EXPLORING LINKS BETWEEN TRANSIT HUBS AND BUILT ENVIRONMENT IN ASIAN CITIES

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by

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ABSTRACT

This study selected a total of 190 transit hubs across Shanghai, Hong Kong, and Tokyo to empirically examine whether the built environment around transit hubs shares the same attributes and how the built environment features may be related to the characteristics of transit hubs. Spatial analysis using ArcGIS was adopted to explore the distribution of built environment features around transit hubs. Linear regression models were established to evaluate the quantitative relationships between six indicators of transit hubs (intramodal connection, intermodal connection, proximity to CBD, proximity to other metro stations, cluster effect, and time effect) and five built environment metrics (population density, building density, land use mix, intersection density, and housing price). Among all the built environment features, building density is the most possible one to be shared around transit hubs. The regression results revealed that the built environment features had different degrees of correlation with the characteristics of transit hubs. Proximity to CBD and years in operation (time effect) for transit hubs were demonstrated to be the most important indicators related to the built environment. The significant relationships between transit hubs and the built environment illustrated in this study are helpful to understand station areas' development dynamics.

Keywords: transit hubs, built environment, Asian cities

Table of Contents

List of Figures and Tables

I. Introduction

With rapid economic growth across developing countries in Asia, the use of motorized vehicles has increased dramatically during recent decades. In order to alleviate the negative externalities of rapid urbanization such as low-density urban sprawl, traffic congestion, lack of mobility, air pollution, and greenhouse gas emission, many Asian cities advocate a high-level integration of public transportation and urban development to aggregate population's daily activities around transit stations (Suzuki et al., 2015). It is expected that urban development could be enhanced in terms of efficiency, convenience, and profitability. The integration of transit stations and surroundings may promote a complex of diverse urban functions and barrier-free space incorporation. Additionally, developers have incentives to improve the efficiency of planning and investment on the land around transit stations because the convenience of transit may lead to a large number of population's gathering as well as an appreciation of land value (Nikken Sekkei ISCD Study Team, 2013).

The former built environment of station areas before the establishment of transit infrastructure could be considerably different from each other. Some of them were originally well-developed regions with high density and a mixture of land use, some were relatively mature neighborhoods form by long-term urban evolvement, and others were growing areas located on city outskirts that may have great potentials of development. Proper and effective approaches to integrate transit stations and ambient built environment should be formed based on the actual situation. Assume desirable outcomes of integration tend to be consistent in terms of urban development. To verify that hypothesis, this study selected a total number of 190 transit hubs across Shanghai, Hong Kong, and Tokyo to empirically examine **whether the built environment around transit hubs shares the same attributes** and **how the built environment features may be related to the characteristics of transit hubs**.

Transit hubs refer to the term “transport centers” defined by Rivasplata and Charles, which are established stations with the interchange between two or more transit lines and some of them can be intermodal with physical integration of multiple public transportation modes (Rivasplata & Charles, 2001). This paper focuses on intracity rail transit systems and thus narrows down the study scope to metro stations with connections between at least two metro lines or modes that consist of metro and rail. The built environment is regarded as the human-made space where people live, work, and recreate on a day-to-day basis (Roof & Oleru, 2008). More specifically, the built environment in this study represents the urban development of a given area located within a radius of 1/2 mile around each transit hub according to the de facto standard for rail-transit catchment areas (Guerra and Cervero, 2013).

In this study, the characteristics of transit hubs are generally measured from three perspectives: connectivity, proximity, and accessibility. Connectivity indicates the capacity to move passengers between the station area and other areas at the city scale through public transportation. Better connectivity can extend the reach from one place to a wider range of destinations and thus lead to more ridership. Proximity measures the physical distance from transit hubs to major urban resources. Since transit hubs serve as convenient points of collection, distribution, and transformation, in closer proximity to commercial, business or transportation resources might contribute to centralized development based on stations (Rodrigue et al., 2016). Accessibility can represent the capacity of transit hubs to be reached or to reach different locations (Rodrigue et al., 2016). Therefore, it measures the spatial interaction of transit infrastructure and human activities in the surroundings. The time effect of public transportation on the peripheral urban development is of great importance to understand transit hubs' influence on the built environment over time.

The transit hub is no longer just the place where riders arrive or depart, it has the potential to become a destination by encouraging the development in or around the station. Transit hubs can bring people together and make them interact with surrounding areas. In response to the demand brought by transit, the built environment may develop itself in multiple ways, such as an increase of population and building density, a mix of land use, and growth of the street network. In addition to such changes in urban form, the effect of transit hubs also works on the real estate market, which is an of great importance factor shaping the built environment.

I select six indicators to represent the characteristics of transit hubs and five indicators to measure the built environment. Spatial analysis is used to visualize and compare whether the built environment features in station areas share similar values. Through quantifying selected metrics of transit hubs and built environment, linear regression analysis is then applied to explore the relationships between transit hubs and the surrounding built environment.

II. Literature Review

1. Transit and Built Environment

Wegener and Fuerst (1999) used the theory of “land-use transport feedback cycle” to explain the association between public transport and land use. In the first place, land use patterns will determine the locations of human activities. Since the spatial division of human activities requires the provision of transportation to overcome the distance between locations, the demand for transit facilities will grow and thus improve the accessibility. Such an enhancement in accessibility finally leads to the feedback in land use patterns by affecting the location decisions of households, firms, and landlords. And this iterative process will continue until a balance is reached or until some external factor intervenes (Meyer and Miller, 2001). In addition, Suzuki et al. (2013) presented a framework to illustrate the interaction effect between public transportation and urban form. Initially, the increase in accessibility by improving transit can stimulate urban development around the station. In return, the newly built urban form will boost the demand for public transportation, as higher densities lead to greater ridership. In addition to density, some other factors can shape travel demand as well, including diversity, design, destination, and distance to transit (Ewing and Cervero, 2010).

To achieve economic values of transit, a large number of potential transit riders will live and work around transit stations (Zykofsky, 1999). Many studies have proved that population density has a strongly positive relevance to transit use that the higher the density, the greater the transit use (Bertaud and Richardson, 2004). In addition, Cervero and Guerra (2011) suggested that the development of light-rail system needs about 30 people per acre around transit station and the corresponding number for heavy rail system is 50 percent higher. However, most of the past research focused on the necessary population density to support rail investments so that increasing density to some extent can lay the foundation for rail transit development.

Density in the urban planning context represents certain quantified human presence divided by land area. In addition to population, building is another expression of urban densities. Two primary linkages between building density and transit can be concluded that high density neighborhoods promote population's use of public transportation and generate more origins and destinations with convenient access to transit (Puget Sound Regional Council (PSRC), 2015). Therefore, transit plays an important role in boosting demand for trips between stations and peripheral neighborhoods. Because of these phenomena, some local governments, transit agencies and other organizations might be encouraged to implement strategies such as compact residential and commercial development in the surroundings (PSRC, 2015). Increasing building density nearby transit stations not only benefits the development of transit systems, it also good for the developers and property owners thanks to the increase in value of commercial and residential projects (Zykofsky, 1999). Therefore, it may give them an incentive on real estate development in station areas.

Increasing the mixing degree of land use has been found to be positively associated with the decreases in vehicle miles traveled (VMT) and automobile ownership rates, as well as the increases in walking, biking, and transit use (PSRC, 2004). Through an improvement in mixed use of land around transit stations, benefits also can be embodied in creating compact and diverse neighborhoods with greater economic and cultural opportunities. Some research has considered more extensive land use distribution to determine the mixability. For instance, Frank et al. (2016) applied six types of land uses including education, entertainment, single-family and multifamily residential uses, retail, and office to calculate the land use mix as an indicator of the built environment. Horizontal land use mixing was taken into account in most cases. However, vertical use mixing is more desirable in promoting compact, intensive, and mixed-use development around transit stations, especially in some urban areas with massive population (Clarion Associates, 2014). Point of interest (POI) can be regarded as a measurement of both horizontal and vertical mixing of uses. Yuan et al. (2018) aggregated fifteen POI types into five broader groups that were commercial and service, business and factory, education, government, and residential locations to estimate the degree of land use mix. Although this approach takes the vertical locations of various human activities into consideration, it ignores the POI's gross area. And it is difficult to determine which measurement is more accurate.

Walkability is an indispensable element to evaluate the effects of transit hubs on their ambience in terms of urban development. As Ewing and Cervero stated (2010), high intersection density and good street connectivity can shorten walking distances and provide more route options for transit riders. Among all the built environment measurements, intersection density has the greatest effect on walkability, which has an essential association with transit use.

In addition to the influence on urban form, economic impacts of transit on the built environment are of great importance embodied in changes in the real estate market. Economic effects are no less significant than other factors and even have potential association with some urban form elements. For instance, developers will be motivated to construct more buildings around transit stations because of appreciation in property value (Zykofsky, 1999). The empirical evidence suggests that there are obvious increases in property values for residential, commercial, and retail development located nearby transit stations (Economic Research Associates (ERA), 1995). While transit infrastructure is believed to have a notable influence on surrounding property values, the mechanism between transit and real estate is complicated and worthy for in-depth discussion. A study in Toronto indicates that the slope of real estate rents becomes steeper around rail transit stations due to an improvement in accessibility and the reduction in commute time. With the provisions of transit facilities, there are changes in travel patterns because locations nearby the stations become more important trip destinations for urban population (Dewees and Donald, 1976). As a result, property values in the surroundings increase with the growth in demand. And this kind of appreciation may happen at any time. A study in Washington County, Oregon found that plans for light rail investments had positive effects on land values in proposed station areas by a 36% increase (Knaap et al., 2001). Furthermore, another investigation on Seoul’s subway Line 5 pointed out the influence of transit stations on ambient residential property values is significant in the first three years of operation (Bae et al., 2003). While the property values of both commercial and residential buildings are linearly related to their distances to transit stations, the intensity of influence may be different. Retail rents close to transit were estimated to be about three times higher than in other areas (ERA, 1995). The corresponding number for residential sites could be diverse.

Last but not least is to understand the importance of the combined development of transit investments and real estate projects. Previous studies demonstrated such combination could increase building densities as well as property prices in station areas (Cervero, 1994). The theory of agglomeration economies presented by Rodrigue et al. (2016) also illustrated the cluster of various human activities in a single location could reduce transportation costs and thus attract more population for its convenience. Therefore, this joint development pattern can be considered an attribute of transit stations to explore its impact on surrounding built environment.

2. Previous Methodologies

Bertolini (1999) has created the node-place model to study the association between transit stations and surrounding urban development by quantifying physical human activities at and around public transportation nodes. Transit stations as nodes represent the provisions of transit facilities. Station areas as places represent the surrounding built environment. Chorus and Bertolini (2011) then applied this model to understand the development mechanism of station areas for a well integration of stations and periphery. Their research conducted a correlation analysis on a great number of transit stations in the city of Tokyo. The results demonstrated that the areas around stations have a higher number of rapid trains, a higher number of train connections, or a location closer to the CBD had relatively small residential populations but large workforces. In addition to explore the interaction between transit station and urban form in the same city, many studies have examined such association cross-sectionally. For example, Currie and Gruyter (2018) used the regression analysis to explore the linkage between sustainability performance of public transportation and land use through 98 cities all over the world. The sustainability performance of transit was evaluated from economic, social, and environmental dimensions respectively. And the land use indicators were composed of population, population density, job density, urban size, sprawl index, and walking mode split. The results indicated that population and job density were most related to the transit's performance compared to other factors. In this case, not only the urban form was considered into the study. The characteristics of transit could be evaluated from multiple perspectives including economy, society, and environment. The built environment should not be limited to land use and density. Therefore, in this study, walkability and real estate are seen as important indicators of transit hubs to analyze.

Draw on previous experiences, the regression model is always used as the approach to analyze the links between transit stations and surrounding built environment quantitatively.

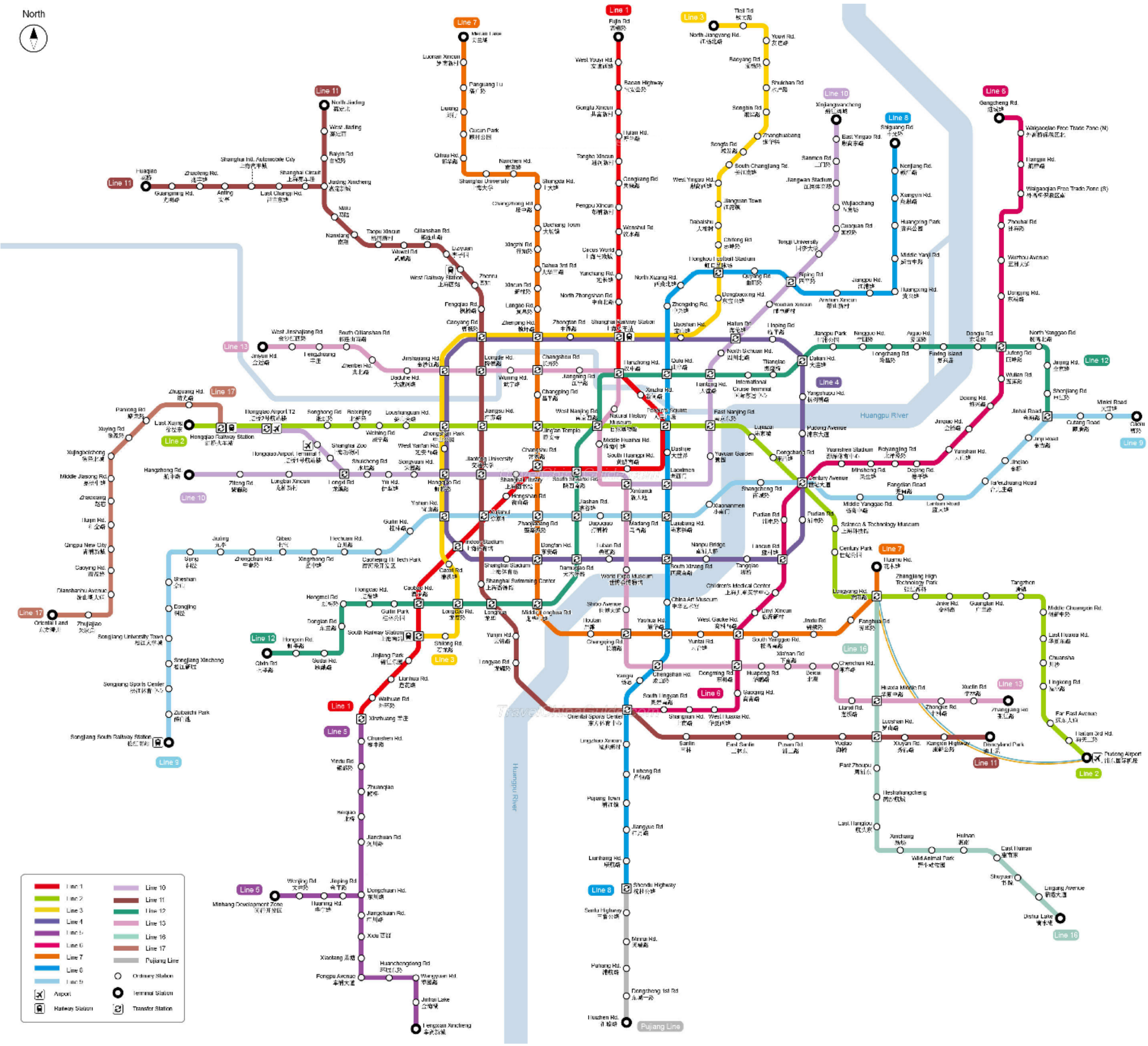
III. Data and Methodology

1. Study Area

I selected three representative cities in Asia with relatively mature and advanced development of urban rail transit systems as well as great efforts in the integration of metro stations and urban development. They are Shanghai, Hong Kong, and Tokyo.

a. Shanghai

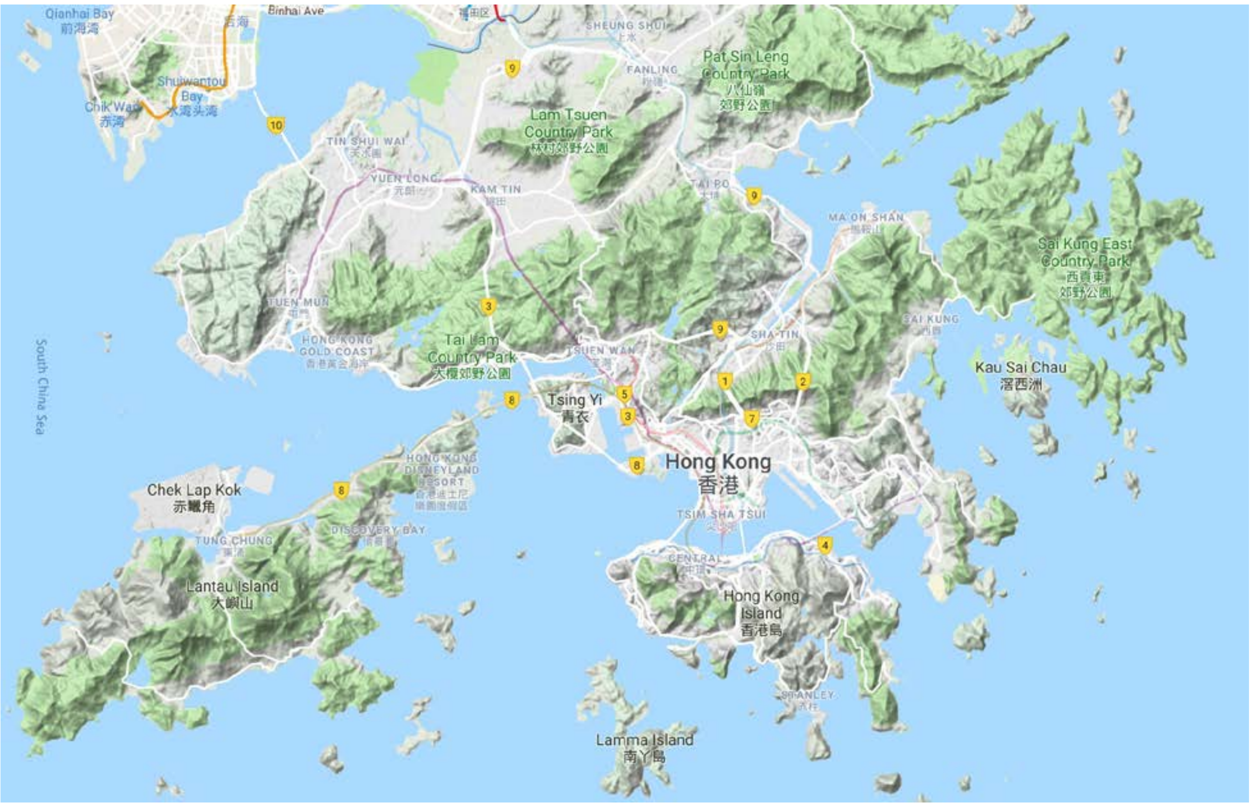
In terms of spatial pattern, the metropolitan area of Shanghai can be divided into four parts by three ring roads that are the inner ring, middle ring, and outer ring. The central business district (CBD) is located inside the inner ring. However, due to conflicts between insufficient resources and oversized population, there has been a trend for the urban population to decentralize and extend to the suburbs. The development of rail transit network has played an indispensable role in such urban sprawl. While Shanghai only started its first metro line in 1993, it has developed to the second largest rapid transit system worldwide by the number of stations with 413 stations on 16 lines (see Figure 3-1). Intracity metro accounts for 13 lines of the total and intercity rail takes up 3 lines (Line 16, 17 and Pujiang Line). Comparatively speaking, intercity railways function as commuter rail serving for residents who live in city outskirts so that they are distributed and connected with intracity metro lines in urban fringe areas. Owing to the extension of the urban rail transit systems, people are able to live in places away from the urban core and thus save a lot of living costs. For now, rail transit has become a prevalent transportation mean people choose to travel by. According to the official statistics, Shanghai Metro’s average daily ridership reached over 10 million in 2018.



Source: Shanghai Metro

Figure 3-1. Shanghai Metro Network Map

b. Hong Kong



Source: Google Maps

Figure 3-2. Terrain Map of Hong Kong

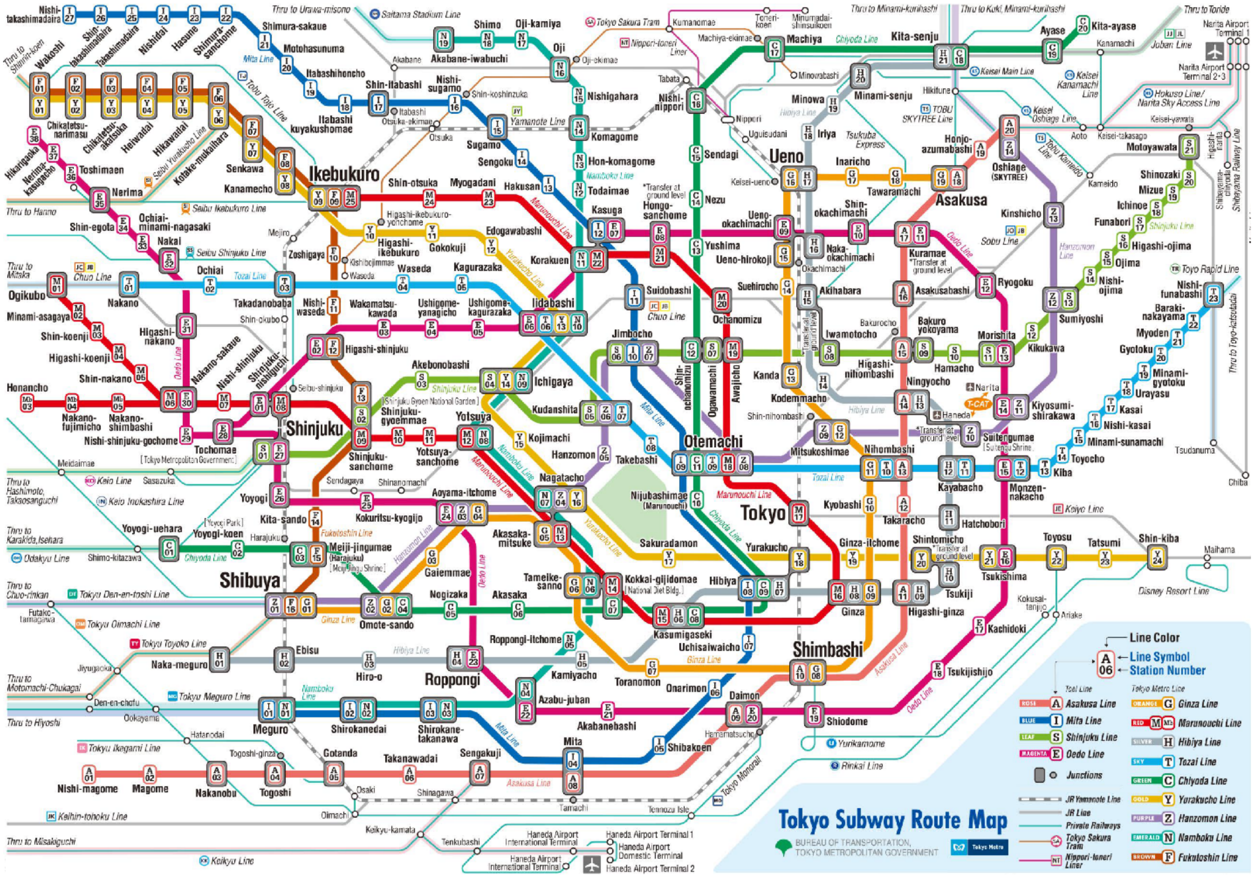
Since Hong Kong is mountainous where flat land accounts for less than 20 percent of the total land, only little space has been occupied for urban development (see Figure 3-2). Consequently, the city is quite scattered from a holistic perspective but highly concentrated in several small-scale regions. In order to mitigate road congestion resulted from fast economic development, the Hong Kong Government encouraged the public to use public transportation instead of automobiles when traveling and thus the system of Mass Transit Railway (MTR) was constructed and initially operated in 1979. MTR in a broader concept consists of heavy rail, light rail, and feeder bus. Among those components, heavy rail comprises 10 intracity metro lines and 1 airport express line (see Figure 3-3). Light rail system, linked with West Rail Line, acts as one of the major travel modes for new towns situated in New Territories. MTR has been commonly adopted by the urban population along with its continuous growth. In 2000, over 90 percent of motorized trips in Hong Kong were completed by public transportation (Cervero and Murakami, 2009). And in 2018, the average daily ridership of MTR was over 5 million.

Source: MTR

Figure 3-3. MTR Network Map

c. Tokyo

The rail transit network in the metropolitan area of Tokyo is so intricate and well-developed that it can be classified into four types: intercity high-speed rail (Shinkansen), intercity rapid transit (East JR), commuter rail, and intracity metro. These four rail transit systems are operated separately but meanwhile closely associated with each other so as to provide highly convenient and efficient public transportation services in the Great Tokyo area. The intracity metro system was divided by two primary operators which are Tokyo Metro and Toei Subway respectively. They corporate together to develop 13 metro lines with 278 stations in total (see Figure 3-4). The first metro line in Tokyo was opened in 1979, which was much earlier than Shanghai and Hong Kong. The Great Tokyo area is composed of eight regional areas and the intracity metro network is principally distributed in the city center of Tokyo including the metropolitan center, sub-center areas, and their adjacent regions. Nevertheless, its service scope can extend to suburbs through the seamless connections to other rail transit systems. It must be clarified that since the distribution area of intracity metro system is geographically limited, I scaled down the study area to the special wards of Tokyo including 23 municipalities that originally made up Tokyo City. Afterward, Tokyo City was abolished in 1943 and the special wards has become part of the newly defined Tokyo Metropolis.



Source: Tokyo Metro

Figure 3-4. Tokyo Metro Network Map

2. Data

a. Dependent Variables on Built Environment

There are five indicators defined in this study to represent the built environment around transit hubs quantitatively, which are population density, building density, land use mix, average housing price, and intersection density respectively.

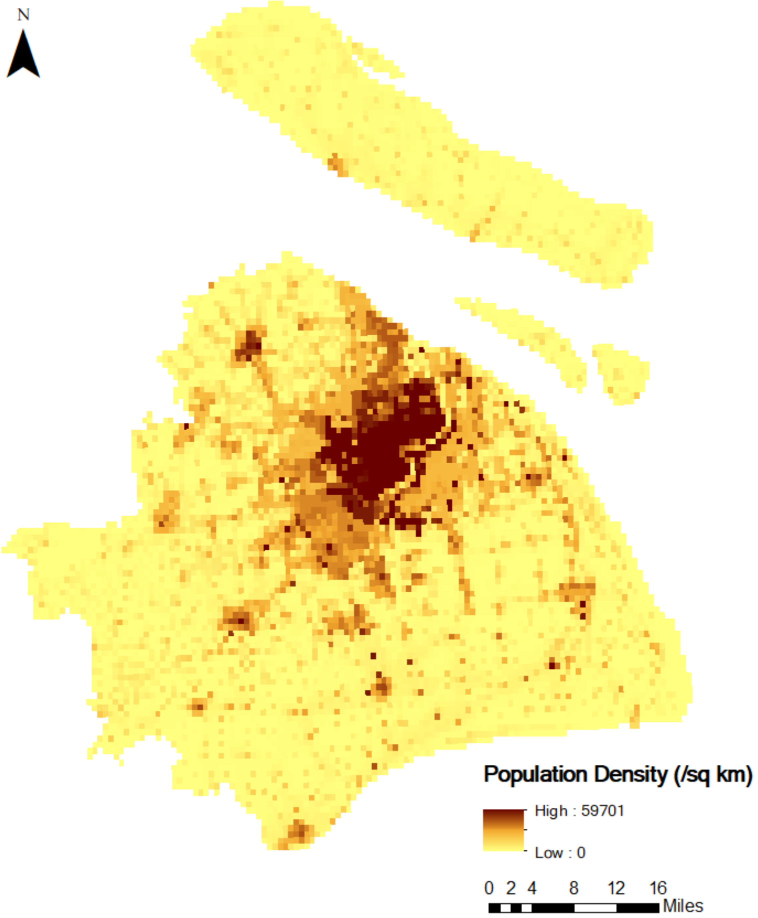
(1) Population density

Population density measures the degree to which of human aggregation at a spatial scope. It can reflect the attraction of a given location to the population. The raw data was obtained from the LandScan Global Population Database produced by the OAK RIDGE National Laboratory (ORNL), which describes the average population distribution over 24 hours in approximately 1km (30'' x 30'') resolution. The LandScan uses the best available demographic and geographic data and remote sensing imagery analysis techniques to disaggregate population data within administrative boundaries (ORNL, 2017). This population data integrates population distribution of various human activities including residential, employment, and recreation. As shown in the figures below, in terms of the study area's size, Shanghai is nearly double larger than Hong Kong and four times the size of the special wards of Tokyo. According to their population patterns, Hong Kong has the highest maximum of population density, approximately twice denser than Shanghai and five times as dense as the special wards of Tokyo. It implies Hong Kong is the most crowded one among those three study areas. Another finding is that both Shanghai and Hong Kong reveal imbalanced population distribution where the urban population is mostly concentrated in CBD. Instead, the population distribution across the special wards of Tokyo is relatively even with a slightly higher population density in sub-center areas.

Figure 3-5.

Population Pattern,

Shanghai

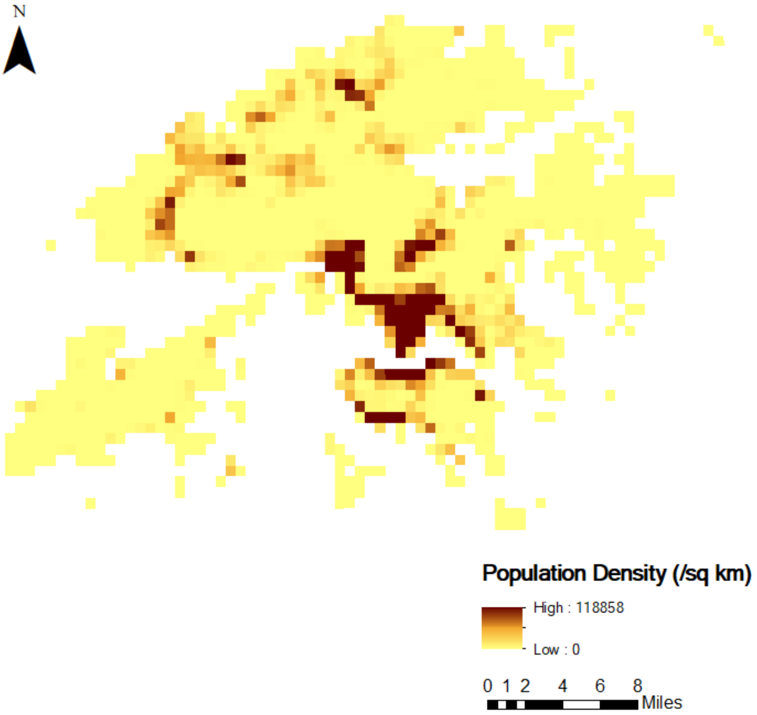


Source: ORNL's LandScan Global Population Database

Figure 3-6.

Population Pattern,

Hong Kong



Source: ORNL's LandScan Global Population Database

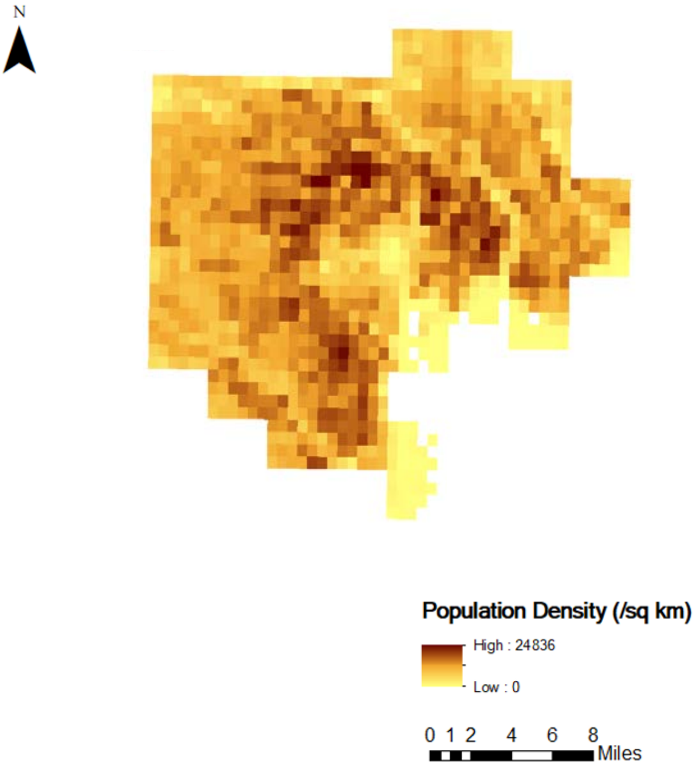


Figure 3-7.

Population Pattern,

Special Wards of Tokyo

Source: ORNL's LandScan Global Population Database

(2) Building density

Building density is a quantitative indicator of land development. The vacancy rate of land is generally higher in underdeveloped regions compared to well-developed regions. Building footprints in each study city was collected from various sources. The building footprint data of Hong Kong and Tokyo were obtained from OpenStreetMap (OSM) with a real-time record of building outlines by administrative regions. As for Shanghai, the building footprints were sourced from Urban Data Party, a big data platform that has captured the building contours on Baidu Maps and measured their coverages. Due to the difficulties in collecting the floor area of each building to calculate the floor area ratio (FAR), I used building coverage data to illustrate building distribution. Very similar to population pattern, Shanghai's buildings are intensely distributed in the city center and progressively decentralized outward from the center. The bulk of buildings in Hong Kong are compactly located in Kowloon and part of Hong Kong Island due to a limitation on topography. The special wards of Tokyo also reflect the nature of inequality with a high concentration of buildings in the city center while some marginal areas have dense buildings.

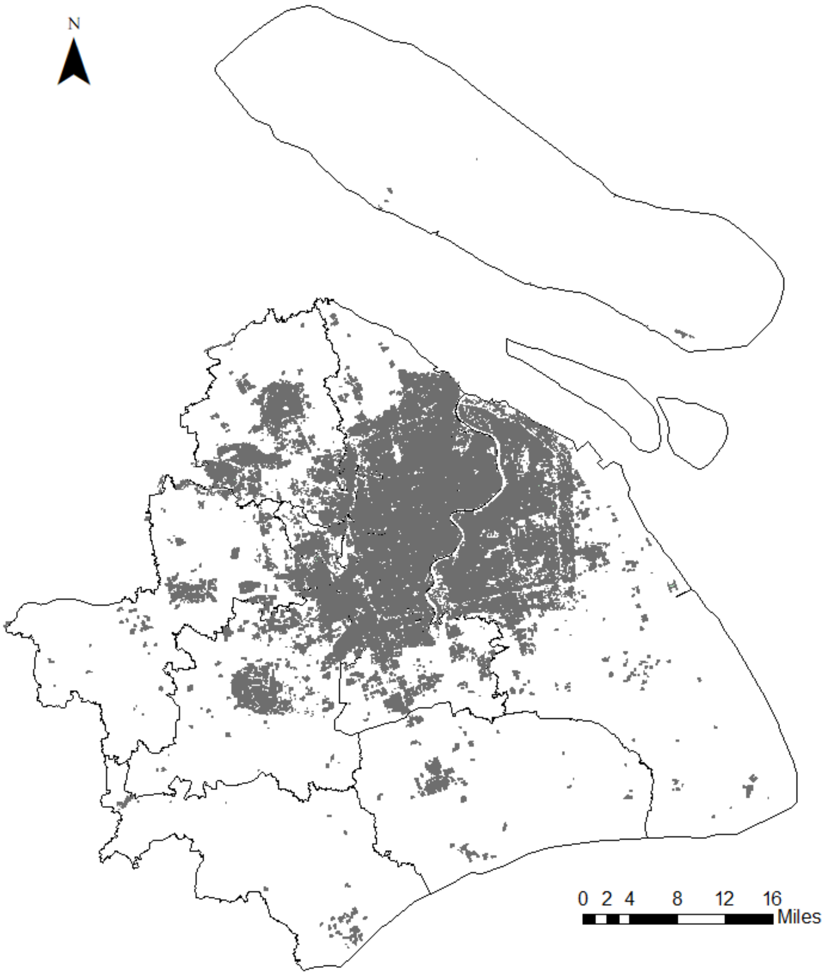


Figure 3-8.

Building Distribution, Shanghai

Source: Urban Data Party

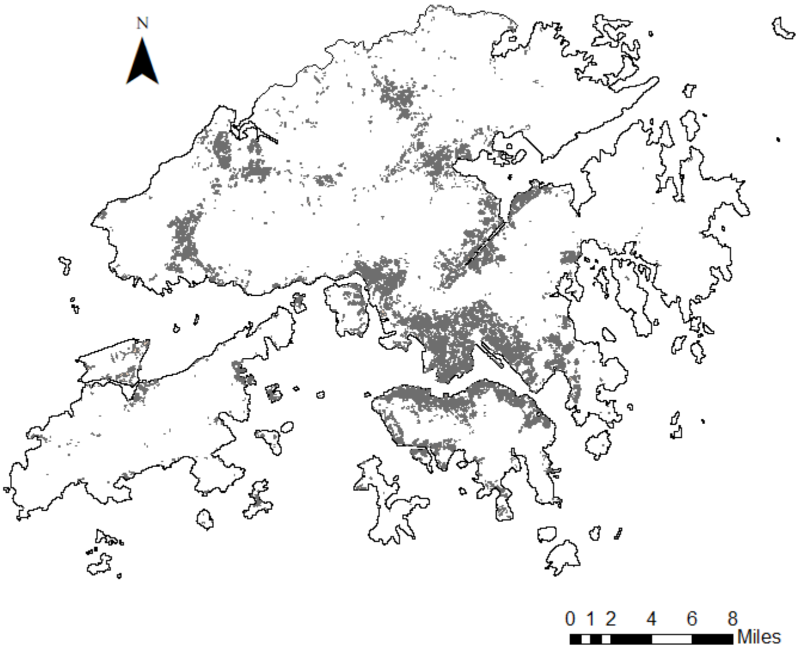


Figure 3-9.

Building Distribution,

Hong Kong

Source: OpenStreetMap

Figure 3-10.

Building Distribution,

Special Wards of Tokyo

Source: OpenStreetMap

(3) Land use mix

To measure the mixing degree of land use distribution, I referred to the research of Frank et al. (2006) where the land use mix was adopted as an index to measure walkability. Four types of land use are considered into the calculation for this study: residential sites, commercial sites, industrial sites, and open space. The specific formula is shown as follows:

$$Land\ Use\ Mix\ =\ -\frac{\sum_{i=1}^{n} p_i \times ln(p_i)}{ln(N)}$$

Where p_i represents the proportion of land use type i among the station area and N is the number of land use types with land area > 0. The range of land use mix is between 0 and 1. And the higher the index value means the greater the mixing degree of land use. Due to a lack of land use distribution data in Shanghai, I used points of interest (POI) data obtained from Urban Data Party as a substitute (see Figure 3-11). POI as point data reveal the distribution of human activities' locations rather than the occupied areas of land use. However, the diversity of POI within the same size of buffer area around transit stations can reflect the mixture of land use as well (Yuan et al., 2018). The land use data in Hong Kong was obtained from OMS and the corresponding data in the special wards of Tokyo was collected from the National Land Numerical Information released by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT).

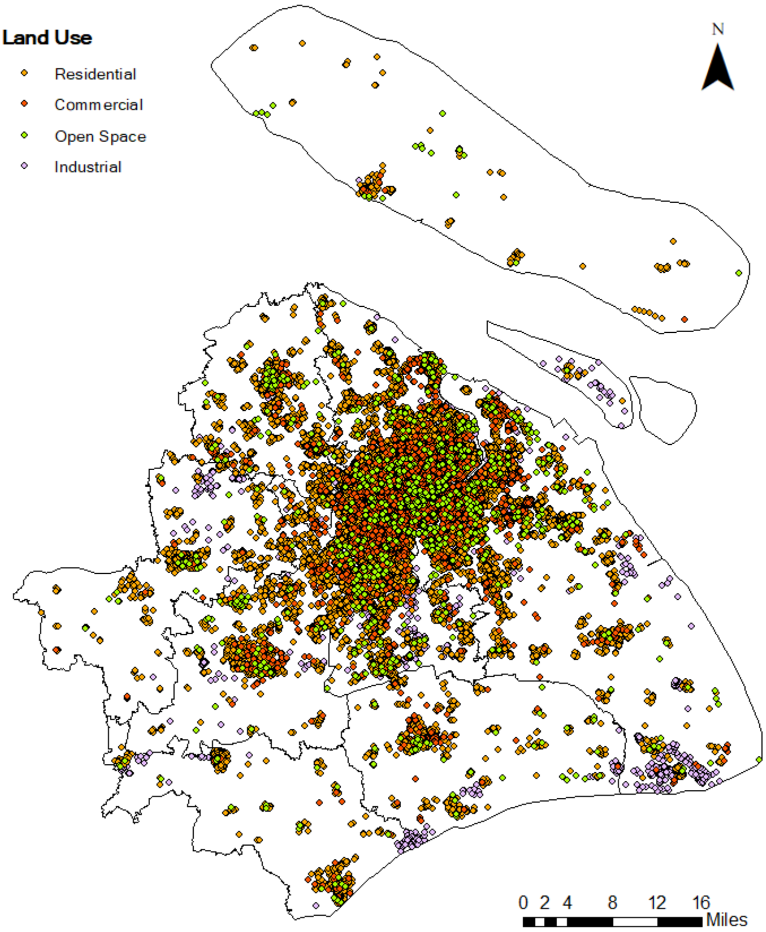


Figure 3-11.

POI Distribution,

Shanghai

Source: Urban Data Party

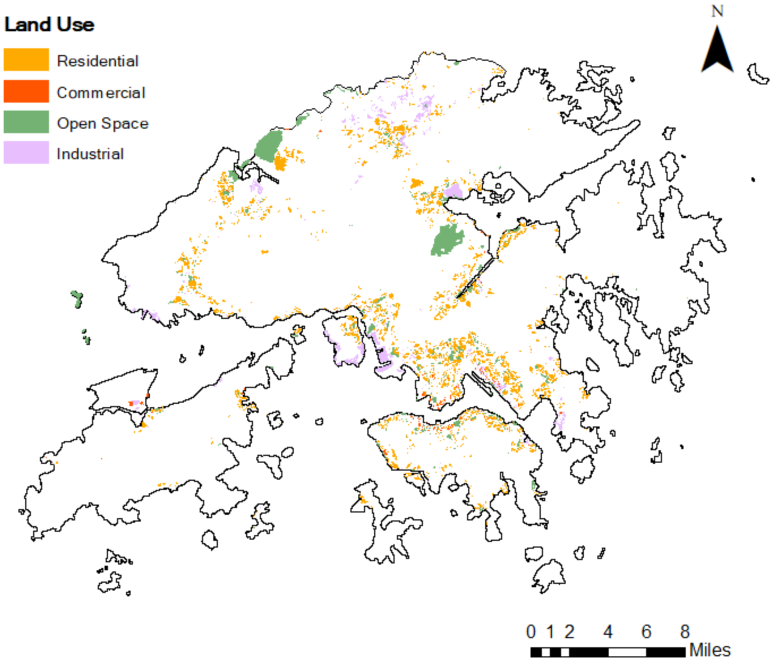


Figure 3-12.

Land Use Distribution,

Hong Kong

Source: OpenStreetMap

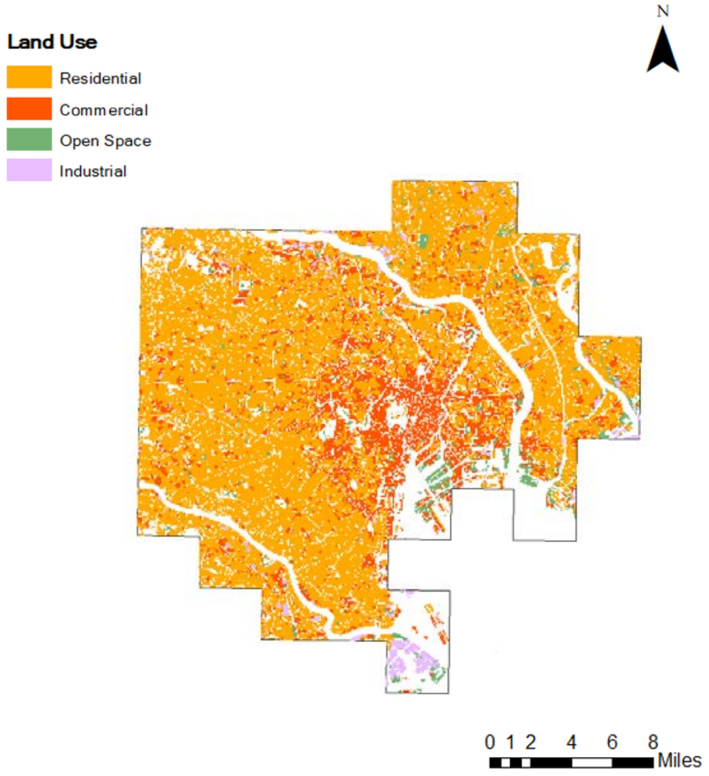


Figure 3-13.

Land Use Distribution,

Special Wards of Tokyo

Source: MLIT's National Land Numerical Information

(4) Housing price

The property value can be monetarily embodied in housing price that somehow reflects the interaction between housing demand and supply. For a location where the average housing price is comparatively higher than other places, it indicates that this location is more appealing to people to live in so that the housing demand exceeds its supply. To understand whether the spatial distinction in the real estate market is related to the presence of transit hubs, I introduced the average housing price as a dependent variable in this study. The data in Shanghai was derived from an investigation produced by Yunfang Data in 2018. It sorted out all the transaction prices of second-hand residential buildings within 1000 meters of each metro station in Shanghai and calculated the average housing price per station area. For Hong Kong, a well-known real estate agent called the Centaline Property releases a map of metro stations with their average housing prices in the past 30 days. The prices were calculated using the transaction data within about 10-minute walking distance from stations and the unit was HKD per square foot. The similar data in Tokyo was processed based on the land price dataset for all land types in 2018 from MILT’s National Land Numerical Information. I only used residential areas to calculate the average land price in each transit hub buffer. The housing price data of three study cities were standardized in the unit (USD) and inflation (in 2018) when running in the regression model.

(5) Intersection density

Intersection density is an expression of the street network due to its close association with block size. The greater the intersection density, the smaller the blocks and thus the more walkable the neighborhood. The road networks of three study cities were provided by OSM. However, not all road types could be considered when calculating the number of intersections. The roads that are typically divided from other roads or pedestrians such as motorway, freeway, and trunk should be excluded since they have no walkability. The streets used to calculate intersection density consist of major streets including primary, secondary and tertiary roads as well as minor streets such as residential roads, living streets, and pedestrian-only streets. According to the comparison of the three study cities’ street networks (see Figures 3-14, 15, &16), the special wards of Tokyo has the most compact and balanced street network followed by Shanghai where streets are relatively intensive across the urban core but getting sparse outward. The street layout of Hong Kong is unique owing to its topographic feature so that only central areas have solid blocks. The extremely high density of walkable streets in the special wards of Tokyo illustrates an optimized road system that can meet the urban population's demand on walking. Transit service's wide coverage across the special wards of Tokyo even the edges has led to a high level of walkability and a well-developed street pattern as an auxiliary transportation infrastructure of transit.

Figure 3-14.

Street Network,

Shanghai

Source: OpenStreetMap

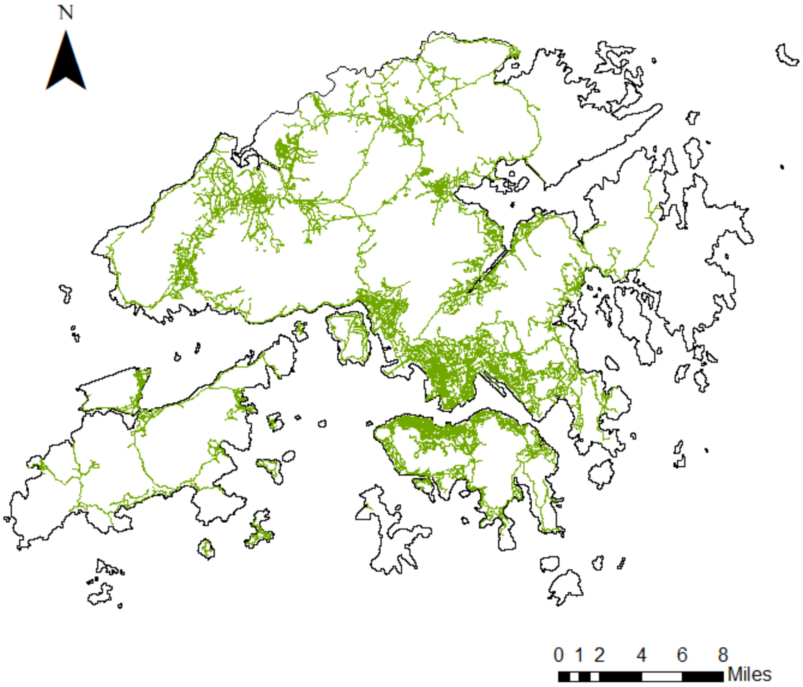


Figure 3-15.

Street Network,

Hong Kong

Source: OpenStreetMap

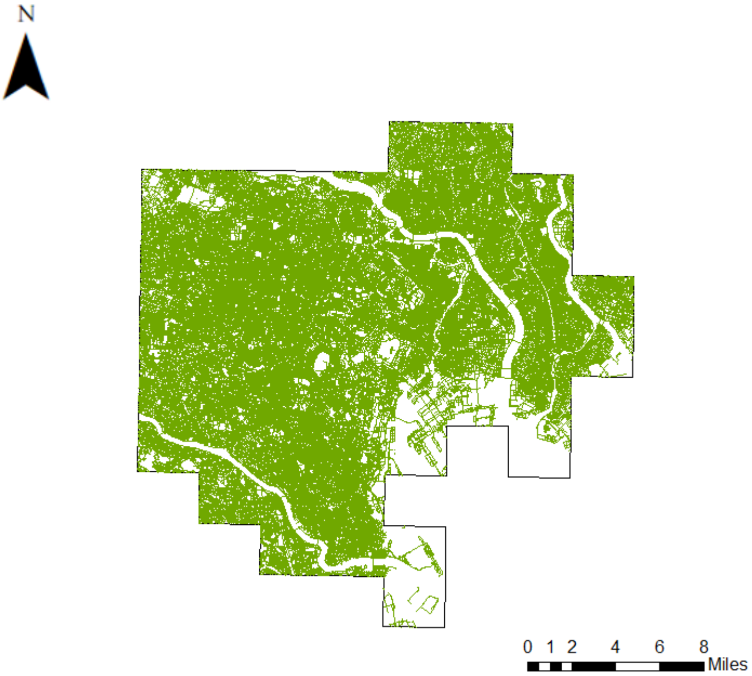


Figure 3-16.

Street Network,

Special Wards of Tokyo

Source: OpenStreetMap

b. Independent Variables on Transit Hubs

Six indicators were adopted to evaluate transit hubs from multiple perspectives. To measure connectivity that represents the ability to move passengers from one line or mode to another at the connecting point, I employed the number of intramodal transfers and the existence of intermodal interchange as variables. Another important attribute of transit hub is proximity. For instance, proximity to central business districts, which are the collections of various urban facilities, can be seen as the measurement of proximity to major urban resources. Additionally, proximity to other transit supplies, the closest distance to other metro stations for this case, implies substitutability of transit hubs as well as the provision of public transportation infrastructure for a locality. Accessibility displays the most significant influence of transportation on location by making the distribution of economic activities more efficient (Rodrigue et al., 2016). Hence, coordinated development of transit facilities and commercial buildings leads to good accessibility for the reduction in transport costs and efficient space utilization. Time effect of transit hubs is measured by years in operation. The variables on the built environment may be influenced differently by transit hubs in short-term or long-term.

(1) Intramodal Connection

The number of metro connections is closely associated with the total volume of passengers. Assume that each metro line has a certain amount of saturation capacity, a transit station with more transfer options can engage a larger number of passengers to move within the station area. Moreover, due to the urban population’s spatial aggregation, stations with multiple connections might have greater potentials to interact with the surrounding context

(Chorus & Bertolini, 2011). The specific number of metro transfers by each transit hub in Shanghai was obtained from the Shanghai metro system map as of December 30, 2018. The data in Hong Kong was counted from the latest MTR system map released on the official website. And the corresponding numbers in Tokyo were measured according to Tokyo Metro's publication of Tokyo subway route map including subway lines operated by Tokyo Metro and Toei Subway.

(2) Intermodal Connection

Metro system essentially serves as a public transportation mode in the city. However, there are many other rail transit systems playing separate roles from the metro. For examples, commuter rail moves people between urban areas and suburbs with a longer distance between each stop and a higher speed. And high-speed rail can even undertake passenger transport across many cities. Therefore, the transit stations with multimodal connections can be provided with diverse levels of public transit services that may be attractive to a wider range of population. This study only considered rail transit systems. If there is a transfer between metro and other rails that consist of light rail, tram, commuter rail, maglev, rapid transit, and high-speed rail, then the transit station is seen to have intermodal connection. I used the three study cities' metro system maps mentioned above and some official transportation information to find out whether there is a multimodal transfer or not for each transit hub.

(3) Proximity to CBD

The spatial locations of transit hubs at the city scale are the same as those of their surrounding built environment. This phenomenon is called “co-location”. The reason that location should be regarded as an attribute of transit hubs rather than the built environment is to examine how human activities within the station areas would vary as the extension of the metro network outward from city center. In general, the central business district (CBD) is situated at the urban core with the highest concentration of commercial and business facilities. Consequently, the urban development in or around CBD is much more intense than other places. But linking with CBD by metro, some decentralized regions may have opportunities to develop themselves. Considering most people prefer the places where housing prices and living expenses are relatively low; nevertheless, they also desire more accesses to a variety of locations with regard to jobs, services, and education. Therefore, regions away from city center with provisions of convenient public transit would be welcome choices for the urban population to carry out daily activities.

To measure the proximity to CBD, the first step is to identify the location of "downtown” in each study city. The city of Shanghai can be separated into four areas by three loops (Inner, Middle, and Outer Rings), which are: (1) inside the Inner Ring, (2) between the Inner Ring and Middle Ring, (3) between the Middle Ring and Outer Ring, and (4) outside the Outer Ring (see Figure 3-17). Since Shanghai's CBD is located inside the Inner Ring, I assigned values of the proximity to CBD to transit hubs depending on which defined area they are in. For instance, People’s Square is located inside the Inner Ring so that the value of its proximity to CBD is equal to 1. And Hongqiao Railway Station is situated outside the Outer Ring, then its proximity to CBD is assigned a score of 4. Hong Kong's CBD is pointed to Tsim Sha Tsui (TST) and Central situated on sides of Victoria Harbor. While Hong Kong does not have a clear geographic division by road network, I outlined three concentric circles with a radius of 3 miles, 6 miles, and 9 miles respectively that set Victoria Harbor as the center. As a result, Hong Kong can be divided into four areas by analogy with Shanghai (see Figure 3-18). CBD is located in the innermost circle and values of the proximity to CBD are also assigned from 1 to 4. Since Tokyo's rail transit systems are diverse that different types of rail have their specific functions, the metro system chiefly serves the special wards of Tokyo representing the most urban area, which is smaller in scale compared to the cities of Shanghai and Hong Kong. Officially this study area is organized into three levels in terms of both geography and function by Tokyo Metropolitan Government. The most central area is defined as the metropolitan center that consist of Chiyoda, Chuo, and Minato. It functions as Japan's capital that gathers government, judicial and executive agencies, and a large number of headquarters and head offices of major corporations. The second level is composed of sub-center areas including Shinjuku, Bunkyo, Shibuya, and Toshima, where commercial facilities are concentrated. And the remaining municipalities in the special wards of Tokyo comprise the third level, representing the outermost scope that the metro service can reach (see Figure 3-19). From inside to outside, the values of the proximity to CBD range from 1 to 3.

Instead of a simple linear relationship, the spatial location relative to CBD is assumed to be curvilinearly related to the built environment for this study.

Figure 3-17. Geographic Division of Shanghai (*Source: Baidu Maps*)

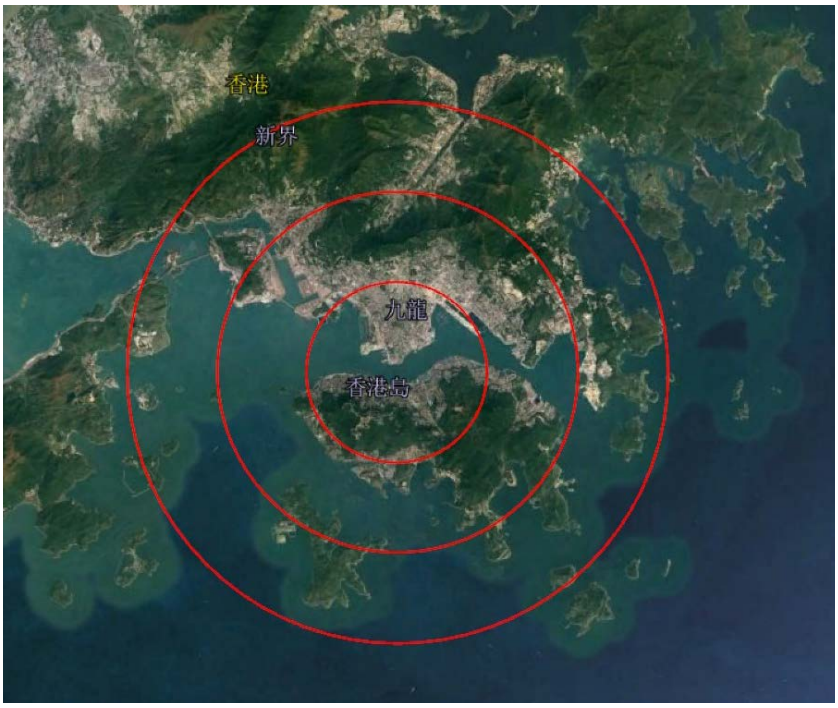


Figure 3-18. Geographic Division of Hong Kong (*Source: Google Maps*)

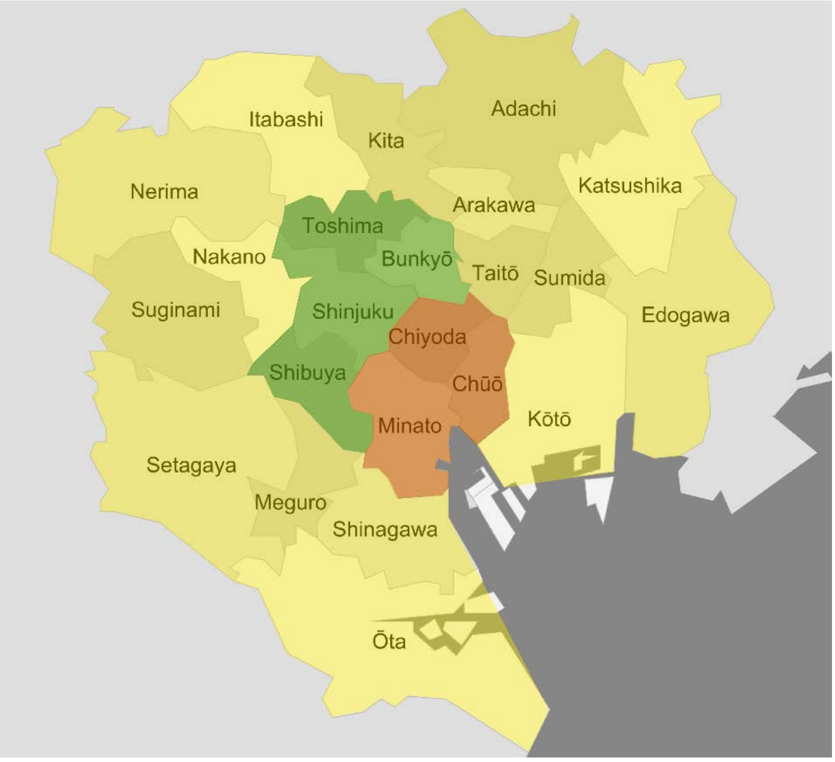


Figure 3-19. Geographic Division of Special Wards of Tokyo

(*Source: Tokyo Metropolitan Government)*

(4) Proximity to Other Metro Stations

Proximity to other metro stations implies the minimum distance between each transit hub and its adjacent metro stations. This distance can indicate the density of metro station distribution. For a given area with a higher density of metro stations, residents will have a better provision of public transportation infrastructure. This advantage can be manifested in shorter walking distance to take a subway or more route options to reach a larger scope of destinations. Nevertheless, from the perspective of a transit hub itself, if there are alternative stations around, the urban resources may not be concentrated encompassing this transit hub but spread out to other station areas as well. The data of distances between metro stations in Shanghai and Tokyo were collected from official statistics. Due to a lack of corresponding data in Hong Kong, I estimated the distances according to the total length and operating schedule for each metro line.

(5) Clustering

Rodrigue (2016) introduced the concept of “agglomeration economies” when describing the relationship between accessibility and location economies in his book. As he stated, clustering points to the agglomeration of various human activities at a specific location for saving costs in transportation. It essentially explains why an increasing number of metro stations are joined with property developments. Take Hong Kong as an example, MTR has applied “Rail plus Property” model to over half of the stations by offering amenities to meet people’s daily needs. This model can realize compound functionality in a limited space. On one hand, the convenience of linked rail and property developments may attract more population to come by or live around. On the other hand, developers could yield revenue from property developments close to transit facilities like MTR. To explore how the “Rail plus Property” model impacts on the surrounding context, I used whether the transit hub is directly connected to a shopping center or commercial street as an indicator of clustering. The data was acquired from Google Maps and Baidu Maps by observing building types connected to each station exit.

(6) Time Effect

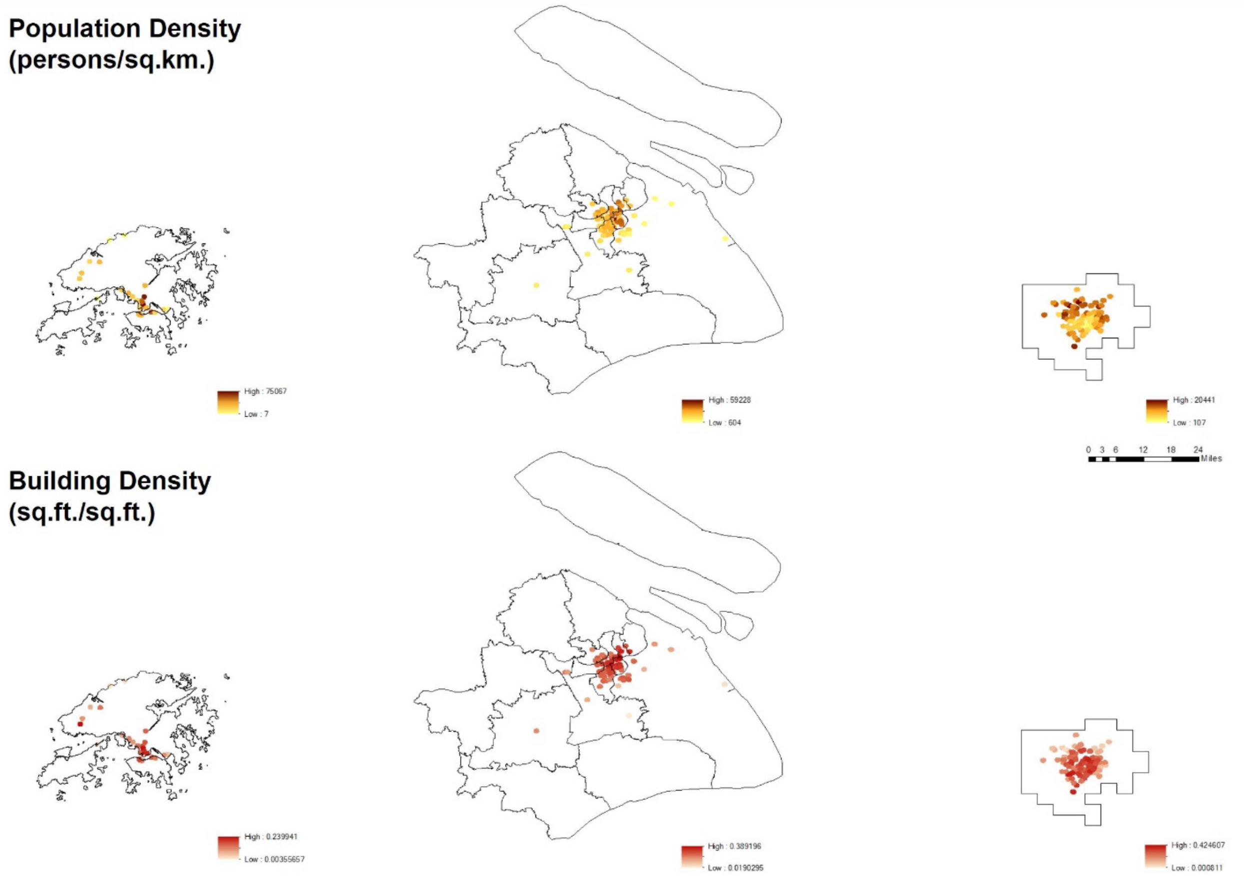
The elasticity of built environment variables to the use of transit infrastructure is inconsistent between each other. Some can respond in a very short term but others need a long period of time to react. For example, the real estate market is often sensitive to a change in transit facilities. The property value may vary according to the popularity of land around transit stations during stages of planning, construction, and operation. Knaap (2001) concluded in his research that after announcing the light rail investment plan, land values in proposed station areas increased by 36%. However, the supply of new buildings will need a relatively long time due to the time cost of construction. So as the street network, in order to provide supplementary facilities to support transit stations, the government may increase ambient street density for more walkable neighborhoods. This process could be time-costing for both planning and construction. Therefore, studying the association between years of transit hubs in use and the built environment is helpful to understand the sensitivity of each indicator to the public transit that may influence the specific strategy of investments for diverse sectors. The time data were generally obtained from statistical yearbooks published by municipal authorities of the three study cities that kept a record about the opening date of each transit hub. And transit hubs' years in operation would be assumed to be curvilinearly related to the built environment in this study.

3. Methodology

a. Spatial Analysis Using ArcGIS

The original data of all dependent variables measuring the built environment were described at a city scale across Shanghai, Hong Kong, and Tokyo. Since this study focused on the walking distance from transit hubs, defined as a 1/2-mile buffer encompassing each station, I subdivided the citywide data into transit hubs' buffers using ArcGIS. Consider the definition of transit hubs that are metro stations with connections between at least two metro lines or modes that consist of metro and rail, I removed metro stations with a single line or mode and only kept those stations with intramodal or intermodal transfer. In addition, invalid data and obvious outliers of the measurements were filtered out to reduce errors. As a result, a total of 190 transit hubs were selected as a sample for this study to explore the links between transit hubs and their surrounding built environment, which consist of 57 metro stations in Shanghai, 26 metro stations in Hong Kong, and 107 metro stations in Tokyo. Through cross-sectional spatial analysis of each independent variable on the built environment including population density, building density, land use mix, intersection density, and housing price, three study cities have different sizes of urban area served by metro system. Shanghai has the largest land area followed by Hong Kong, and special wards of Tokyo are the smallest. The spatial distribution of transit hubs in these cities varies from one to another as well. Tokyo's transit hubs are concentrated in the city center. While Shanghai has a similar characteristic as Tokyo, it also extends the metro system to further far area from the core. On the contrary, Hong Kong has a relatively scattered metro network compared to Shanghai and Tokyo due to its particular landform.

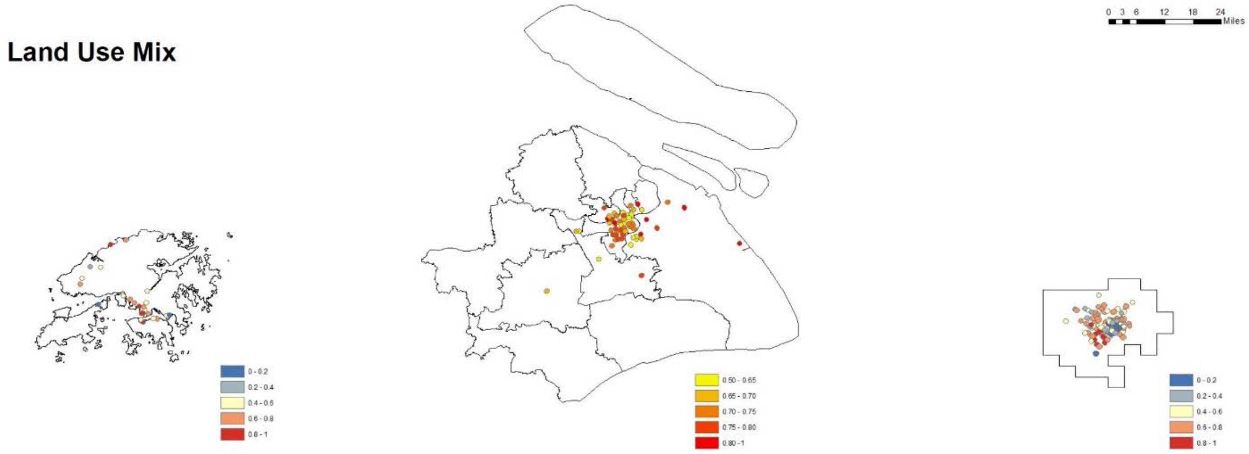
In terms of population and building density (see Figure 3-20), the color of station buffers from light to dark means the value of density from small to large. Among all of station buffers across cities, the smaller the color difference between buffers, the more balanced the distribution of density. It is not difficult to find the distribution of building is more well-proportioned than that of population. For example, Shanghai and Hong Kong have more intensive population around transit hubs situated in CBD. However, building density in both cities can be large as well in the areas outside the city center. Besides, for the special wards of Tokyo, urban population are more concentrated in sub-center areas when buildings are distributed evenly across the whole region. Compared to the metropolitan center, sub-center areas have a larger number of commercial facilities that may promote population gathering.



Source: ORNL's LandScan Global Population Database; OpenStreetMap; Urban Data Party

Figure 3-20. Cross-Sectional Comparision of Population & Buildng Density

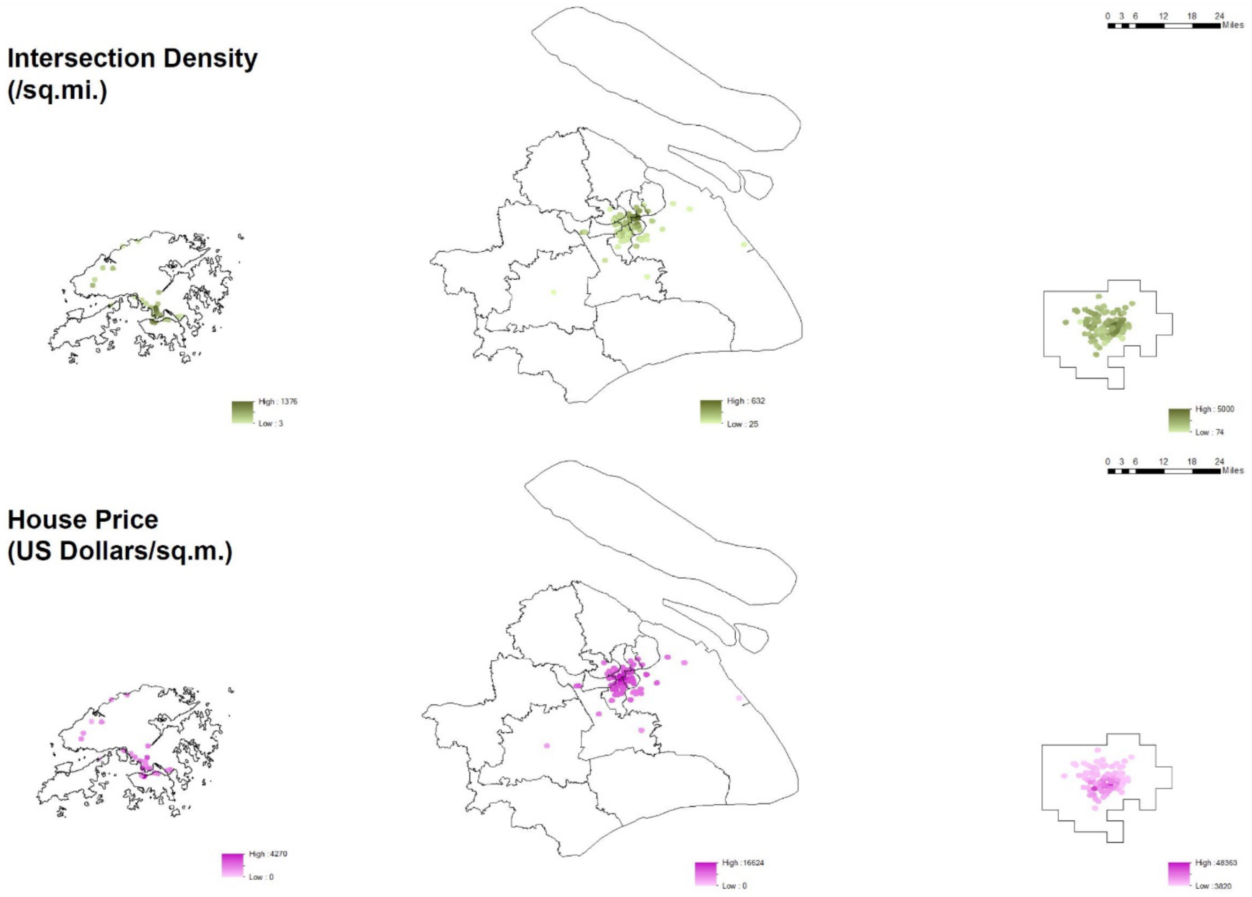
None of the three study cities have much in common in terms of the mixing degree of land use in station buffers. While land use mix for Shanghai is generally no less than 0.5 indicating a high level of mixed-use in urban development, the distinction of land use mix between station buffers shown in Figure 3-21 is still considerable. In downtown, some station areas have a land use mix up to 1 whereas others are only around 0.5. More significant differences are occurred in Hong Kong and the special wards of Tokyo where the land use mix can be lower than 0.5. And there is no commonness on spatial location.



Source: OpenStreetMap; Urban Data Party; MLIT’s National Land Numerical Information

Figure 3-21. Cross-Sectional Comparision of Land Use Mix

In this study, I used the intersection density index to reflect the compactness and connectivity of walkable street network. As displayed in Figure 3-22, intersection density in the special wards of Tokyo is much greater than other two cities. The maximum can be up to 5,000 intersection per square mile in the station areas. Comparatively, the maximum of intersection density is 1,376 in Hong Kong and only 632 in Shanghai. It seems like blocks in the special wards of Tokyo are small and compact while there are more superblocks in Shanghai. In addition to the maximum, the average level of intersection density across the special wards of Tokyo is more intense and spatially balanced compared to Shanghai and Hong Kong where dense blocks are only concentrated in the city center. Therefore, street network in Tokyo's urban areas is well-developed to build more walkable neighborhoods around metro stations. As far as housing price, after unifying the housing price data for three study cities in US dollars with an inflation of 2018, while Tokyo has the highest maximum value, it only occurs in one or two station areas. Through a cross-sectional comparison, despite the average level of housing price varies from city to city, housing price in station areas is considered to share commonly high values according to their very small color difference illustrated in the maps.



Source: OpenStreetMap; Centaline Property; Yunfang Data; MLIT

Figure 3-22. Cross-Sectional Comparison of Intersection Density and Housing Price

b. Linear Regression Models

Five multiple linear regressions were established to analyze the relationships between various indicators of transit hubs (independent variables) and built environment features (dependent variables) using 190 metro stations as testing sample for each regression. The symbolic linear regression model was defined as below:

$$Y_i = a + b_1X_1 + b_2X_2 + b_3X_3 + b_4{X_3}^2 + b_5X_4 + b_6X_5 + b_7X_6 + b_8{X_6}^2$$

Where Y_i represents built environment metrics including population density, building density, land use mix, intersection density, and housing price. A summary of dependent variable definitions and data sources is displayed in Table 3-1. In addition, X_1 to X_6 together represent explanatory variables that can illustrate the characteristics of transit hubs from multiple aspects. A review of independent variables in terms of definition and data sources is shown in Table 3-2. It is noteworthy that the proximity to CBD and the time effect are considered curvilinearly related to the built environment attributes so that relative indices used in the regression model include their square numbers. Moreover, b_1 to b_8 are coefficients to reflect quantitative relationships between independent variables and each dependent variable. For this study, the purpose and goal are to determine the values of coefficients by solving linear regressions and at the same time, test the significant degree of linear relations between the characteristics of transit hubs and the built environment features.

Table 3-1. Dependent Variable Definitions and Data Sources

Symbol	Variable	Definition	Data Source
Y_1	Population Density	Average population in each station buffer ($\text{persons}/km^2$)	ORNL’s LandScan Global Population Database
Y_2	Building Density	Average building coverage in each station buffer ($\text{sq. ft.}/\text{sq. ft.}$)	Baidu Maps & Open Street Map (OSM)
Y_3	Land Use Mix	The mixing degree of land use including residential, commercial, industrial and open space	Baidu Maps & OSM & MILT’s National Land Numerical Information
Y_4	Intersection Density	Compactness of street network in each station buffer ($/\text{sq. mi.}$)	OSM
Y_5	Housing Price	Average real estate transaction price of residential areas in each station buffer ($\text{US Dollars}/\text{m}^2$)	Yunfang Data & Centaline Property & MILT’s National Land Numerical Information

Table 3-2. Independent Variable Definitions and Data Sources

Symbol	Variable	Definition	Data Source
X_1	Intramodal Connection	The number of metro lines connected at each transit hub	Shanghai Metro & MTR & Tokyo Metro
X_2	Intermodal Connection	Whether there exists an intermodal interchange or not	Shanghai Metro & MTR & Tokyo Metro
X_3	Proximity to CBD	The spatial location of each transit hub in the urban area.	Baidu Maps & Google Maps & Tokyo Bureau of Industrial and Labor Affairs
X_4	Proximity to Other Metro Stations	The closest distance from each transit hub to other metro stations (km)	Shanghai Metro & MTR & Tokyo Metropolitan Bureau of Transport
X_5	Clustering	Whether there is a commercial complex directly connected to the exits of each transit hub	Baidu Maps & MTR & Google Maps
X_6	Time Effect	Total years in operation after completion of each transit hub	Shanghai Metro & MTR & Tokyo Metropolitan Bureau of Transport

IV. Results

1. Descriptive Statistics

I adopted Stata as a tool to deal with the multivariate linear regressions for this study. Table 4-1 displays a summary of descriptive statistics including minimum, maximum, mean, and standard deviation. The ratio of standard deviation to mean is used to indicate the degree of scatter for each variable. Intermodal connection and clustering are dummy variables so that the ratios are quite large. Except for them, intersection density has the greatest ratio because there is a huge difference between three study cities' street patterns. The special wards of Tokyo have developed a dense and compact street network with up to 5,000 intersections per square mile, while Shanghai's walkable street system is made up of superblocks that result in greater spacing between intersections. In addition, the variables with relatively scattered distribution include population density, housing price, and proximity to other metro stations. Since housing price is relevant to the city's economic conditions, it is reasonable to have very different values for this index. In contrast, the variables with relatively centralized distribution consist of building density, land use mix, and intramodal connection. To explore whether the built environment around transit hubs shares the same attributes, some conclusions have been made based on the spatial analysis mentioned above. According to the descriptive statistics of independent variables, I found it is the least possible to share a common population density in station areas. Instead, it has the greatest probability to share a similar building density around transit hubs.

Table 4-1. Descriptive Statistics of Dependent and Independent Variables

Variables	Min	Max	Mean	Std. Dev.	Std. Dev. / Mean	Unit
Population Density	7	75067	16297	13149	0.81	$\text{persons}/km^2$
Building Density	0.001	0.425	0.248	0.100	0.40	ft^2/ft^2
Land Use Mix	0	1	0.560	0.238	0.42	
Intersection Density	3	5001	1497	1360	0.91	$\text{intersections}/mi^2$
Housing Price	0	48365	11039	8242	0.75	$\text{US Dollars}/m^2$
Intramodal Connection	1	6	2.1	0.9	0.43	
Intermodal Connection	0	1	0.46	0.5	1.09	
Proximity to CBD	1	4	1.9	1.0	0.53	
Proximity to Other Metro	0.3	5.2	1.1	0.8	0.73	km
Clustering	0	1	0.46	0.5	1.09	
Time Effect	1	91	35.5	23	0.65	years

2. Linear Regression Results

The linear regression results contain two parts. In the first place, the standardized B coefficients suggest the relationships between the characteristics of transit hubs and the selected built environment features. Positive numbers represent positive relations and negative numbers represent negative relations. However, only the coefficients are not enough, the test of p-values can examine whether the relationships are significant or not. Table 4-2 shows a summary of the linear regression results for this study. The adjusted R-square for each regression model ranges from 0.214 to 0.528 and their p-values are lower than 0.00001. Therefore, it is demonstrated that the built environment is significantly related to the characteristics of transit hubs on the dimensions of population density, building density, land use mix, intersection density, and housing price. And those characteristics of transit hubs can explain the variances in the built environment to varying degree ranging from 21.4% to 52.8%. In order to avoid the problem of multicollinearity that independent variables are closely related to each other resulting in large errors, I tested the variance inflation factor (VIF) for independent variables. According to Table 4-3, all values of VIF are much less than 4 so that multicollinearity has no impact on the regression results. The detailed analysis of regression results will be discussed subsequently.

Population density is significantly and positively related to intramodal and intermodal connection, which implies that a larger number of urban populations in the surroundings if the transit hub serves more metro connections or has an intermodal interchange. The coefficients for proximity to CBD and its square move in different direction indicating that population density has an insignificant curvilinear relationship with the transit hub's distance to CBD. Population density is significantly and positively associated with proximity to other metro stations, which means if a transit hub is more distant from other metro stations, its station area will have higher concentration of population. A significantly positive linkage with clustering represents more urban population will gather around the transit hub under the joint development of transit facility and commercial complex. In terms of time effect, it turns out that population density is not significant related to the transit hub’s years in operation.

Table 4-2. Standardized B Coefficients of Linear Regressions

Variables	Population Density	Building Density	Land Use Mix	Intersection Density	Housing Price
Intramodal Connection	0.249^{***}	0.044	0.074	0.055	0.282^{***}
Intermodal Connection	0.241^{***}	0.213^{***}	-0.077	0.324^{***}	0.259^{***}
Proximity to CBD	-0.368	-0.408	-1.418^{***}	0.052	-1.294^{***}
Proximity to CBD - Square	0.084	-0.035	1.408^{***}	-0.116	0.960^{***}
Proximity to Other Metro	0.145^{**}	-0.338^{***}	0.154^{**}	-0.266^{***}	-0.341^{***}
Clustering	0.247^{***}	0.054	0.210^{***}	-0.181^{***}	-0.024
Time Effect	-0.038	0.525^{**}	0.814^{***}	0.768^{***}	-0.178
Time Effect - Square	-0.204	-0.688^{***}	-0.509^{**}	-0.309	0.377^{**}
Adjusted R^2	0.294^{***}	0.431^{***}	0.214^{***}	0.528^{***}	0.510^{***}

*p<0.1, **p<0.05, ***p<0.01.

Table 4-3. VIF of Independent Variables

Variables	VIF
Intramodal Connection	0.61
Intermodal Connection	0.59
Proximity to CBD	0.03
Proximity to CBD - Square	0.03
Proximity to Other Metro Stations	0.74
Clustering	0.91
Time Effect	0.06
Time Effect - Square	0.06

The regression results demonstrate that building density is insignificantly relevant to intramodal connection, proximity to CBD and clustering. Except for them, building density in the station area is higher when the transit hub owns an intermodal connection. Since other metro stations can be considered as supplements of a transit hub, the closer the distance between a transit hub and its closest metro station, the higher the building density around the transit hub. Building density has a positive relationship with time effect but negative related to the square of time effect which demonstrates a curvilinear relationship between building density and time effect. It means the aggregation degree of buildings around transit hubs has been greater over time while the increasing rate of building density will become slower with time. It may illustrate that after a transit hub is constructed and come into use, there would be more structures built up in the surroundings. And it would be a fast growth at the beginning. As time goes by, the building speed would slow down.

Relationships between land use mix and two independent variables including intermodal connection and intermodal connection have been proved to be insignificant. Nevertheless, the index of land use mix has significantly negative relationship with proximity to CBD and positive relationship with squared proximity to CBD, which implies land use mix is curvilinearly associated with transit hubs' relative position to downtown. And along with the transit hub's distance to CBD getting longer, the mixing degree of land use decreases and the decreasing rate will become slower. Moreover, and use mix is significantly and positively associated with clustering, which indicates the transit hubs where commercial facilities directly linked to their exits have a higher mixing degree of land use. As a matter of fact, commercial complex itself is a collection of diverse land uses. Hence, the spatial adjacency of commercial building and transit station will definitely improve the mixture of land use in the surroundings. The significantly positive relationship between land use mix and time effect and negative relationship between land use mix and square of time effect suggest that as the usage time of the transit hub becomes longer, the diversity of human activities in terms of locations in the surroundings has been increased. However, the rate of increase in land use mix will become smaller over time. Similar to building density, the mixing degree of land use will quickly improve at first and become slower as the time passes.

Positive coefficient of intermodal connection to intersection density indicates he neighborhood around a transit hub with interchange between metro and other rail systems has more compact street pattern and thus more walkable for riders to and from the transit hub. Proximity to CBD is curvilinearly but insignificantly related to intersection density. Significantly negative relationships are found between intersection density and proximity to other metro stations as well as clustering. Therefore, the closer the proximity to other metro stations, the higher the street density. It indicates that provisions of transit infrastructure encourage the growth in walkability in terms of intersection density. However, the joint development of transit hubs and commercial properties relates to poorer street network in station areas. It may because the spatial integration of the station and the commercial complex enables people to complete human activities in a given location and thus it hinders population’s interaction with station areas. Intersection density has a significantly positive association with time effect but insignificantly negative association with its square. It implies that as the passage of time, intersection density in the surroundings has become higher but there is no curvilinear relationship between them.

As stated in the section of literature review, real estate market is associated with provisions of public transportation. Through the regression model in this study, the correlation between real estate and transit has been proven once again. In terms of significant relationships between characteristics of transit hubs and housing price, an increase in the number of metro connections is related to the appreciation in residential property value of surrounding areas.

Similarly, housing price around the transit hub with intermodal transfer is higher than other station areas served by single metro line. From the perspective of proximity, housing price is negatively linked with proximity to CBD but positively related to its square, which demonstrates a curvilinear association between housing price and distance to CBD. The farther the transit hub to CBD, the lower the housing price in the surroundings. As the distance to CBD gets farther, the slower the housing price falls. In addition, an increase in the closeness to other metro stations is considered to link with higher real estate market. It is reasonable people always pursue the convenience to reach a variety of urban resources so that the land in a close proximity to CBD and other transit provisions are more desirable for population. The increasing gap between housing supplies and demands in those lands will ultimately drive up the residential property price. Besides, real estate market is proved to be insignificantly related to clustering and time effect.

Since the coefficients have been standardized, they are able to be compared quantitatively to discuss relative importance of variables. Through comparisons of standardized B coefficients, intramodal and intermodal connections, and clustering are seen as the most important characteristics of transit hubs related to population density. Building density is the most associated with time effect. In terms of land use mix, the most important indicator in relevance is proximity to CBD. Intersection density has a highest degree of correlation to time effect. Last but not least, the most significant measurement of transit hubs is proximity to CBD for the real estate market.

V. Conclusion

Based on empirical evidence from 190 metro stations across Shanghai, Hong Kong, and Tokyo, this study adopted linear regression models to evaluate the relationships between six indicators of transit hubs (intramodal connection, intermodal connection, proximity to CBD, proximity to other metro stations, clustering, and time effect) and five built environment features (population density, building density, land use mix, intersection density, and housing price). According to both the spatial analysis using ArcGIS and statistical analysis using Stata, it is demonstrated that among all the built environment features, building density is the most possible one to be shared around transit hubs.

Moreover, based on the linear regression results, intramodal connection which is the number of metro lines served within the station, is significantly and positively related to population density and residential property price in station areas. Intermodal connection to measure the existence of multimodal interchange between metro and other rails has significantly positive relationships with population density, building density, intersection density and housing price in the surroundings. Proximity to CBD, the relative location between transit hubs and commercial and business centers in the city, is significantly and curvilinearly associated with land use mix and housing price. Proximity to other metro stations, the closest distance from each transit hub to adjacent metro stations, is significantly relevant to all explanatory variables of transit hubs. More specifically, it is positively related to population density and land use mix, but negatively connected with building density, intersection density, and housing price, which indicates that the spatial closeness of transit infrastructure will result in a higher building and intersection density, as well as an appreciation in residential property value. In contrast, urban population will be more concentrated and land use will be more mixed around transit hubs farther from other provisions of transit. Clustering in this study is defined to measure the joint development of transit stations and commercial properties. It has been demonstrated to have significant associations with population density, land use mix, and intersection density. Furthermore, the clustering points in a single location on the basis of transit hubs are positively related to population density and land use mix but negatively linked with intersection density. There is an overlapping effect between clustering and land use mix. Time effect has significantly curvilinear relationships with building density and land use mix. In addition, it is significant positively associated with intersection density.

In conclusion, the most important characteristics of transit hubs to the built environment are proximity to CBD and time effect. Land use mix and housing price are most relevant to proximity to CBD, and building density and intersection density are most connected with time effect. Unlike them, population density has the closest relationships with intramodal and intermodal connections, as well as clustering. While the regression results cannot explain the causality, the significant relationships between transit hubs and built environment do help to understand development dynamics in station areas. Those indicators of transit hubs with the most noticeable interaction with the built environment should be taken into account for the policy makers.

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