable to pay for the acquisition cost—they were not affordable to us as of this manuscript was drafted. Thus, we decided to stick to the Baidu population heatmaps, the acquisition cost of which was manageable to us—also to other researchers who want to do similar studies.

We hypothesized that it takes time for accessibility to form a relationship with TOD-nesses in MSAs or MSACs. In other words, there is a temporal lag between accessibility and TOD-nesses. Based on the data/indicators that we could access; we formulated four sets of TOD-ness and accessibility indicators (See Table 2). The two -year lag in the table is not ideal—few changes might take place. However, the data for two years was the best that we could achieve. If possible, data for more years should be employed so as to better understand how long it takes for good accessibility to result in good TOD-nesses at the MSAC level.

Table 2. Two sets of the TOD-ness and accessibility indicators

Indicators / Year	**Set 1**	**Set 2**
TOD-nesses**	2016*	2018#
Accessibility (ABT)##	2014	2016

* The TOD-ness indicators at the MSAC level are based on the data for 2014, adapted from Gu et al. (2019) and CityDNA (2020);

The TOD-ness indicators at the MSAC level are based on the data for 2016, adapted from Gu et al. (2019) and CityDNA (2020);

Both years' nighttime and daytime populations are estimated based on the Baidu population heatmaps in 2016. More technical details regarding how to estimate the populations can be found in Zhou et al. (2018).

In terms of *t*'s used to define the MSAC-level accessibility, we adopted those by the existing studies, e.g., Farber and Marino (2017) and Papa and Bertolini (2015), which used travel time by public transportation to define ABT. Specifically, for a *t*-min MSAC, its accessibility is defined as the total number of opportunities in all the MSAs that belong to that MSAC. Similar to Deboosere et al. (2018), we considered opportunities as the daytime/nighttime population (for 2014 and 2016) in this study.

For *t*-min MSAC's accessibility:

$$A^{t}_{M-SAC_i} = \sum_{t[MSA_i, MSA_j] < t\ min} N_{MSA_j} \quad (1)$$

where $MSAC_i$ is a subset of MSAs within a *t*-min metro ride from MSA_i, say 10, 15, 30, 45, and 60 minutes. $NMSA_j$ is the number of opportunities within a member MSA in

$MSAC_i$. Here, each MSA is defined as areas within 10 minutes' or 800 meters' walk from a metro station.

We also consider other factors that might relate to TOD-nesses, in particular, station (area) characteristics (See Table 2). Similar factors such as how the centrality of a station within the local metro network and the incidence of new development (See Table A in Appendix) were also accounted for in many existing studies, e.g., Cervero and Landis (1997), Chatman (2013), and Farber and Marino (2017). Thus, we are defendable in terms of considering or controlling for factors other than accessibility that could possibly be related to TOD-nesses.

3.4 Descriptive statistics

Table 1 presents the details about the TOD-ness and accessibility indicators in this study. Interestingly, the differences in the TOD-ness indices across MSACs in Shenzhen were so small, which were all less than one for both 2016 and 2018. This could mean that few changes took place in two years. In 2016, Design, which is quantified by the street network and transit facility provision, saw higher scores than Density and Diversity. This could be because the earliest metro lines were located in the most developed subareas of the city, where street networks were dense and transit facilities were relatively abundant. In 2018, Diversity enjoyed higher scores than Design and Density. This might be because locales with more mixed land uses had started being served by metro services. The MSAC-level accessibility between 2014 and 2016, as expected, increased notably as more people could access metro services in different locales, where there used to be fewer or no metro services. Table 1 also presents station (area) characteristics of the different MSACs. Two most notable changes were that: (a) the percentage of stations/MSAs by MSAC enjoyed by different districts (except for Longhua and Longgang) remained relatively stable despite the local metro network's constant and large-scale expansion; (b) there were higher percentages of terminal stations within the 30, 45-, and 60-min MSACs as the local metro network expanded.

3.5 Index analyses

Because we dealt with the (spatial) correlation between two sets of indicators measuring TOD-nesses and accessibility, we started from three simple quantitative methods: the coefficient of geography association (CGA), Gini index, and pairwise correlation. These methods all produce some absolute values between 0 and 1. Based on the magnitudes of these values, we can quickly ascertain whether and to what degree the correlation exists.

The CGA measures the variance in the spatial distribution pattern of two items. The function was introduced by Alexander (1963) and later adapted by Hu (1986) and Liu and Chen (2004) to compare the spatial pattern of industries and population in China (Hu, 1986; Liu & Chen, 2004):

$$\mathrm{CGA} = 100 - \frac{1}{2}\sum_{i=1}^{n}|F_i - S_i| \tag{2}$$

F_i is the percentage of Item F that location i has; S_i is the percentage of Item S that location i has; n is the total number of locations.

In our study, F_i is the ranking of the overall TOD-nesses in $MSAC_i$ and S_i is the ranking of the accessibility to the daytime and nighttime population of $MSAC_i$. Our CGA analyses indicate that the 15-min MSACs enjoyed the highest CGA value across the four levels of MSACs (see Figure 3a). This means that the 15-min MSACs were more likely to supply TOD-nesses according to their enjoyed accessibility. As the local metro network expanded, the spatial correlation between F_i and S_i measured by the CGA decreased except for the 60-min MSACs. In other words, the supply of TOD-nesses no longer followed the accessibility to a degree like it did in the past when there was relatively insufficient supply of metro services across the city.

Gini index is often used as a measure of inequality of the income or wealth distribution of a nation's residents. It is calculated as follows.

$$\text{Gini} = \frac{A}{A + B} \tag{3}$$

A is the area between a Lorenz curve and the line of equality; B is the area under the Lorenz curve. The ratio of A in the total area under the line of equality (A+B) is the Gini index. A Lorenz curve is a cumulative proportion of the population (listed by their income or wealth in the ascending order) against the cumulative proportion of the income earned by the population (Bowman, 1945; Morgan, 1962).

In our study, the Lorenz curve is a cumulative proportion of the accessibility (listed by the overall TOD-ness ranking in the ascending order) against the cumulative proportion of the overall TOD-ness ranking. In the ideal scenario, the higher the accessibility that an MSAC enjoys, the higher its TOD-ness ranking should be. Thus, the smaller the Gini indices, the more concentrated that the high TOD-ness ranking is among few MSACs with high accessibility. Our Gini Index analyses indicate that:

(a) The 30-min and the 45-min MSACs saw a higher concentration of the (high-ranking) TOD-nesses among few MSACs than the 15- and 60-min MSACs for both the periods: 2014-2016 and 2016-18.

(b) For the 15-min and 60-min MSACs, the (high-ranking) TOD-nesses were shared across more of the MSACs for both the two periods.

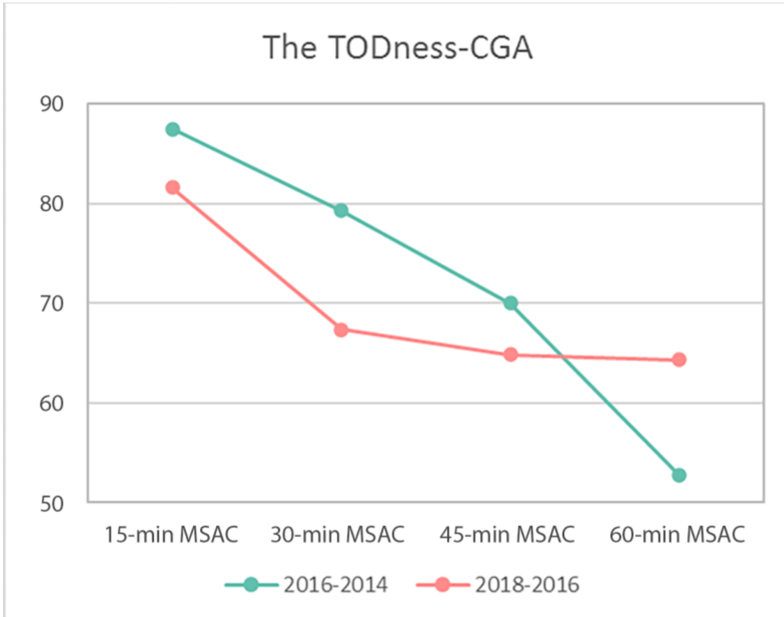
(c) For the 60-min MSACs, the relative concentration of the (high-ranking) TOD-nesses across the MSACs seemed to increase notably over time (see Figure 3b). This could mean that as the local metro network expanded, more and more MSAs had emerged but their TOD-nesses might not be there or were far below the long-established MSAs.

Pairwise correlation is a statistical measure indicating the strength of the relationship between two variables. The value of the coefficient ranges from -1 to 1. The larger the absolute value, the stronger the relationship. A correlation of 0 means no connection between two variables. In this study, we computed the correlation coefficients between the overall TOD-nesses and accessibility at the MSAC level, i.e., all the daytime and nighttime population in all the MSAs that are within a *t*-minute metro ride from a metro station.

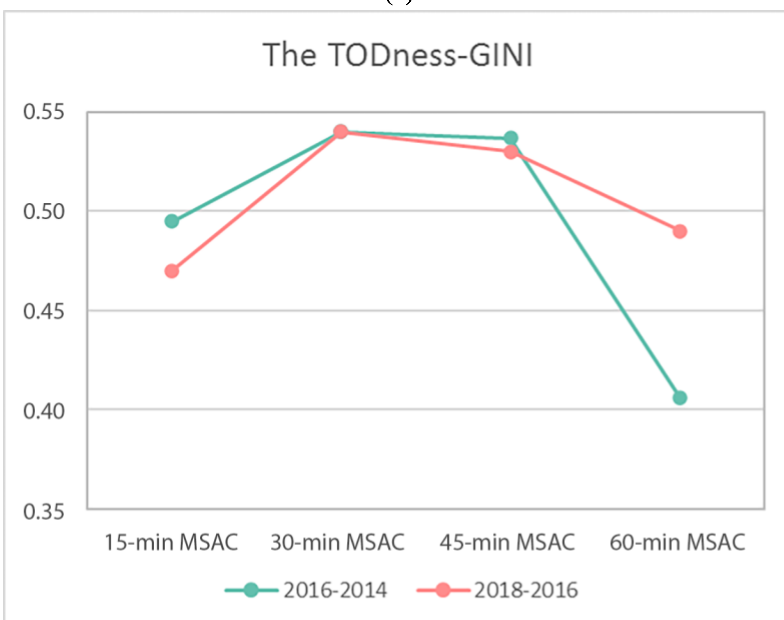
$$\rho_{xy} = \frac{\text{Cov}(x,y)}{\sigma_x \sigma_y} \tag{4}$$

Cov is the covariance of variables. σ is the standard deviation of variables.

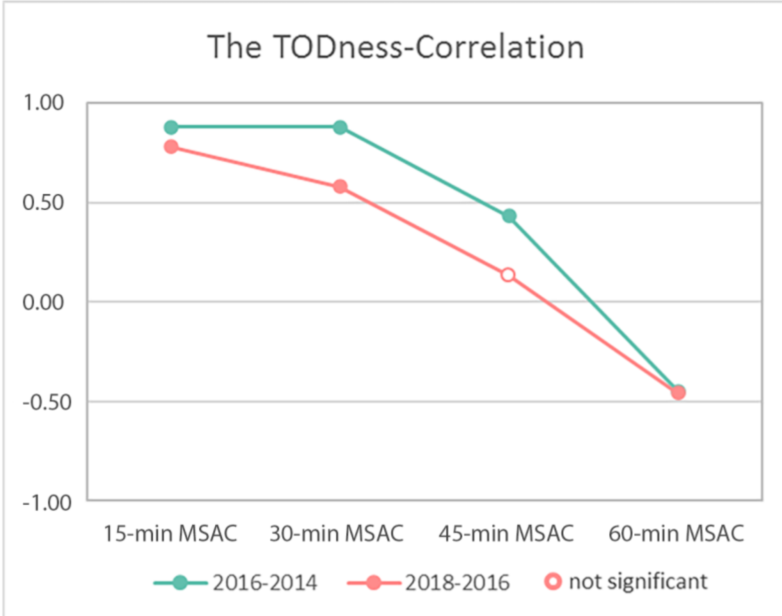
Our correlation coefficient analyses indicate that except for the 60-min MSACs, there was always a strong positive correlation between the overall TOD-nesses in 2018/2016 and the accessibility in 2016/2014 for the MSACs (see Figure 3c). This finding supplements Lyu et al. (2019), which found that Density and Diversity had mixed impacts on the accessibility for the 60-min MSACs in Beijing. The correlation between the overall TOD-ness and the accessibility at the 15-min MSAC level was the strongest across the four levels of MSACs, which indicates that the 15-min MSACs on average enjoyed a better match between the TOD-nesses and accessibility than other MSACs.


The TODness-CGA
90
80
70
60
50
15-min MSAC
30-min MSAC
45-min MSAC
60-min MSAC
2016-2014
2018-2016

(a)


The TODness-GINI
0.55
0.50
0.45
0.40
0.35
15-min MSAC
30-min MSAC
45-min MSAC
60-min MSAC
2016-2014
2018-2016

(b)



(c)

Figure 3. Index analyses
Sources: Figure created by author

3.6 OLS regression results

The above analyses indicate that it was always the 15-min MSACs that saw the strongest correlation between the TOD-nesses and accessibility over time. We thus selected the 15-min MSACs as the representatives of the four levels of the MSACs to quantify to what degree the 2014/2016 accessibility can predict the 2016/2018 TOD-nesses.

We first ran simple regression models to see whether and to what degree the 2014 and 2016 accessibility alone could predict the 2016 and 2018 TOD-nesses. Then, we executed the stepwise regression models in Stata 15 to see how the accessibility and station (area) characteristics together were related to the TOD-nesses. We used a Variance Inflation Factor value of 4 to handle the collinearity issues. That value is considered a robust standard to obtain unbiased standard errors when heteroscedasticity exists (Wooldridge, 2006). Given that we were unable to collect data to quantify as many as independent variables as we would like to, we had to overlook impacts of many possible variables (e.g., MSAs receiving more private investment) on the TOD-nesses, including time and fixed effects of some omitted variables (e.g., non-random, continued, and increased investment occurring at some MSAs), which can vary over time. Moreover, we could only quantify the 2016 accessibility due to data constraints and used related indicators for both 2014 and 2016. Lastly, we used only dummy variables for the station (area) characteristics. As a result, we were unable to run fixed effect regression models either.

3.6.1 Overall TOD-nesses, accessibility, and station (area) characteristics

In Table 3, without station (area) characteristics, the 2014 or 2016 accessibility alone explains at least 60% of the variation of the 2016 and 2018 overall TOD-nesses for the 15-min MSACs, respectively.

Not surprisingly, the accessibility to daytime population, nighttime population, or both was positively correlated to the overall TOD-nesses across all eight prediction models. This was generally in line with Papa and Bertolini (2015) and Singh et al. (2017), which both found a positive correlation between the accessibility to residents and/or employment and TOD-nesses across different geographical levels. Compared to those studies, however, our results indicate more nuanced relationships of the different levels of the accessibility on the TOD-nesses. The accessibility to the daytime and nighttime populations combined always explained the most variations in the overall TOD-nesses. However, the correlations between the accessibility and the overall TOD-nesses declined as the local metro network expanded. Station (area) characteristics also partially and notably explained the variations in the overall TOD-nesses. Specifically, being in the youngest administrative district (Longhua) would see lower overall TOD-nesses whereas being in the oldest district (Luohu) would see higher one. Moreover, our results indicate the temporal lag effects of the accessibility on the TOD-nesses, which were not reported in the existing studies.

Table 3. The Regression results for the overall TOD-ness

	2016				**2018**			
Ind. Variable / TOD-ness (2016 or 2018)	**15-min MSAC (Model 1)**	**15-min MSAC (Model 2)**	**15-min MSAC (Model 3)**	**15-min MSAC (Model 4)**	**15-min MSAC (Model 5)**	**15-min MSAC (Model 6)**	**15-min MSAC (Model 7)**	**15-min MSAC (Model 8)**
2014 Accessibility to					**2016 Accessibility to**			
Daytime & Nighttime population (million)	5.28***	3.74***			2.15***	1.24***		
	(0.27)	(0.18)			(0.14)	(0.11)		
	[0.88]	[0.62]			[0.78]	[0.45]		
Daytime population (million)			21.26***				7.53***	
			(1.12)				(0.81)	
			[0.56]				[0.39]	
Nighttime population (million)				4.46***				1.46***
				(0.23)				(0.13)
				[0.63]				[0.45]
Longhua		-3.81***	-4.20***	-3.74***				
		(0.41)	(0.50)	(0.44)				
		[-0.23]	[-0.25]	[-0.22]				
Luohu		6.37***	8.02***	6.12***		6.24***	6.99***	6.14***
		(0.41)	(0.51)	(0.56)		(0.33)	(0.38)	(0.33)
		[0.36]	[0.46]	[0.35]		[0.52]	[0.59]	[0.51]
Cons	78.57***	79.02***	79.06***	79.03***	78.30***	78.28***	78.27***	78.29***
	(0.22)	(0.15)	(0.18)	(0.14)	(0.22)	(0.20)	(0.21)	(0.19)
R^2	0.77	0.93	0.91	0.93	0.60	0.77	0.75	0.77

*** Indicators significance at the 99% level.

** Indicators significance at the 95% level.

* Indicators significance at the 90% level.

Notes: (Robust) standard coefficients in brackets and (Robust) standard deviation in parentheses. The number of observations is 116.

3.6.2 Ds, accessibility, and station (area) characteristics

Table 4 shows the stepwise regression results concerning how the accessibility and station (area) characteristics together are related to the three Ds: Density, Diversity, and Design. Several notable findings can be observed. First, the accessibility always significantly predicts the Ds.

Second, except for the relationship between the 2014 accessibility and the 2016 Design, it was the accessibility to the nighttime population that explained the most variations in the Ds' scores. This indicates that the supply of the three Ds, assuming that it was purely determined by the market force, was better predicted by the accessibility to the nighttime population.

Third, besides the accessibility, different station (area) characteristics were significantly related to the Ds. When the accessibility was controlled for, for instance, the percentage of stations in Longhhua and Longgang, two administrative districts in the outskirts of Shenzhen were negatively correlated to the Diversity and Design scores, respectively.

Fourth, the explanation power of the accessibility for Design diminished over time, which indicated that the correlation between the accessibility and Design scores became weaker as the local metro network expanded into more low-density suburbs that had yet well-developed. Somehow surprisingly, the correlations between the accessibility and Density/Diversity scores became stronger as the local metro network expanded. We had expected that MSAs along the new metro lines would form 15-min MSACs that saw lower Density/Diversity scores.

4 Discussion and conclusions

TOD is a popular strategy and model for promoting the symbiosis of land use and public transportation. The existing scholarship, however, has paid more attention to the correlation of TOD-nesses (as a special form of land use) and TBA (as the underlying goal of public transportation) for one period or as an end state than to the co-evolution and interactions between the two over time or as continued processes. In this study, we show that there are such gaps to be filled. We illustrate how to collect empirical data or use existing indicators to measure both the TOD-ness and TBA and what kind of quantitative methods can be employed to examine their co-evolution and interactions, especially how TBA of one period is related to TOD-nesses in the ensuing period.

More specifically, by treating TOD-nesses and TBA as two separate variables based on empirical data from Shenzhen, China, we found that there always existed a strong correlation between the TBA to night/daytime populations or both in the past and TOD-nesses at present at the MSAC level in the city—similar findings had not been presented in the existing literature we reviewed (see Table A in Appendix). Plus, the correlation was often stronger at first but became weaker over time. This could mean that the accessibility was correlated to the TOD-nesses more prior to the local metro network expansion. In other words, some consumers of the TOD-nesses might suffer decreased TBA despite the local metro network expansion. This was inconsistent with what the existing literature had argued for (e.g., Bertolini & le Clercq, 2003; Geurs et al., 2006)—there should be a match between TBA and TOD-nesses.

Across different levels of MSACs (e.g., 15- and 30-min MSACs), the correlation between the TOD-nesses and TBA saw different patterns of evolution over time. Most notably, the 15-min MSACs were more likely to "supply" the TOD-ness according to the accessibility that they enjoyed. This is in general consistent with what the 15-minute cities advocates have argued for. In other words, riders/people would like to have and "consume" facilities and services within some reasonable travel time from their residences or workplaces, ceteris paribus. Except for the 60-min MSACs, the supply of TOD-nesses no longer followed the accessibility to a degree like it did in the past as the local metro network expanded. It was possible that with more locales, MSAs, and/or MSACs being connected to one another by the local metro network, people would "consume" facilities and services (including the TOD-nesses) in more (once remote) locales, MSAs, and even MSACs. It was also possible that more facilities and services were available or concentrated in MSAs along the (expanded) local metro network. With newly provided metro services and/or improved metro-based accessibility, metro riders thus have more options along the network. This also explained why the correlation between the TOD-nesses and accessibility over time became stronger for the 60-min MSCAs, despite that many new MSAs were often (once) less developed than the existing ones as the local metro network expanded. In the existing literature we reviewed, we were unable to identify similar nuanced findings concerning the correlation between TOD-nesses and TBA across different levels of MSACs across periods. These findings, however, are important for us to evaluate issues such as whether consumers of TOD-nesses enjoy the same level of TBA across different levels of MSACs and where the correlation between TOD-nesses and TBA should be strengthened so as to retain or increase the number of consumers.

We noticed that the variations in the TOD-ness and its three dimensions: Density, Diversity, and Design in one period were significantly explained by the accessibility in an earlier period. However, the explanation power of the accessibility changed over time. In other words, when predicting how much TOD(-ness) can emerge or change at the MSAC level in the future given the current or future population (distribution) and transit services serving it, we should not overlook such possible "diminishing returns" and varying demand for, and supply of different Ds at the MSAC level. This has not been presented in the existing literature, which mostly dealt with TOD-nesses and accessibility at the MSA level. Compared to the existing literature, our study has also shown more nuanced differences in the relationships between the accessibility in one period and TOD-nesses in a later period at the MSAC levels. Notably, at the 15-min MSAC level, the 2014/2016 accessibility was positively correlated to 2016/2018 Density and Diversity scores and the positive correlations became larger over time. Also, the 2014/2016 accessibility was positively correlated to the 2016/2018 Design scores whereas the relationships became smaller over time.

In addition to the above, we found that when the accessibility was controlled for, station (area) characteristics could at times significantly predict different dimensions of TOD-ness at the 15-min MSAC level. For example, all the three Ds' variations tended to be explained by only one station characteristic: the percentage of MSAs of the same MSAC in certain administrative district(s). This can mean that institutions at the local level might have significant/more impacts on the supply of TOD-ness.

Table 4. Regression results for the three Ds: Density, diversity, and design

Ind. Variable	**Density**							
	2016				**2018**			
2014 or 2016	**15-min MSAC**				**15-min MSAC**			
Accessibility to	**(M1)**	**(M2)**	**(M3)**	**(M4)**	**(M5)**	**(M6)**	**(M7)**	**(M8)**
Daytime & Nighttime population (million)	3.51 *** (0.33) [0.71]	1.49 *** (0.20) [0.30]			2.83 *** (0.16) [0.83]	1.74 *** (0.14) [0.51]		
Daytime population (million)			8.31 *** (1.22) [0.26]				11.33 *** (0.85) [0.48]	
Nighttime population (million)				1.79 *** (0.24) [0.31]				2.02 *** (0.17) [0.51]
Longhua		-1.72 ** (0.68) [-0.12]	-1.88 *** (0.71) [-0.14]	-1.69 ** (0.68) [-0.12]				
Luohu		9.58 *** [0.66] (0.47)	10.28 *** [0.71] (0.44)	9.47 *** [0.65] (0.49)		7.45 *** (0.52) [0.50]	8.25 *** (0.41) [0.56]	7.37 *** (0.55) [0.50]
Baoan								
Longgang								
Longhua & Longgang								
Cons	72.62 *** (0.27)	72.81 *** (0.21)	72.84 *** (0.22)	72.81 *** (0.21)	73.63 *** (0.24)	73.61 *** (0.19)	73.52 *** (0.20)	73.64 *** (0.19)
R^2	0.50	0.82	0.82	0.82	0.68	0.83	0.84	0.83

Ind. Variable	**Diversity**							
	2016				**2018**			
2014 or 2016	**15-min MSAC**				**15-min MSAC**			
Accessibility to	**(M1)**	**(M2)**	**(M3)**	**(M4)**	**(M5)**	**(M6)**	**(M7)**	**(M8)**
Daytime & Nighttime population (million)	1.32 *** (0.20) [0.50]	1.14 *** (0.21) [0.43]			1.19 *** (0.17) [0.48]	1.98 *** (0.12) [0.80]		
Daytime population (million)			5.70 *** (1.37) [0.34]				12.06 *** (1.24) [0.70]	
Nighttime population (million)				1.38 *** (0.23) [0.44]				2.34 *** (0.14) [0.81]
Longhua		-2.46 *** (0.57) [-0.33]	-2.74 *** (0.60) [-0.37]	-2.41 *** (0.41) [-0.32]				
Luohu								
Baoan								
Longgang								
Longhua & Longgang						4.14 *** (0.40) [0.71]	3.80 *** (0.42) [0.65]	4.18 *** (0.40) [0.71]
Cons	75.09 *** (0.20)	75.38 *** (0.18)	75.55 *** (0.19)	75.36 *** (0.21)	75.50 *** (0.29)	73.82 *** (0.16)	74.05 *** (0.27)	73.81 *** (0.16)
R^2	0.25	0.35	0.29	0.36	0.23	0.63	0.52	0.64

Ind. Variable	**Design**							
	2016				**2018**			
2014 or 2016	**15-min MSAC**				**15-min MSAC**			
Accessibility to	**(M1)**	**(M2)**	**(M3)**	**(M4)**	**(M5)**	**(M6)**	**(M7)**	**(M8)**
Daytime & Nighttime population (million)	5.64 *** (0.21) [0.92]	4.40 *** (0.17) [0.72]			0.81 *** (0.11) [0.52]	0.68 *** (0.13) [0.44]		
Daytime population (million)			28.82 *** (1.43) [0.74]				3.93 *** (0.94) [0.37]	
Nighttime population (million)				5.09 *** (0.20) [0.71]				0.80 *** (0.15) [0.44]
Longhua		-4.95 *** (0.39) [-0.29]	-5.34 *** (0.47) [-0.31]	-4.96 *** (0.40) [-0.29]				
Luohu								
Baoan		-1.35 *** (0.32) [-0.11]	-0.45 (0.42) [-0.04]	-1.60 *** (0.32) [-0.14]				
Longgang		-2.76 *** (0.27) [-0.27]	-2.49 *** (0.34) [-0.25]	-2.88 *** (0.27) [-0.28]				
Longhua & Longgang						-0.72 * (0.40) [-0.20]	-0.86 ** (0.40) [-0.23]	-0.70 * (0.40) [-0.19]
Cons	73.82 *** (0.21)	75.61 *** (0.19)	75.37 *** (0.25)	75.74 *** (0.19)	74.61 *** (0.19)	74.90 *** (0.25)	75.01 *** (0.26)	74.89 *** (0.25)
R^2	0.85	0.95	0.93	0.95	0.27	0.31	0.26	0.31

*** Indicators significance at the 99% level. ** Indicators significance at the 95% level. * Indicators significance at the 90% level.

Notes: (Robust) standard coefficients in brackets and (Robust) standard deviation in parentheses. M=Model. The number of observations is 116.

A good correlation between TBA and TOD-nesses across different spatial scales over time is always desirable. But it is not guaranteed. Our empirical study of Shenzhen enables us to show that the city had in general maintained a good correlation between the TBA and TOD-nesses at the MSAC level over time. This is uneasy given that the city had significantly expanded its metro network and built-up areas and had seen big population growth in few decades. Without the MSAC level analyses, we would be unable to identify many of the meso-level dynamics among the accessibility, station characteristics, and TOD-nesses highlighted above. Knowing these dynamics allows us to better monitor, predict, and plan for "the supply" of the TOD-nesses (or the lack of it) across MSAs within a short metro ride, i.e., at the meso- or MSAC-levels. The existing literature we reviewed contains little information about such dynamics. Thus, we had filled a gap therein.

Despite the above progresses made; our study can be improved in several aspects in the future. First, we could have introduced more accurate indicators when measuring TOD-nesses. Now, only several composite indices concerning three Ds by a third party are used. These indices did not allow us to see exactly which of the individual TOD-ness elements, e.g., street network and restaurant densities, was correlated to the accessibility. There can also be endogeneity issues because the 2014/2016 accessibility to daytime/nighttime population and the 2016/2018 Density index could somehow overlap—for instance, both consider employees in MSA(s).

Second, we could collect additional information concerning people's perception of the TOD-ness and accessibility—in the end, the benefits of TOD or TOD-ness such as increased transit usage and agglomeration effects of employers/employment in MSAs and MSACs would depend on people's actual perception and "consumption" of the TOD-ness and accessibility (c.f., Laaly, et al., 2017).

Third, we could test more hypotheses concerning the accessibility and TOD-nesses, e.g., accessibility as one component of TOD-ness (c.f., Singh et al., 2017) and their bilateral relationship, i.e., how the accessibility and TOD-nesses interact with each other over more time periods. Of course, doing that would require more continuous input data concerning TOD-nesses and accessibility, e.g., land-use density and diversity data by year and even by month and corresponding up-to-date schedules and quality of service information of different transit services. It would also involve an innovative formulation of new and/or better indicators/indices to measure TOD-nesses and accessibility and simultaneously applying more advanced statistical models, e.g., structural equation models and non-recursive models.

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Author contribution

J. Zhou: Conceptualization. J. Zhou and Y. Yang: Methodology and formal analysis. J. Zhou and Y. Yang: Writing.

Appendix

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