Are Singapore's new towns self-contained? An examination based on the post-COVID-19 public transport smart card data*

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Abstract

Self-containment is a major planning objective for new town development. This study assesses the self-containment levels of Singapore's new towns and planned centers by analyzing the geography of commuting and non-commuting passenger flows among selected regional centers, sub-regional centers and town centers. Specifically, we utilize the public transport smart card data from the Land Transport Authority – Singapore's transit authority – in 2021-2022, and explore two sets of questions: 1) are the service sheds of new towns/planned centers for commuting and non-commuting travel purposes locally confined or city-wide? 2) how does the spatial extent of new towns'/centers' service sheds vary by the regional-, sub-regional- and town-center ranks? The findings imply whether and to what extent the new towns/centers in Singapore are "self-contained" or economically interdependent with each other, and provide insights for Singapore's future transport and land use planning.

Keywords: New town, urban form, polycentricity, commuting trips, non-commuting trips, smartcard data

1. Introduction

Polycentric and new town planning aims to improve the job-housing balance and alleviate congestion and housing pressure in the over-concentrated urban core/downtowns through the construction of new centers and/or new towns (Bristow, 1989). The polycentric and new town development patterns in Singapore are shaped by the Concept Plans of Singapore since the 1970s. The first new town (Queenstown) was constructed in the 1950s with a town center supporting seven neighborhoods. The 1960s witness the construction of a few more new towns such as Toa Payoh, Bedok, Paya Lebar, and Kallang. However, it is until in the 1971 Concept Plan that high-density new towns were firstly outlined as a population decentralization strategy to provide public housing for an increasing population, and a town center was planned and developed for each new town by the Housing and Development Board (HDB) to provide daily amenities and commercial/service facilities (e.g., shops, markets, and community clubs) for local residents (Cheong, 2017; Sim, Yu, & Malone-Lee, 2002). However, the role of the Central Business District (CBD) as the primary employment center was emphasized in the 1971 Concept Plan and the transport system was planned to effectively connect new towns and the CBD (Heng & Yeo, 2017). The 1991 Concept Plan, also called the "Constellation Plan", aims to decentralize commercial and employment activities from the traditional urban core and reconcentrate them in a hierarchy of secondary centers, such as regional centers, sub-regional centers, and town centers (Urban Redevelopment Authority [URA], 1991). Though most of them are anchored at new towns, regional and sub-regional centers were planned with mixed land use and much larger scale of employment/commercial activities than town centers to partially substitute the CBD functions and reduce long-distance travel (URA, 1991). The three planned regional centers, Tampines, Woodlands, and Jurong East are located about 10-13 km from the CBD with the largest planned size (e.g., 1.5 million sqm each) and the largest share of commercial development for office use (i.e., 50%) (URA, 1991). The 5 sub-regional centers, Buona Vista (One-North), Paya Lebar (Geylang), Bishan, Serangoon, and Marine Parade are located about 5 km (i.e., 10-minutes' drive) from the CBD and connected by the circle MRT line; their planned size is about 1/3 of regional centers and their share of office use in the commercial development is planned to be smaller than that of regional centers (i.e., 40%) (URA, 1991). The rest of town centers compose the lowest tier of secondary centers in the intra-urban hierarchy and were planned without any non-daily amenities such as hotel and entertainment uses (URA, 1991; Sim et al., 2002). To facilitate passenger flows between new towns and centers of different tiers, urban rapid transport infrastructure including expressways and rail-based mass rapid transit (MRT) system have been planned and constructed since the 1980s. The polycentric and new town development strategies have also been reflected in the Concept and Master Plans of Singapore in the following decades. As of 2022, there are in total 23[1] HDB new towns in Singapore and 6 new towns accommodates regional/sub-regional centers. All new towns in Singapore are also called HDB towns as they are created by the country's public housing authority, the HDB, and offer public housing (i.e., HDB flats) for Singaporeans.

Besides the continuous polycentric and new town development over the decades, Singapore has released the "Land Transport Master Plan 2040" in 2018, which includes an ambitious concept called the "20-Minute Towns and 45-Minute City" (Manifesty & Park, 2022). This concept is similar to the 15-minute city concept (Moreno, 2019), which advocates for

[1] The 24th town, Tengah, is currently under construction and will see the first residents by 2025.

chrono-urbanism and supports proximity-based planning that would allow residents to access basic services within a 15-minute radius by walking or cycling, thus reducing car dependence, oil consumption, and pollution (Moreno, Allam, Chabaud, Gall, & Pratlong, 2021).

The achievement of planning goals of both polycentric and new town development and "20-Minute Towns and 45-Minute City" thus depend critically on whether and to what extent new towns/planned centers achieve self-containment (or self-sufficiency) by providing employment and other opportunities for local and nearby residents (Alonso, 1970; DCLG, 2006; Wannop, 1999). In the face of public health emergencies such as the COVID-19 outbreak, the self-containment of new towns/centers is considered as a potential planning response to strengthen urban resilience and maintain people's daily lives (Allam, Nieuwenhuijsen, Chabaud, & Moreno, 2022). However, previous studies also suggest the importance of interconnections and interdependence between constituent parts of a metropolitan area through commuting flows (i.e., labor exchange), interfirm exchange, information and knowledge spillover, occasional consumption activities, and other "weak ties" in effectively pairing supply and demand of various goods, services and amenities that are unevenly distributed within a metropolitan area/region and thus maintaining the metropolitan-wide agglomeration benefits (Shearmur & Motte, 2009). As a typical planned polycentric city, the extent to which new towns/centers of Singapore achieve self-containment or show interdependence with each other after the lift of COVID-19 lockdown, and how the planning goals reflect the travel needs of Singaporean residents in the post-COVID period are still unclear.

This study aims to explore the self-containment and interconnectivity of new towns/centers in Singapore in the post-COVID period (i.e., after the lift of COVID-19 lockdown in July, 2021). As mass public transport investments including MRT rail network and public bus are important mode of transport in Singapore that take a steady share of more than 40% since 2008 (Land Transport Authroity [LTA], 2018; Cheong & Toh, 2010), we focus on the two modes of public transport to represent Singapore's traffic flow pattern. Using rail and bus transit passenger flow data, we explore the geography of each new town/center's service shed for different travel purposes and the overlapping patterns of the centers' service shed in two 8-month periods before and after the complete removal of COVID prevention and control policies (i.e., August 2021 – March 2022 and May 2022 – December 2022). The self-containment and overlapping levels of centers' service shed for commuting (i.e., peak-hour travel) and non-commuting (i.e., off-peak hour and weekend travel) purposes are compared across centers of different tiers in the two study periods to understand how local residents' travel pattern reflect the distribution of public transit network and the intra-region commercial hierarchy of Singapore in the post-COVID period. The results of this study provide insightful suggestions for the future development of 20-minute town and 45-minute city in Singapore, which may also be considered as a planning response to enhance urban resilience and improve residents' quality of life in the face of public health emergency in the future.

2. Literature Review

2.1 Polycentric urban development and self-containment of new towns

Monocentric urban spatial structure is the simplest urban form that assumes all social and economic activities to be centered in one special area (Cabrera-Arnau, Zhong, Batty, Silva, & Kang, 2023). This urban structure is conducive to the accumulation of social interactions and creativity and enhances metropolitan-wide agglomeration economies (Anas, 1988; Rosenthal & Strange, 2001). However, many empirical studies have found that in monocentric cities suburban residents have longer commuting distances and times than urban residents. This is because the balance between job opportunities and housing units in the suburbs is poorer than that of the urban area (Guerra, 2017; Zhao, Lü, & De Roo, 2011). The longer commuting time and costs bring problems such as traffic congestion, job dispersion, unbalanced development, and environmental pollution (Natalia & Heinrichs, 2020; Park et al., 2020). To alleviate those problems, many cities have proposed and implemented polycentric urban development strategy (Brinkman, 2016), such as the cohesion policy by the European Union (Van Meeteren, Poorthuis, Derudder, & Witlox, 2016), the networked compact city policy by Japan (Ozawa, Takami, & Harata, 2017), and the new town planning and constellation development strategies by the Housing and Development Board (HDB) of Singapore ([URA]", 1991).

Empirical studies show mixed evidence on whether the construction of new towns can better balance the work and life of new town residents. Some studies have found that new town development is indeed effective in reducing the commuting time of residents (Jun, 2012; Zhao, Lu, & de Roo, 2011) and improving their quality of life (He, Tao, Ng, & Tieben, 2020). However, many other studies found that new towns do not fully function as dependent towns, resulting in a significant amount of commuting between the new towns and the traditional urban cores (Hall, 1974; Self, 1972). For example, He et al. (2020) and He et al. (2023) also found that new-town residents in Hong Kong experience longer commutes because of the larger spatial separation between their residential locations and job opportunities. As a result, new-town commuters had lower levels of travel satisfaction, work-life balance, and subjective well-being (He, Chen, & Tao, 2023; He et al., 2020). There are also negative issues related with new town development such as spatial segregation, income inequality, and a decrease in GDP (Brezzi & Veneri, 2015; Firman, 2004; Veneri & Burgalassi, 2012; Wang, Zhong, Gao, & Cabrera-Arnau, 2022). Similarly, studies on the commuting impacts of polycentric urban form found that the commuting shed for employment subcenters are not locally confined. For example, Shearmur and Motte (2009) defined the commuting sheds of each employment center based on the first, second, third quarters of commuting inflows to the center and found that more than 36% of subcenters' 1st and 2nd tier labor sheds highly overlaps with the CBD commuting shed, implying the interdependence between the CBD and subcenters' labor markets. Jun (2020) analyzed the temporal changes in urban form and individual commuting behavior in the Seoul metropolitan area from 2000 to 2015 and found that though the commuting time to inner city sub-centers has significantly decreased over the past 15 years, the commuting time to new suburban sub-centers has increased due to attracting more workers from a wider employment market (Jun, 2020).

With the advent of the big data era, studies on human mobility and urban structure in the recent decade apply new data sources such as taxi trajectory data (Zhou, Fang, Thill, Li, & Li, 2015), mobile phone data (Xiao, Wang, Miao, & Niu, 2021), social media data (Wang et al., 2022), and smart card data (Cats, Wang, & Zhao, 2015; Roth, Kang, Batty, & Barthélemy, 2011; Wang et al., 2022). Compared with traditional data sources such as questionnaires, population censuses, and administrative records that have been widely used in urban structure studies, those new sources of data have finer spatial and temporal granularity (Cabrera-Arnau et al., 2023). In particular, smart card data not only provide rich and high-quality records of public transportation passenger check-ins, but also have lower acquisition costs (G. Cheng, Sun, Zhou, & Wu, 2021; Ma, Liu, Wen, Wang, & Wu, 2017; Ma, Wu, Wang, Chen, & Liu, 2013; Tao, Rohde, & Corcoran, 2014) and higher legitimacy by covering a larger area and a larger number of population (Sun & Yang, 2018). Many recent studies on urban structure thus have applied smart card data. For example, Zheng et al. (2021) conducted network community detection based on smart card data and found that the urban structure of London from 2013 to 2017 has developed towards a more multi-centered and compact pattern (Zhang, Marshall, Cao, Manley, & Chen, 2021). Cheng (2021) identifies urban centers and analyzes their interactions using smart card data. The research findings indicate that Xi'an has developed a polycentric structure, with significant connections between business centers and residential centers (G. Cheng et al., 2021). Using this new data source, the effectiveness of polycentric and new town development in addressing urban issues such as traffic congestion and regional development inequality may be revisited and further explored (Wegener, 2013).

2.2 Daily mobility changes in the post-pandemic period and the '15-minute city' as an urban planning response

During the COVID-19 pandemic, many cities around the world implemented social distancing measures, which directly reduced the frequency and distance of residents' travel, especially for commuting purposes (De Haas, Faber, & Hamersma, 2020; Pan & He, 2022; Schlosser et al., 2020). In addition, most of the studies found that there has been a significant change in residents' choice of transportation modes, which most shifted from public transportation to private cars, walking, and cycling (Abdullah, Dias, Muley, & Shahin, 2020; Currie, Jain, & Aston, 2021; Palm et al., 2021), while some studies found a minimal modal shift in high-density, transit-oriented cities (He, Sun, Luo, Lee, & Parady, 2023). As the pandemic gradually subsides and some cities lift lockdown measures, residents' travel has rebounded, but there exist differences in the recovery speed of different areas within cities (Kim & Kwan, 2021; Schlosser et al., 2020). For example, Yang et al. (2023) found that the number of subway commuters dropped sharply in the short term due to the pandemic, but quickly rebounded as the pandemic eased, and returned to pre-pandemic levels within six months. In addition, compared with other areas, the city center recovered faster (Yang et al., 2023). Moreover, the reduction in long-distance, nighttime, and non-essential travel has led to a more fragmented distribution of passenger flows (Y. Cheng, Li, Zhang, He, & Chen, 2022).

The changes in residents' travel frequency and travel modes caused by the pandemic imply the importance of the proximity of residence to public facilities and public spaces (Moreno et al., 2021). Therefore, it is urgent for urban policy makers and planners to establish more appropriate urban planning mechanisms as a means for different cities to cope with pandemics or other public health emergency (Allam & Jones, 2020). In this context, the concept of the 15-minute city has gradually gained attention.

Though firstly proposed by firstly proposed by Moreno in 2016, the 15-minute metropolis is not a novel idea. Similar concepts can be found in earlier ideas such as Ebenezer Howard's garden city and Clarence Perry's neighborhood unit (Howard, 1898; Perry, 2015). Therefore, the 15-minute city is seen as the latest iteration of early block planning and architectural concepts, prioritizing the livability of neighborhoods and the well-being of people's time and welfare (Abdelfattah, Deponte, & Fossa, 2022; Poorthuis & Zook, 2023; Weng et al., 2019). In recent years, some global cities have proposed similar plans inspired by this concept, such as Ottawa and Melbourne's 15/20-minute neighborhoods, Milano 2020 Adaptation Strategy Plan (Government, 2021; Ottawa, 2021), and Singapore's 20-Minute Towns and 45-Minute City announced in the city-state's "Land Transport Master Plan 2040" (Manifesty & Park, 2022).

Although the "15-minute city" concept has promising prospects and has been adopted by many cities as a development policy, some researchers have raised critical questions about it. For example, the prioritization of neighborhood efficiency in the 15-minute city model may result in the overlooking of transportation needs of disabled individuals and those who cannot afford to live in dense urban areas (Zivarts, 2021). The construction of 15-minute cities can trigger neighborhood transformations that may lead to gentrification and social displacement, exacerbating urban inequality (Gower & Grodach, 2022; Herbert, 2021). The extent to which the 15- (or 20-) minute city concept aligns with human mobility pattern and meet local residents' daily travel needs for accessing various facilities, spaces and opportunities during and after the COVID-19 pandemic deserve to be further explored.

3. Research design

3.1 Study area

Until 2022, Singapore has in total 26 HDB new towns (including three HDB estates). One HDB estate is located within the CBD, which functions as the center for commercial, financial, and cultural activities. Three new towns accommodate regional centers while four other new towns accommodate sub-regional centers. Furthermore, there are 18 town centers that do not accommodate any higher-tier commercial centers but serve as the primary centers in the new towns to meet the daily needs of residents. Out of these new towns, 24 of them have

MRT stations located within their boundaries.

To explore whether and to what extent the planned secondary centers of different tiers achieve the planning goal of building “self-contained” (or “self-sufficient”) regions/new towns and to understand their interrelationships with the CBD and with each other in terms of commuting and non-commuting passenger flows, we identify the service sheds for a selected set of centers and the overlapping patterns of the selected centers’ service sheds. First, all regional centers are selected because of their planned functions of serving the residents of different regions/sub-regions. Second, 3 sub-regional centers, Bishan, Paya Lebar, and Serangoon that are anchored with new towns and have at least one MRT station within the 1 km vicinity are selected. Third, among those 18 town centers not accommodating any regional/sub-regional centers, 6 town centers that accommodate at least one MRT station are selected to represent new towns of different sizes, construction years and regions. Table 3.1 shows the basic information of the chosen centers and their associated new towns.

Table 3.1 Basic information of 13 chosen centers and their associated new towns

Center’s Name	Region	Hierarchy	Residents of associated new town (as of March, 2018)	HDB flats of associated new town (as of March, 2018)[2]	MRT lines[3]
CBD (anchored at Central Area)	Central	CBD	27,700	12,316	NS, EW, NE, DT, CC
Jurong East	West	Regional	78,000	23,897	NS, EW
Tampines	East	Regional	232,700	68,812	EW, DT
Woodlands	North	Regional	242,500	68,153	NS
Bishan	Central	Sub-Regional	63,200	20,072	NS, CC
Paya Lebar (anchored at Geylang new town)	Central	Sub-Regional	87,300	30,304	EW, CC
Serangoon	North-East	Sub-Regional	68,800	21,634	NE, CC
Toa Payoh	Central	Town (HDB)	105,000	37,900	NS
Bedok	East	Town (HDB)	194,700	61,828	EW
Ang Mo Kio	North-East	Town (HDB)	143,800	50,733	EW

[2] Source: https://www.hdb.gov.sg/cs/infoweb/about-us/history/hdb-towns-your-home/
[3] Note: NS: North-South Line, EW: East-West Line, NE: Northeast Line, DT: Downtown Line, CC: Circle Line.

Punggol	North-East	Town (HDB)	187,800	49,909	NE
Yishun	North	Town (HDB)	196,600	62,786	NS
Jurong West	West	Town (HDB)	258,100	74,301	EW

Figure 3.1 shows the spatial distribution of the selected centers. The boundary of the CBD is defined by the Land Transport Authority (LTA) of Singapore. The boundaries of all other centers are defined as the subzones where the MRT stations named by the centers/new towns are located.

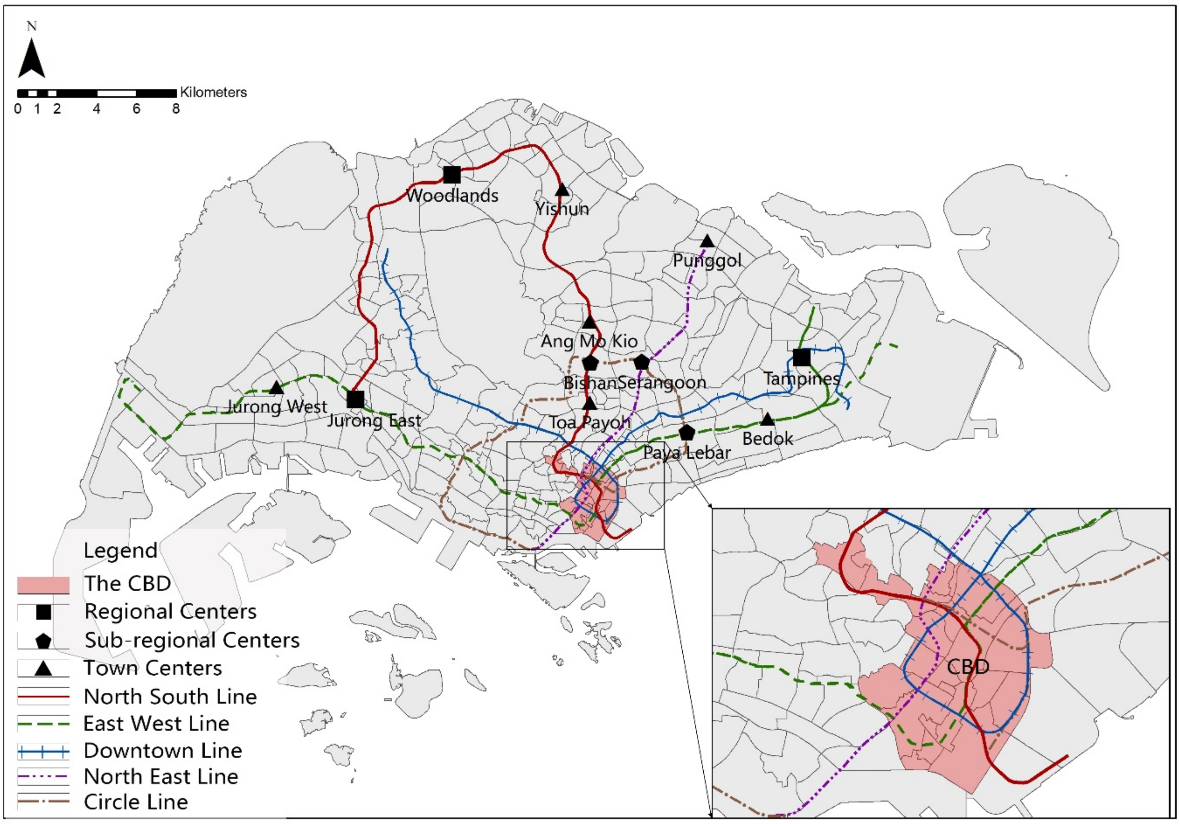

Fig 3.1 Spatial distribution of the selected centers

3.2 Data source

The passenger volumes by original and destination train stations and bus stops were extracted from the Dynamic Datasets of the Singapore Land Transport Authority (LTA) via API access. The original dataset provides station-to-station or stop-to-stop passenger volume data of each month that are aggregated by each hour of weekdays and weekends, respectively, and are updated monthly. We have continuously collected this dataset from July 2021 to December 2022.

To examine the impacts of prevention and control policies that may inhibit human mobility even after the COVID-19 lockdown period ends in July 2021, we split the data according to two 8-month study periods: 1) Social distancing (SD) Control Period (Aug 2021 – March, 2022), which is normally considered as the precise prevention and control period that social gathering of more than 8 people is not allowed; 2) Non-control Period (May 2022 – Dec 2022), in which no prevention or control policies were reinforced. We use subzones as the basic unit of analysis and construct origin-destination (O-D) passenger flow matrices for pairs of subzones in each study period by 1) assigning the bus stops and MRT stations to subzones, 2) summing up the bus and train passenger volumes between the pairs of subzones, and 3) using the monthly average total transit (i.e., train and bus) passenger flows of each 8-month period as the value of elements in the O-D matrices for each study period. To explore the differences in commuting and non-commuting travel patterns, the passenger volumes of peak hours (i.e., 6 – 9.30 am and 5 – 8 pm, Monday to Friday), off-peak hours of weekdays, and weekends (i.e., Saturday and Sunday) are calculated and analyzed separately. In the following sections, peak hour and off-peak/weekend passenger flows are used to represent commuting and non-commuting flows, respectively.

3.3 Methods for identifying the service sheds of centers

Following Shearmar and Motte's work (2008), we identify the geography of the service shed of each center (including the CBD, regional centers, sub-regional centers, and new town centers) as any subzones that have at least one passenger travel to the center. We then sort all subzones of a center's service shed by the percentage of total passenger inflows they contribute to the center, sum the percentage contributions in descending order, and further distinguish the core, strong, and weak sheds of each center's service shed as the first (i.e., 25%), second (i.e., 25-50%), and third quartiles (i.e., 50-75%) of transit passenger flows to the center (Shearmur & Motte, 2009). The core and strong service sheds are identified as the principal (service) sheds of centers. The service sheds of each center are identified separately for peak-hour, off-peak hour, and weekend transit passenger flows in each of the 8-month study period. The spatial extent of service sheds identified for each travel purposes in the two study periods are then compared to explore the changes in the self-containment level of employment and other functions of new towns/planned centers before and after the complete removal of COVID-19 prevention and control measures.

3.4 Methods for identifying the interdependence pattern among centers

To explore how the service sheds of the selected centers overlap with each other, we construct a matrix for each type of service shed (i.e., constructed based on peak-hour, off-peak hour, weekend passenger flows) of which the element ($\mathbf{O_{ij}}$) is calculated as the percentage of subzones that are identified as the principal shed of a pair of Centers i (in the row direction) and j (in the column direction) to the total number of subzones in Center j's principal shed (Shearmar and Motte, 2008). The matrices are thus non-symmetric in nature and the value in the diagnosis reveals the self-containment level of a center (i.e., percentage of subzones that are unique to the center's principal shed) in terms of or other functions; the higher value of an element $\mathbf{O_{ij}}$, the higher overlapping level of Center i's and Center j's service sheds and the higher level of Center j's reliance on (or attractiveness to) Center i's residents for passenger inflows in terms of a particular travel purpose (i.e., peak-hour, off-peak hour, weekend travel). The matrices for each type of service shed are generated for the two study periods separately to explore how the self-containment and functional interdependence levels of centers/new towns change over time with the complete removal of prevention and control polices.

4. Results

4.1 Analysis of the spatial distribution characteristics of center's service sheds

Figure 4.1–4.7 depict the core, strong, and weak service sheds of the CBD, regional centers and sub-regional centers. In both the social distancing (SD) control and the non-control periods, the CBD as the largest city center has the greatest number of subzones identified as its principal (i.e., core and strong) shed, which are mostly clustered within 10 km of the CBD and along the MRT lines (Figure 4.1). The weak sheds of the CBD are within 10-15 km and distributed along the MRT lines. The principal (service) sheds of the CBD identified for commuting (i.e., peak-hour) travel is larger than those for non-commuting (i.e., off-peak hour/weekend) travel.

The principal sheds of regional centers are more spatially confined than those of the CBD, mostly within 5 km buffer zones around the centers (Figure 4.2-4.4). Weak sheds and a few strong sheds of regional centers are generally distributed within 5-10 km of the centers and along the MRT lines (Figure 4.2-4.4). Some subzones within the CBD are identified as strong and weak sheds of Jurong East and Woodlands in the SD control period but only as periphery sheds of these two centers in the non-control period (Figure 4.3-4.4), suggesting that the two centers' attractiveness to CBD residents are higher in the SD control period. Similar observations are found for sub-regional centers and several town centers.

Compared with the CBD and regional centers, sub-regional centers exhibit much larger changes in the service sheds between the control and non-control periods. The principal sheds of the 3 selected sub-regional centers extend significantly from the 5 km buffer zone around the centers in the SD control period to the 5-10 km buffer zone in the non-control period, and the extended sheds are mainly distributed along the MRT lines (Figures 4.5-4.7). The dependence of sub-regional centers on CBD residents during the SD control period is also higher than the non-control period.

The spatial distribution of the 6 selected town centers' principal sheds exhibits two distinct characteristics[4]. First, the principal sheds of town centers are mainly distributed within 5 km of the centers and are mainly located along the same MRT line that contains the main MRT station of the centers (i.e., named by the new town/center). In contrast, the principal sheds of higher-tier city centers are distributed along multiple MRT lines. Second, town centers show a strong dependence on CBD residents in the SD control period, which is significantly weakened in the non-control period.

[4] Figures of the 6 town centers' service sheds are not shown here but available upon request.

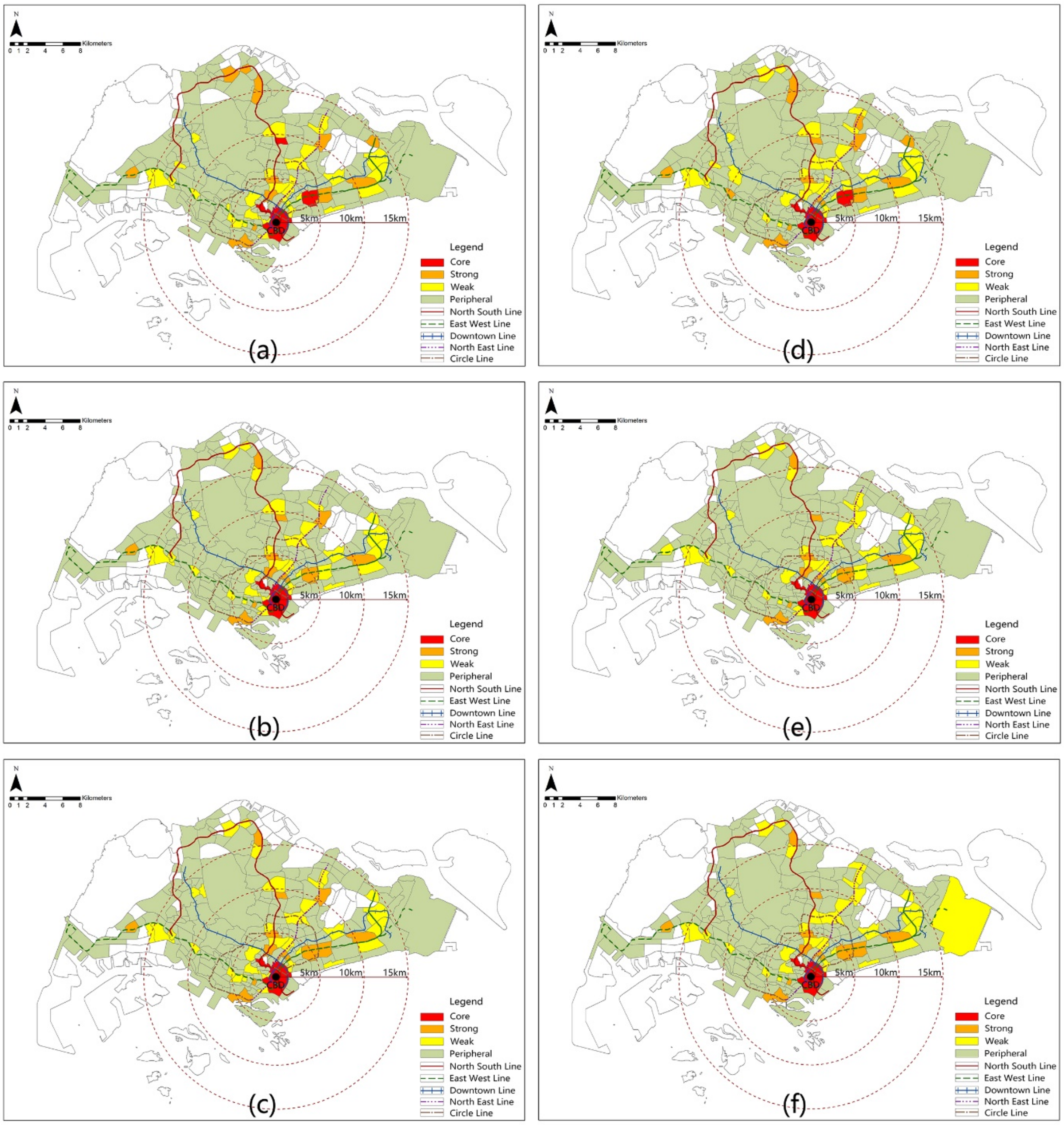

Fig 4.1 The service shed of the CBD: (a) Peak hour in the SD control period; (b) Off-peak hour in SD control period; (c) Weekend in SD control period; (d) Peak hour in non-control period; (e) Off-peak hour in non-control period; (f) Weekend in non-control period.

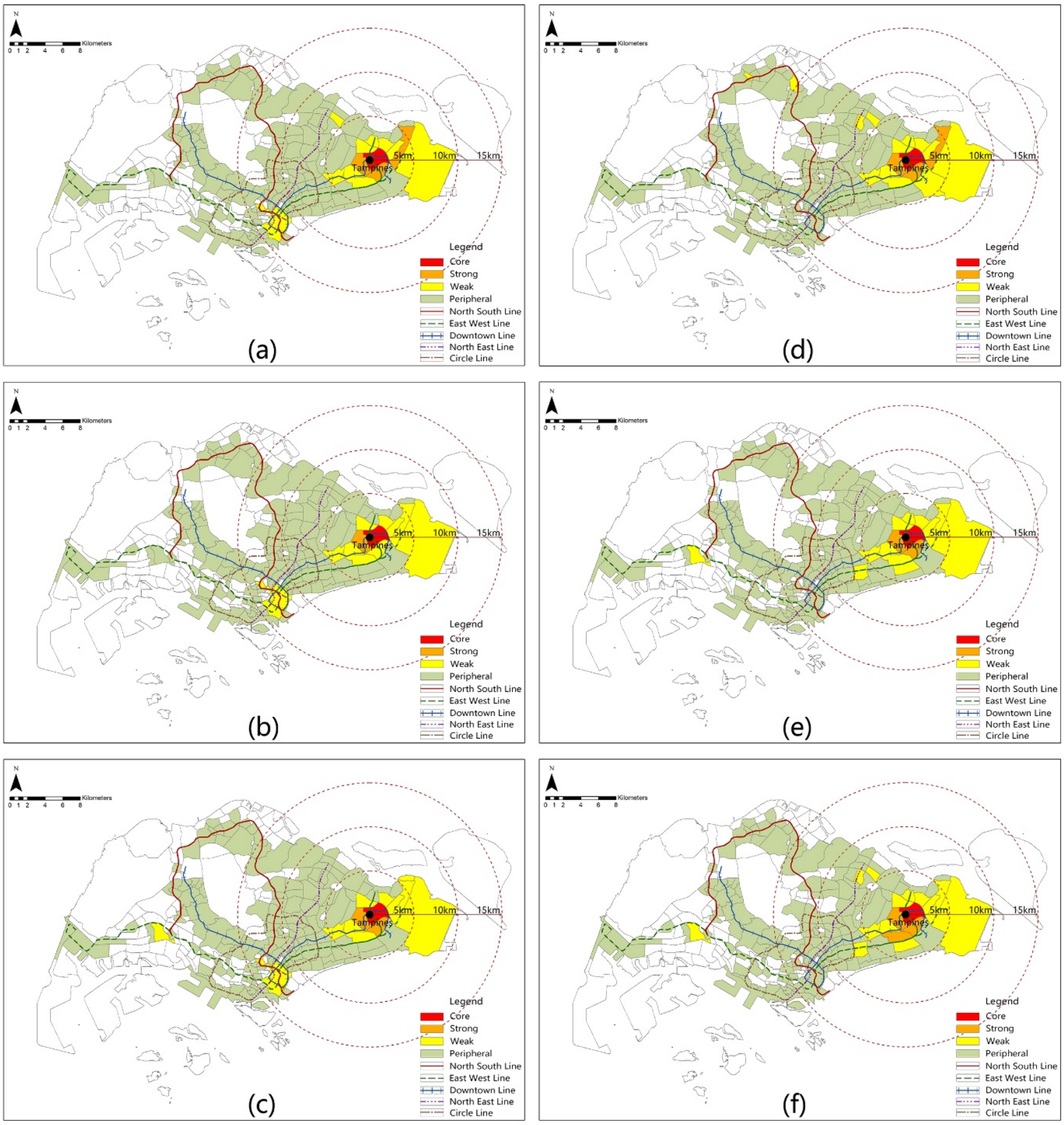

Fig 4.2 The service shed of Tampines: (a) Peak hour in SD control period; (b) Off-peak hour in SD control period; (c) Weekend in SD control period; (d) Peak hour in non-control period; (e) Off-peak hour in non-control period; (f) Weekend in non-control period.

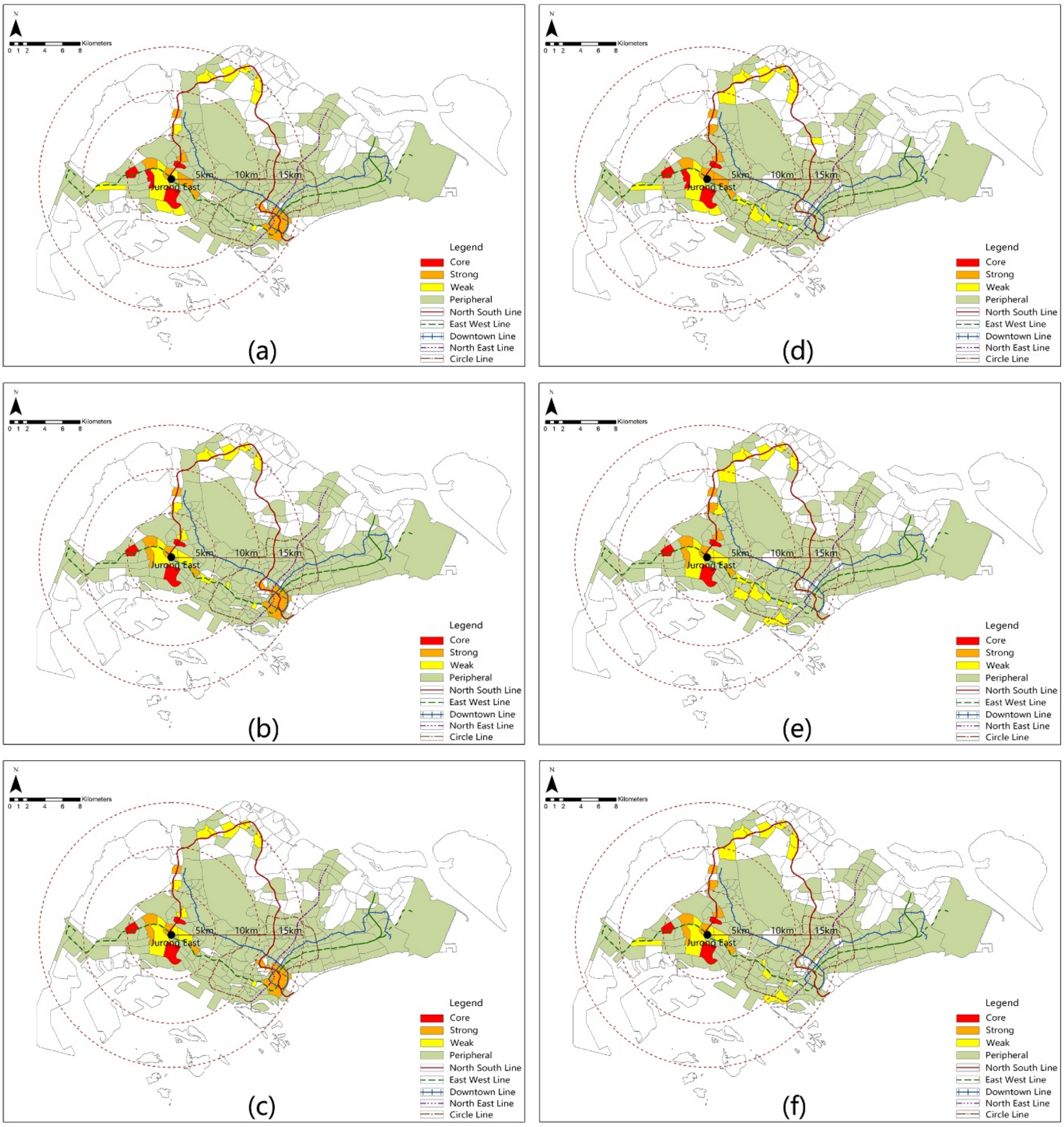

Fig 4.3 The service shed of Jurong East: (a) Peak hour in SD control period; (b) Off-peak hour in SD control period; (c) Weekend in control period; (d) Peak hour in non-control period; (e) Off-peak hour in non-control period; (f) Weekend in non-control period.

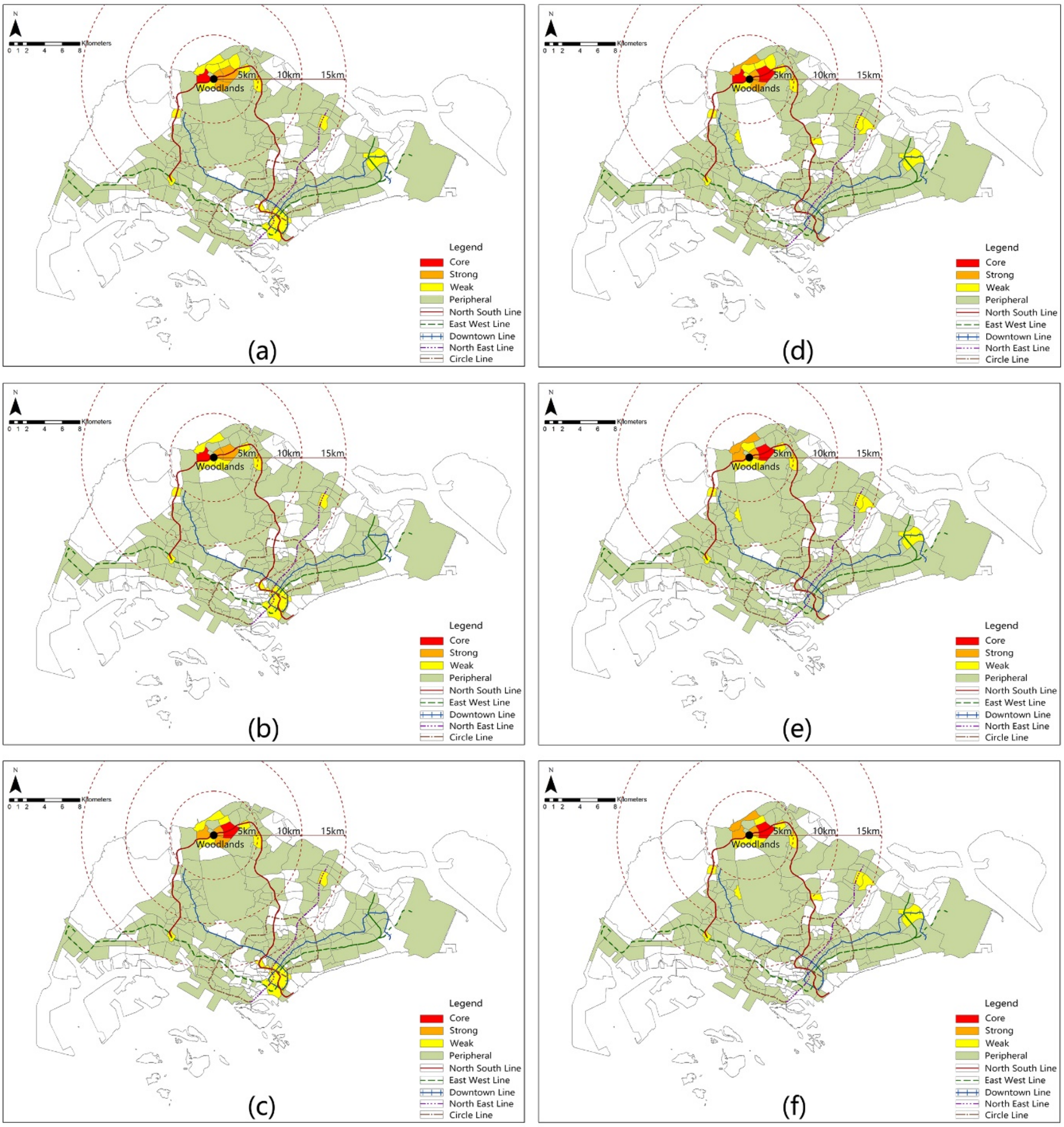

Fig 4.4 The service shed of Woodlands: (a) Peak hour in SD control period; (b) Off-peak hour in SD control period; (c) Weekend in SD control period; (d) Peak hour in non-control period; (e) Off-peak hour in non-control period; (f) Weekend in non-control period.

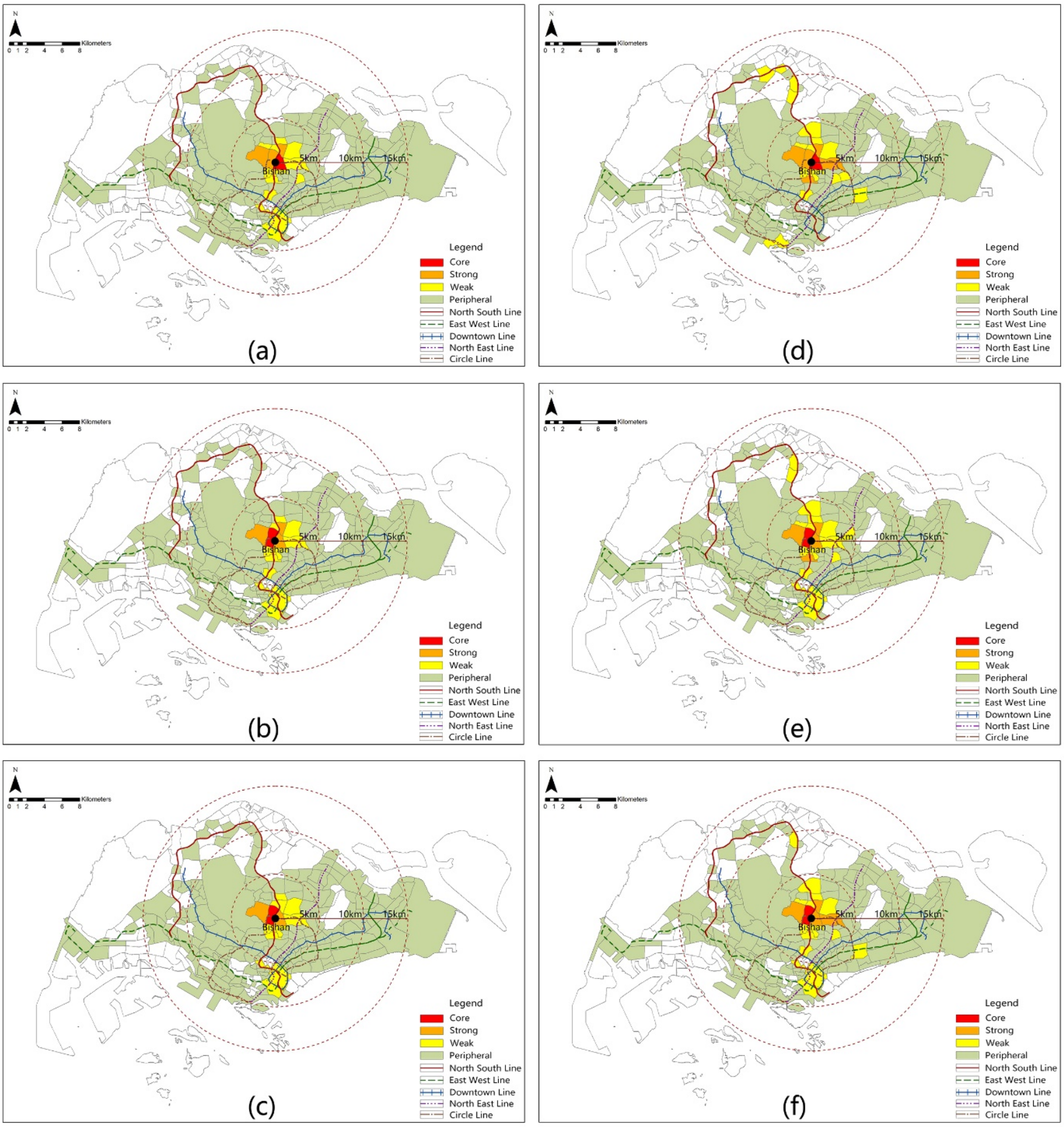

Fig 4.5 The service shed of Bishan: (a) Peak hour in SD control period; (b) Off-peak hour in SD control period; (c) Weekend in SD control period; (d) Peak hour in non-control period; (e) Off-peak hour in non-control period; (f) Weekend in non-control period.

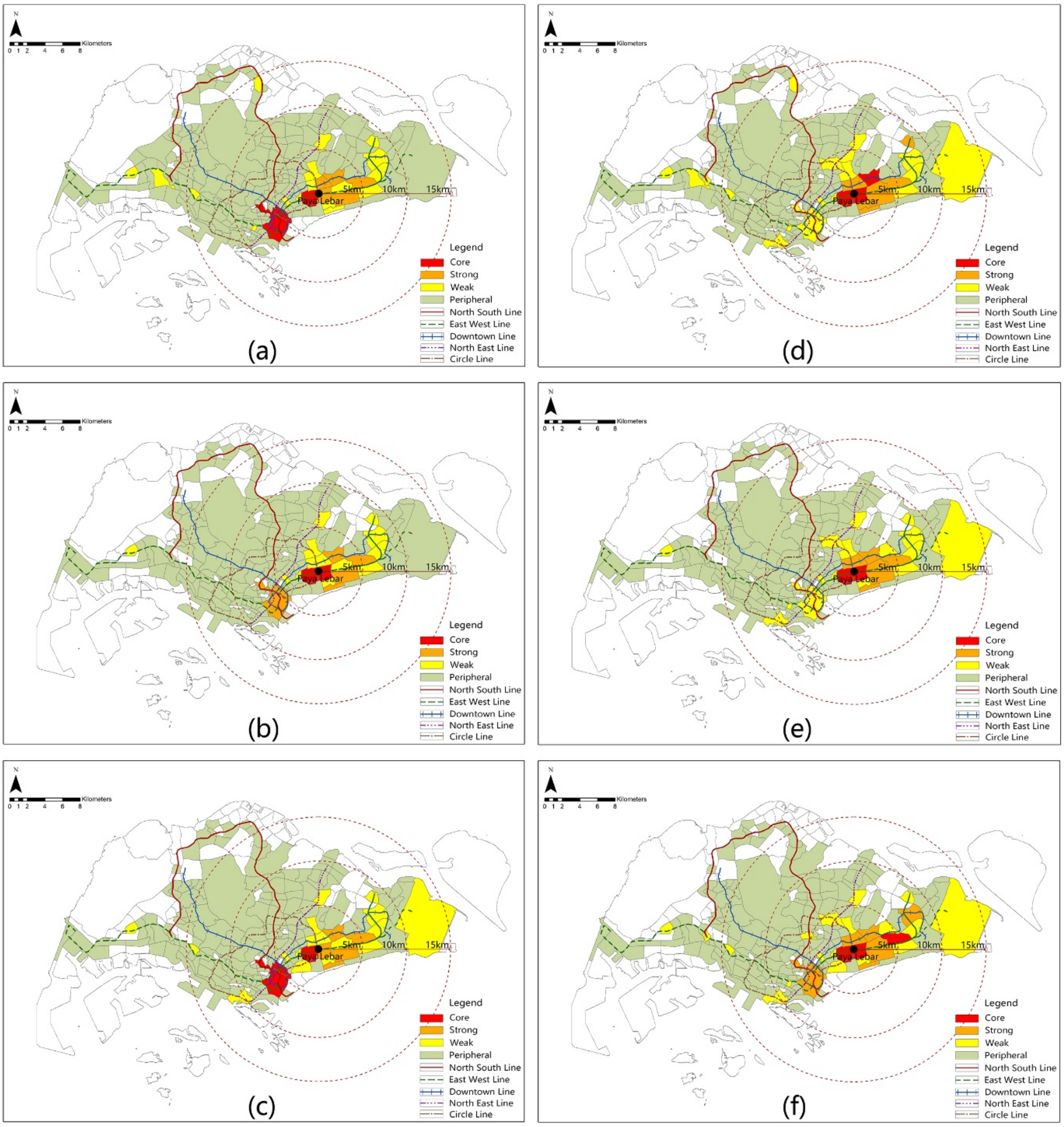

Fig 4.6 The service shed of Paya Lebar: (a) Peak hour in SD control period; (b) Off-peak hour in SD control period; (c) Weekend in SD control period; (d) Peak hour in non-control period; (e) Off-peak hour in non-control period; (f) Weekend in non-control period.

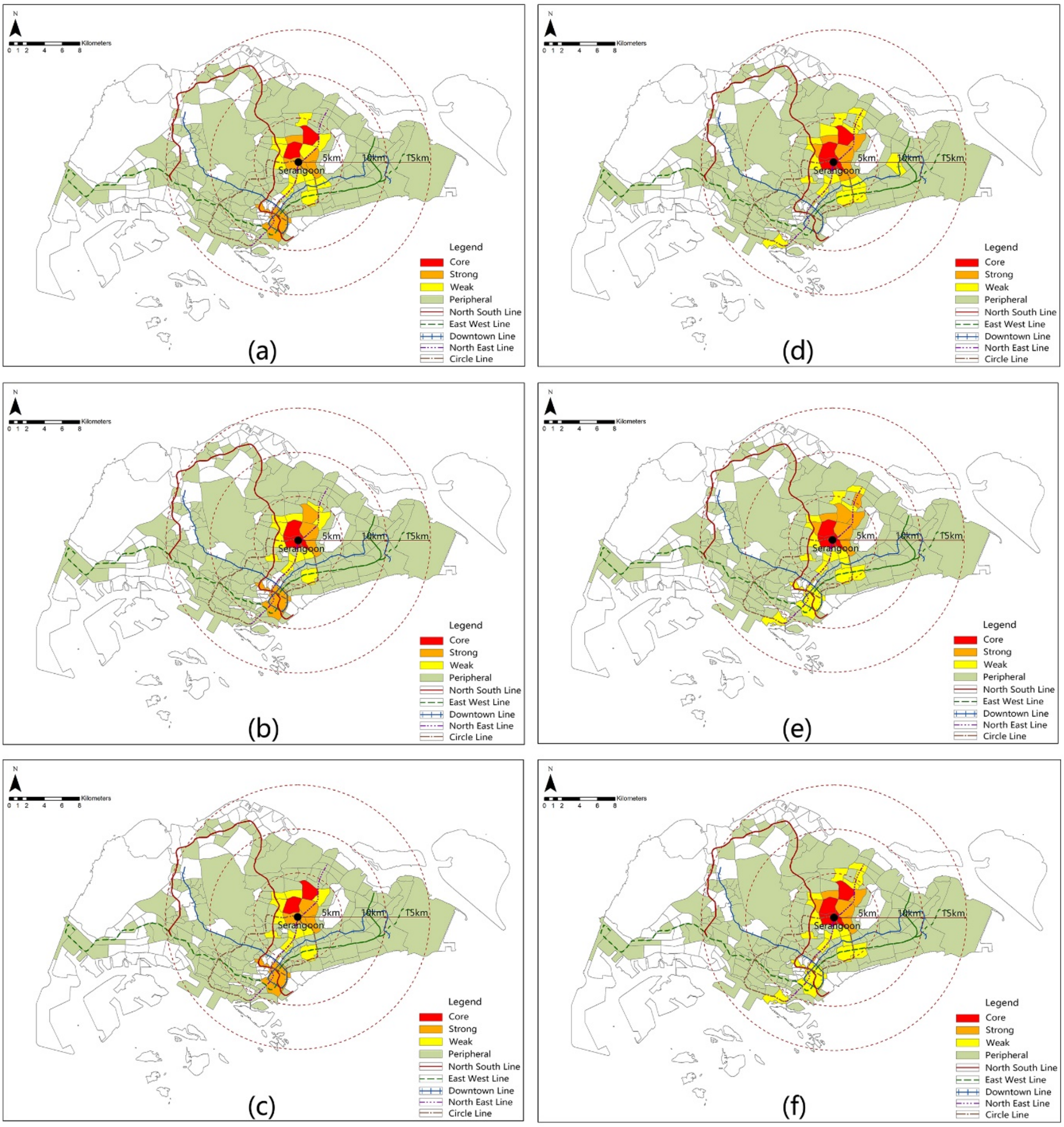

Fig 4.7 The service shed of Serangoon: (a) Peak hour in SD control period; (b) Off-peak hour in SD control period; (c) Weekend in SD control period; (d) Peak hour in non-control period; (e) Off-peak hour in non-control period; (f) Weekend in non-control period.

4.2 Analysis of overlapping of principal sheds of urban centers

4.2.1 The CBD

As shown in Table 4.1, 7 centers are functionally interdependent with the CBD in the SD control period, including 1 regional center, 2 sub-regional centers, and 4 town centers. The overlapping rates between the 7 centers' and the CBD's commuting (i.e., peak-hour) sheds are larger than those between the centers' non-commuting (i.e., off-peak hour/weekend) sheds. In the non-control period, the number of centers that are interdependent with the CBD increases to 9 (Table 4.2). In both periods, all centers that are highly interconnected with the CBD are distributed within a 15 km radius of the CBD and a large share of those centers are within the 5–10 km radius.

Compared with the SD control period, the dependence of the CBD on some centers' commuting passenger inflows is reduced in the non-control period. For example, 12% of subzones in the CBD's principal commuting shed are also in Woodland's labor shed in the SD control period, but no overlapping of the two centers' principal commuting sheds is found in the non-control period. The overlapping level of the CBD's principal commuting sheds with those of Yishun, Ang Mo Kio, Toa Payoh, and Paya Lebar is greater than 10% in the SD control period but decreases to less than 10% in the non-control period. In contrast, other centers such as Jurong East, Serangoon, and Punggol become interdependent with the CBD for commuting travel only after the complete removal of prevention and control policies. The three centers are 10-15 km from the CBD, suggesting an expansion of the CBD's commuting shed in the non-control period.

Compared with the peak hour passenger flow pattern, the number of centers that are interdependent with the CBD for off-peak and weekend travel is smaller. With the complete removal of prevention and control policies, the overlapping level of the CBD's principal service sheds with those of some other centers such as Yishun, Ang Mo Kio and Toa Payoh have reduced significantly for commuting travel but not for non-commuting travel.

Table 4.1 Overlapping of Principal Service Sheds of the CBD in SD Control Period

Center's name	Peak hours	Off-peak hours	Weekend
CBD	56.0%	69.2%	65.0%
Woodlands	12.3%	0%	0%
Paya Lebar	13.9%	10.2%	14.5%
Ang Mo Kio	18.6%	11.4%	4.6%
Bedok	3.6%	3.2%	3.3%
Jurong West	3.7%	2.8%	3.3%
Toa Payoh	10.8%	11.7%	9.4%
Yishun	29.8%	3.6%	3.6%

Table 4.2 Overlapping of Principal Service Sheds of the CBD in Non-control Period

Center's name	Peak hours	Off-peak hours	Weekend
CBD	52.7%	70.4%	59.1%
Jurong East	7.6%	0%	0%
Paya Lebar	16.3%	9.5%	13.9%
Serangoon	3.8%	0%	4.8%
Ang Mo Kio	4.2%	10.2%	8.7%
Bedok	3.3%	2.9%	3.0%
Jurong West	11.0%	0%	3.1%
Punggol	3.2%	0%	0%
Toa Payoh	3.9%	10.6%	9.3%
Yishun	8.6%	3.0%	3.0%

4.2.2 Regional centers

The number of centers that are functionally interdependent with regional centers remains unchanged in the SD control and the non-control periods (Table 4.3 and 4.4). These centers are mainly distributed within 5-10 km of regional centers. The principal commuting sheds of Tampines and Bedok exhibit a high degree of overlapping in both the control and the non-control periods, as the two centers are within 5 km of each other and the two corresponding main MRT stations are next to each other along the East line. The principal commuting shed of Jurong East overlaps with that of Jurong West and the degree of overlapping is much larger in the non-control period than in the SD control period. Woodlands show a great dependence on the CBD for commuting passenger inflows in the SD control period but not in the non-control period.

Compared with commuting flow patterns, the spatial patterns of non-commuting flows for Tampines and Jurong East changed significantly from the SD control period to the non-control period. Tampines show a complete "self-containment" pattern for off-peak and weekend travel in the SD control period but a much higher dependence on passenger inflows from Bedok in the non-control period. Jurong East shows some degree of reliance on CBD residents in terms of non-commuting travel inflows in the SD control period but not in the non-control period.

Table 4.3 Overlapping of Principal Service Sheds of Regional Centers in SD Control Period

Center's name	Peak hours			Off-peak hours			Weekend		
	Tampines	Jurong East	Woodlands	Tampines	Jurong East	Woodlands	Tampines	Jurong East	Woodlands
CBD	0%	6.6%	59.2%	0%	8.5%	0%	0%	8.8%	0%
Tampines	88.2%	0%	0%	100%	0%	0%	100%	0%	0%
Jurong East	0%	40%	0%	0%	47.9%	0%	0%	48.0%	0%
Woodlands	0%	0%	72.5%	0%	0%	64.1%	0%	0%	68.7%
Bedok	22.9%	0%	0%	0%	0%	0%	0%	0%	0%
Jurong West	0%	46.3%	0%	0%	21.1%	0%	0%	21.4%	0%
Yishun	0%	0%	59.2%	0%	0%	54.0%	0%	0%	47.3%

Table 4.4 Overlapping of Principal Service Sheds of Regional Centers in Non-control Period

Center's name	Peak hours			Off-peak hours			Weekend		
	Tampines	Jurong East	Woodlands	Tampines	Jurong East	Woodlands	Tampines	Jurong East	Woodlands
CBD	0%	33.3%	0%	0%	0%	0%	0%	0%	0%
Tampines	87.7%	0%	0%	86.9%	0%	0%	82.1%	0%	0%
Jurong East	0%	48.8%	0%	0%	41.4%	0%	0%	33.1%	0%
Woodlands	0%	0%	75.4%	0%	0%	68.9%	0%	0%	67.6%
Jurong West	0%	77.6%	0%	0%	45.4%	0%	0%	64.6%	0%
Yishun	0%	0%	37.4%	0%	0%	44.1%	0%	0%	46.3%

4.2.3 Sub-regional centers

In the SD control period, all the 7 centers showing interdependence with the 3 selected sub-regional centers (Table 4.5) are within 5 km of sub-regional centers. Compared with the SD control period, The overlapping rate between principal sheds of the 7 centers and sub-regional centers decrease significantly in the non-control period. Moreover, the service sheds of sub-regional centers are more spatially extended in the non-control period than in the SD control period; three more centers, Tampines, Punggol, and Toa Payoh that are within 5-10 km of sub-regional centers also become interdependent with the centers in the non-control period (Table 4.6).

In terms of commuting passenger inflows, the overlapping rate between principal sheds of sub-regional centers and other centers are much higher in the non-control period than in the SD control period. For example, Bishan's principal commuting shed does not overlap with any other centers' sheds in the SD control period but overlaps with the principal commuting sheds of Serangoon, Ang Mo Kio, and Toa Payoh in the non-control period. During the SD control period, Serangoon is more reliant on other centers' service sheds for commuting passenger inflows than for non-commuting inflows. During the non-control period, the overlapping level of the Serangoon's and other centers' principal sheds has increased, and the overlapping rates are higher for non-commuting travel than commuting travel.

Compared with the commuting passenger flow pattern, sub-regional centers rely on a smaller number of other centers' service sheds for non-commuting passenger inflows. For example, 25% and 62% of subzones in Serangoon's principal commuting shed are also within Ang Mo Kio's sheds in the control and the non-control period, respectively, while 0% of subzones in Serangoon's principal sheds for off-peak hour/weekend travel overlap with Ang Mo Kio's sheds or any other centers except the CBD. With the complete removal of COVID prevention measures, the increases in the overlapping rate between principal sheds of sub-regional centers and other centers for non-commuting travel are larger than those commuting trips. For example, the share of subzones in Paya Lebar's principal commuting sheds that are also found in Bedok's shed increased from increases from 10.3% in the SD control period to 36.9% in the non-control period, while the increase in the overlapping rate between the two centers' principal weekend service sheds center increases from 11.6% to 64.6% with the removal of all prevention and control policies.

Table 4.5 Overlapping of Principal (Core and Strong) Service Sheds of Sub-regional Centers in SD Control Period

Center's name	Peak hour			Off-peak hou			Weekend		
	Bishan	Paya Lebar	Serangoon	Bishan	Paya Lebar	Serangoon	Bishan	Paya Lebar	Serangoon
CBD	0%	79.5%	9.4%	0%	76.8%	8.4%	0%	82.4%	9.3%
Bishan	100%	0%	0%	100%	0%	0%	100%	0%	0%
Paya Lebar	0%	36.6%	0%	0%	27.5%	0%	0%	25.1%	0%
Serangoon	0%	0%	80.8%	0%	0%	91.6%	0%	0%	90.7%
Ang Mo Kio	0%	0%	25%	0%	0%	0%	0%	0%	0%
Bedok	0%	10.3%	0%	0%	12.1%	0%	0%	11.6%	0%

Table 4.6 Overlapping of Principal Service Sheds of Sub-regional Centers in Non-control Period

Center's name	Peak hour			Off-peak hour			Weekend		
	Bishan	Paya Lebar	Serangoon	Bishan	Paya Lebar	Serangoon	Bishan	Paya Lebar	Serangoon
CBD	0%	82.5%	22.40%	0%	62%	0%	0%	67.4%	31.8%
Tampines	0%	0%	0%	0%	0%	0%	0%	4%	0%
Bishan	71.9%	0%	37.9%	79%	0%	16.3%	78%	0%	16.3%
Paya Lebar	0%	39.00%	0%	0%	38.5%	0%	0%	32.9%	0%
Serangoon	42.6%	0%	52.50%	32.5%	0%	71.3%	43.9%	0%	70.2%
Ang Mo Kio	36%	0%	62%	32.5%	0%	50.7%	36.1%	0%	49.9%
Bedok	0%	36.90%	0%	0%	40.9%	0%	0%	64.6%	0%
Punggol	0%	0%	0%	0%	0%	9.6%	0%	0%	0%
Toa Payoh	6.4%	0%	0%	8.3%	0%	0%	0%	0%	0%

4.2.4 Town centers

The number of centers that are functionally interdependent with the 6 selected town centers increased from 11 in the SD control period to 13 in the non-control period. The two additional centers, Bishan and Paya Lebar, are sub-regional centers (Table 4.8). During the SD control period, apart from the CBD, most of the interdependent centers are located within 5-km buffer zones around the town centers. The spatial range of the town centers' principal sheds extended from the 5-km buffer zone in the SD control period to the 10-km buffer zone in the non-control period. Compared with the SD control period, several town centers such as Ang Mo Kio, Bedok, Toa Payoh, and Yishun significantly reduced their reliance on CBD's residents in the non-control period (Table 4.7). Because of its geographic proximity to many centers, Ang Mo Kio has an average of four interdependent centers in both the control and non-control periods, which is the largest among the 6 town centers.

In terms of commuting travel pattern, the dependence of some town centers on the CBD has decreased significantly in the non-control period compared with the SD control period. For example, the overlapping rate between the principal commuting sheds of Ang Mo Kio and the CBD has dropped from 97.2% in the SD control period to 0% in the non-control period, while the overlapping rate between the principal commuting sheds of Toa Payoh and CBD has decreased from 52.2% to 0%. In contrast, the dependence of Jurong West and Punggol on the CBD for commuting passenger inflows has increased in the non-control period.

In terms of non-commuting travel patterns, the overlapping rates between the principal sheds of town centers and the CBD exhibit a similar declining trend with the complete removal of prevention and control policies. For instance, the overlapping rate between the principal sheds of Toa Payoh and the CBD for weekend travel decreases from 62.9% in the SD control period to 38.3% in the non-control period. Similarly, the overlapping rate between the principal sheds of Bedok and the CBD for off-peak hour travel drops from 12.5% in the SD control period to 0% in the non-control period. Apart from these two centers, the dependence of Yishun and Jurong West on the CBD for non-commuting travel also decreased significantly to varying degrees in the non-control period compared with the SD control period. Apart from the CBD, the overlapping rates between the principal non-commuting sheds of other tiers of centers and the selected town centers increase in the non-control period compared to the SD control period.

Table 4.7 Overlapping of Principal (Core and Strong) Service Sheds of selected town centers in Control Period

Center's name	Peak hour						Off-peak hour						Weekend					
	Ang Mo Kio	Bedok	Jurong West	Punggol	Toa Payoh	Yishun	Ang Mo Kio	Bedok	Jurong West	Punggol	Toa Payoh	Yishun	Ang Mo Kio	Bedok	Jurong West	Punggol	Toa Payoh	Yishun
CBD	97.2%	0%	0%	0%	52.2%	11.4%	77%	12.5%	0%	0%	62.9%	17.2%	31.6%	13.6%	10.9%	0%	54.9%	18%
Tampines	0%	26.6%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Jurong East	0%	0%	27.1%	0%	0%	0%	0%	0%	14.2%	0%	0%	0%	0%	0%	15.6%	0%	0%	0%
Woodlands	0%	0%	0%	0%	0%	47.2%	0%	0%	0%	0%	0%	42.2%	0%	0%	0%	0%	0%	43.7%
Serangoon	23.5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ang Mo Kio	21.6%	0%	0%	0%	38.6%	35.8%	39.3%	0%	0%	0%	37.4%	0%	40.1%	0%	0%	0%	7.6%	20%
Bedok	0%	87.1%	0%	0%	0%	0%	0%	87.5%	0%	0%	0%	0%	0%	86.4%	0%	0%	0%	0%
Jurong West	0%	0%	78.3%	0%	0%	0%	0%	0%	85.8%	0%	0%	0%	0%	0%	73.4%	0%	0%	0%
Punggol	0%	0%	0%	100%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	100%	0%	0%
Toa Payoh	41.9%	0%	0%	0%	60.2%	0%	56.5%	0%	0%	0%	62.2%	0%	8.9%	0%	0%	0%	53.7%	0%
Yishun	48.9%	0%	0%	0%	0%	37.7%	11.9%	0%	0%	0%	0%	68.6%	39.5%	0%	0%	0%	0%	52.7%

Table 4.8 Overlapping of Principal (Core and Strong) Service Sheds of selected town centers in Non-control Period

Center's name	Peak hour						Off-peak hour						Weekend					
	Ang Mo Kio	Bedok	Jurong West	Punggol	Toa Payoh	Yishun	Ang Mo Kio	Bedok	Jurong West	Punggol	Toa Payoh	Yishun	Ang Mo Kio	Bedok	Jurong West	Punggol	Toa Payoh	Yishun
CBD	0%	0%	19.4%	98.2%	0%	24%	49.7%	0%	0%	0%	38.3%	0%	42.7%	0%	0%	0%	32.5%	0%
Tampines	0%	27.9%	0%	0%	0%	0%	0%	27.2%	0%	0%	0%	0%	0%	19.2%	0%	0%	0%	0%
Jurong East	0%	0%	45.2%	0%	0%	0%	0%	0%	29.4%	0%	0%	0%	0%	0%	46.3%	0%	0%	0%
Woodlands	0%	0%	0%	0%	0%	43.3%	0%	0%	0%	0%	0%	51%	0%	0%	0%	0%	0%	52.4%
Bishan	21.6%	0%	0%	0%	0%	0%	19.5%	0%	0%	0%	0%	0%	21.2%	0%	0%	0%	0%	0%
Paya Lebar	0%	20.5%	0%	0%	0%	0%	0%	21.5%	0%	0%	0%	0%	0%	43.2%	0%	0%	0%	0%
Serangoon	68.5%	0%	0%	0%	0%	0%	60.6%	0%	0%	48.6%	0%	0%	64.7%	0%	0%	0%	0%	0%
Ang Mo Kio	20.2%	0%	0%	0%	37.6%	37.2%	39.1%	0%	0%	0%	59.3%	8.0%	23.5%	0%	0%	0%	59%	43.9%
Bedok	0%	71.2%	0%	0%	0%	0%	0%	71.7%	0%	0%	0%	0%	0%	65.8%	0%	0%	0%	0%
Jurong West	0%	0%	72.9%	0%	0%	0%	0%	0%	76.9%	0%	0%	0%	0%	0%	67.1%	0%	0%	0%
Punggol	0%	0%	0%	80.6%	0%	0%	0%	0%	0%	71.5%	0%	0%	0%	0%	0%	100%	0%	0%
Toa Payoh	42.8%	0%	0%	0%	71.1%	4.9%	77%	0%	0%	0%	73.5%	0%	77.4%	0%	0%	0%	73.3%	0%

Yishun	48.4 %	0%	0%	0%	5.6%	41.2 %	10.4 %	0%	0%	0%	0%	72.0 %	61.9 %	0%	0%	0%	0%	45.4 %

5. Discussion and Conclusion

This study examines the levels of self-containment of new towns/centers in Singapore and the interdependence among the centers in the post-COVID period. Based on the MRT and bus passenger flow data of the two 8-month periods after the lift of COVID-19 lockdown in July 2021, we analyze the passenger flows for both commuting (i.e., peak-hour) and non-commuting (i.e., off-peak hour/weekend) travel purposes before and after the complete removal of COVID prevention and control measures in Singapore, with particular focus on the spatial characteristics of service sheds of 13 centers of different tiers (regional, sub-regional and town centers), as well as the overlapping patterns of principal commuting and non-commuting sheds between the centers. The main findings are summarized and discussed below.

First, MRT lines have considerable impacts on residents' daily travel pattern and the spatial distribution of centers' service sheds. Since all of the selected centers are located along the MRT lines, their principal service sheds show a clear distribution along the MRT lines. However, given that centers of different tiers have different positions of the MRT network, the principal service sheds of a town center are usually distributed along the MRT line where the new town's main MRT station (i.e., named by the new town) is located, while those of higher-tier centers are distributed along multiple MRT lines. This finding is also consistent with Chen et al.'s (2023) study that the spatial patterns of MRT passenger flows in Singapore before and after the COVID pandemic indicates a multi-center city structure.

Second, there are substantial differences in the spatial range of principal service sheds of different tiers of centers. The CBD as the largest center and occupying the central location in the MRT network has the widest spatial range of principal sheds, mainly within a 10 km radius, while the principal sheds of other tiers of centers are mainly concentrated within 5 km of the centers. This shows that Singapore's polycentric system exhibits clear a hierarchical pattern. Furthermore, in the non-control period when no prevention and control measures were reinforced, daily mobility of residents were increased, and the spatial range of centers' service sheds has expanded greatly: more subzones within 5-10 km radius of the centers are identified as the principal sheds.

Third, even though population mobility and the overall number of trips decreased in the SD control period, all centers except Bishan are closely connected to several other centers in this period, implying that they have not completely achieved self-containment when facing the COVID pandemic. The dependence of other centers on the CBD is higher in the SD control period compared with the non-control period; during the control period, the degree of other center's interdependence with the CBD is higher for commuting travel than for non-commuting travel. Apart from the CBD, most of centers having their principal service sheds overlapping with each other in the SD control period are usually within 5 km of each other, regardless of whether they belong to the same tier, while in the non-control period more centers that are interdependent with each other are within 5-10 km. However, the higher tier of the centers, the more likely that they are interdependent with a larger number of other centers.

Fourth, there are considerable differences between commuting and non-commuting travel flows across centers. In both control and non-control periods, passenger flows in peak hours are always greater than those in off-peak hours and weekends, and the interdependence among centers in terms of commuting passenger flows are usually larger than non-commuting passenger flows.

These findings advance the knowledge of Singapore's multi-center system and the features of locals' travel patterns in the post-COVID period. Additionally, the results can serve as a guide for developing 20-minute towns and 45-minute cities, as well as for refining the service sheds of various levels of urban centers and the interrelationships between centers (Manifesty & Park, 2022). On the one hand, given that most of new towns/planned centers have not achieved complete self-containment and are strongly dependent on the CBD during and after the removal of COVID measures. To further enhance the preparedness and response capabilities of new towns/centers for public health emergencies in the future, it is necessary to strengthen the supply of essential daily facilities and services in those centers. Given that passenger flows between new towns/planned centers within 5 km of each other occur very frequently, it is also important to further enhance connectivity between new towns/centers that are within a 5 km radius and facilitate the sharing of commercial service and public facilities around those proximate centers to strength their complementary relationship and lessen their reliance on the CBD. Besides, the designing of 20-minute towns should also consider various modes of transportation, including public transportation and private vehicles, rather than solely relying on walking and non-motorized vehicles.

On the other hand, our results reveal the differences in commuting and non-commuting passenger flows patterns that should be taken into account when designing the “45-minute” city. In the non-control period, except for a few higher-tier centers such as the CBD, Jurong East, Woodlands, most of centers’ principal commuting sheds are concentrated within 10 km buffer zones around the centers. In contrast, most of centers principal service shed for off-peak hour/weekend travel are beyond the 10 km buffer zones of the centers. Although the original policy objective of the “45-minute city” only focus on commute travel (LTA, 2018), we believe such standard should also apply to non-commuting travels in order to promote more sustainable land transport system. Hence, the development of ‘45-minute city’ may propose different development strategies for residents of different centers for different travel purposes. For example, for centers with an average commuting time exceeding 45 minutes, there should be a focus on enhancing job creation. For centers where off-peak hour/weekend travel exceeds 45 minutes, priority should be given to enhancing the development of entertainment and recreational facilities. Moreover, given the central position of the CBD in the MRT network that easily accessible by regional-wide residents, the role of CBD in providing employment, service and amenities for new town residents during the public health emergence should also be considered when developing the “45-minute city”.

In Singapore, new town planning is an important strategy to decentralize population and economic activities, thereby alleviating pressure on the CBD. The recent goals of "20-minute towns" and a "45-minute city" further emphasize the importance of a certain level of self-containment in Singapore's new town development. In this context, this study analyses the self-containment level at the town level in both the SD Period and the Non-control Period. The findings and analysis can provide valuable insights and guidance for achieving a balance between the local self-reliance of new towns and the integration of these towns within the broader city context. However, this paper also has some limitations. First, due to the availability of data, this article only studied the travel of rail transit and bus transit during the SD control and non-control periods. The travel of private cars and bicycles and other modes of transportation are not considered. Second, due to the accuracy of the data, it is not possible to analyze personal travel chains more accurately. As a result, determining whether the trips between these centers primarily serve daily needs or other economic purposes is not feasible. In the future, a more detailed classification study of residents' travel purposes can be conducted by combining smartcard data, mobile signal data and other data sources.

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