Road Space Allocation for Multi-Modal Transportation in the Dynamics of Intra-City Population

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Abstract

Urban form, demographic features, and other socio-economic elements correlate with transportation system design and usage. Transportation system design is preferred to respond to urban conditions. While active modes, including walking and cycling, are promoted as sustainable and healthy means of transportation, vehicle innovations increase the species of road users, like e-bikes, e-scooters, other micro-mobilities, and driverless cars. A wide variety of road users are using road space simultaneously. Thus, a scope of multi-modal transportation design is required to realize and maximize their strengths while reconciling the conflicts between road users. Among road users, this thesis focuses on cyclists as well as other modes of transportation, including cars, public transit, and walking. The abstracts of each chapter are as follows.

In Chapter 1, I tried to describe the different proportions of commuting by different modes of transportation, including walking, bicycle, railway, bus, motorcycle, and private car, in Japanese municipalities. Based on these, I summarized the geographic, demographic, and climatic characteristics of the cities where the popular modes of transportation are located. Although these are choices for transportation modes, there are more emerging types of vehicles as industrial development answers to people's demands. Among the newly emerging vehicle types, I picked up e-bikes and e-scooters and introduced their increase in sales, usage, and the regulations regarding them. Introducing the concept of "microbility" which includes e-bikes and e-scooters, I mentioned the variety in means of transportation can bring a variety in vehicle size and fleet characteristics, requiring reconsidering from various perspectives, including space allocation, safety issues, fairness in mobility, users' demands, and regulations. Then, I mentioned road space allocation for multi-modal users and bicycle-considered road allocation methods in the real world. Introducing the status quo on Japanese streets that cyclists face stressful environments from cars and are involved in conflicts with pedestrians, I chose special attention to bicycles and e-bikes as sustainable and healthy means of transportation. Then, I proposed the objectives of this thesis to contribute to finding ways to provide better mobility services for residents while considering the dynamics of population distribution. I will focus on road space because the growing ridership, vehicle size, and fleet characteristics can be problematic.

Corresponding to the objectives, I reviewed studies on urban form metrics, bicycle

convenience evaluation, cycling considered facilities, and bicycle-car mix traffic simulation. I found the research gaps to fill in the following studies and the supportive and inspiring reports.

Regarding the classification of urban form, while previous studies have revealed insights into the regional diversity of urban form, research on urban form at the global scale is rare. Among urban form metrics, I chose one for its focus on socio-economic, thus suitable for analyzing transportation usage, and its simplicity, thus making it more likely to access required data for calculation. Regarding bicycle convenience, while previous studies on bicycle convenience focused on the cycling environment itself, they need to be specified to consider a new transport mode like e-bikes that requires insights into their potential and limitations. Regarding e-biking, although studies confirmed the advantages of e-biking for saving physical energy consumption, there is no complete set of data on e-biking corresponding to different slopes, especially the Japanese-style electric assistant bicycle. Regarding bicycle-considered road space and intersection design, cellular automata and microscopic models are valuable tools for simulating bicycles. Although the studies simulate mixed traffic and road space re-allocation, research gaps also exist in comparing how different road space allocations affect efficiency involving e-bikes, and there needs to be a discussion of a systematical strategy to separate them into different roads at a network scale. I tried to fill these research gaps mentioned above in the studies in the following chapters.

In the first step in analysis in Chapter 3, I aimed to grasp the correlation between transportation mode usage and urban form to provide background information on mobility service provision. I classified the urban form using metrics proposed initially in (Tsai, 2005) by applying four indices: population size, population density (pop/km2), the degree of equal distribution (Gini coefficient), and the degree of clustering (Moran coefficient). There are three analysis parts in this chapter: Part (1): a comparison among cities worldwide in 2015 at the global scale, to fill the research gap in global urban form comparison. Part (2): I summarized the trends in population distribution dynamics over the long term in the global agglomerations and Japanese municipalities. Part (3): I analyzed the correlation between modal share and population distribution in Japanese municipalities.

The long-term dynamics analysis in Parts (1) and (2) reveals that the most populated cities have been growing fastest with the highest levels of density and agglomeration. Asian cities have an intense trend of clustering and even while growing larger, but they have slowed down to be denser recently. In Japanese municipalities, population distribution in large cities became dense, even, and dispersed in the past but otherwise in suburban areas. In the future, municipalities will see a major trend to be sparse, unequal, and concentrated. Part (3) connected the urban form indices to the usage of transportation modes in Japanese municipalities. Railway, bus, bicycle, and motorcycle users have similarities in correlation with equal and dense distribution and large population size.

If viewing the results of part (2) and part (3) against each other, as the Japanese municipalities will see a major trend to be sparse, unequal, and concentrated, private cars are the natural choice for most future urban commuters. In contrast, there seems to be a dim future for active modes and public transportation in Japanese cities. The hope to increase public transit and bicycle usage may lie in the following findings: There are large growing cities that fit with the usage of transit and bicycle usage; motorcycles, which are similar to bicycles, show relatively weak correlations, probably suggesting they are adaptable to a broader range of urban forms; While the relationship shown here between usage rates and urban form is a static status quo, the factors affecting mobility provision are variable, especially detailed condition changed in specific subdivided areas can make difference in transportation method choices.

Answering the discussion in Chapter 3 that motorcycles may fit more various urban forms than bicycles, I focused on a vehicle in-between bicycles and motorcycles, electric bikes (e-bikes) in this chapter. I analyzed subdivided urban areas after choosing target cities considering urban form features. I aimed to explore the applicability of e-bikes in the transportation system within the urban environment, specifically by answering two questions. (1) Whether and where e-bikes can improve resident mobility compared to bicycles and transit (community-wide scale). (2) What are the ranges of applicable time and physical energy costs for e-bikes (city-wide scale)? The two alternative transport modes selected for comparison are conventional bicycles and public transit, which, as shown in Chapter 2, share similarities in mode choices regarding urban forms.

I evaluated e-bikes, used a comparative assessment against other modes of transportation, and quantitatively considered the physical energy expenditure. All of these are the originalities in this research. The method is applied to four Japanese cities with different environments, including road gradient and transit density, and with their urban form and bicycle modal shares as a case study.

Results showed that e-bikes are applicable in areas with steeper road grades or with geographical obstacles requiring a detour and in areas lacking public transportation, e.g., fringe areas in large cities or local cities. At the city scale, e-bikes are applicable for short-distance trips in cities with well-developed transit systems, as the applicable travel time and physical energy expenditure are 65 min and 1.25 MET-h round trip. They are also promising alternative means of transport in local cities.

After realizing e-bikes have advantages in improving mobility services for residents by means of both physical energy cost and travel time cost for residents, especially outside of urban centers where transit is not widely available in Chapter 4, I considered maximizing their strengths while reconciling the conflicts between road users in the scope of multi-modal transportation design mainly on road space in the following Chapters 5 and 6.

Chapter 5 focused on space allocation strategies on road links, intersection models, and a local network between multiple transportation methods. I used multi-agent models and microscopic models to concentrate on exploring the knowledge of how traffic efficiency is affected by allocation.

The results are as follows. (1) In road link models, the road space usage efficiency of 1 e-bike ≈ 1.24 bicycles. E-bikes use road space less efficiently than buses when they accommodate 9 persons. When e-bikes increase, mixed traffic provides better with bicycles on a 2m bike lane; no physical separation between car and bicycle can be better on a 4m road when e-bike density > 10veh /100m. Sharing all 4m bus lanes can be efficient when few passengers are on board and/or dense bicycle volume. When the passenger total amount remains unchanged, the modal shift from cars to e-bikes/bicycles, physically separating the bike lane and car lane, is efficient; a modal shift from bicycles to e-bikes, mixed allocation leads to better efficiency. (2) In intersection models, the bike boxes can produce shorter average passing times among the three bicycle-considered intersection designs: an intersection with a one-direction bikeway, a two-direction bikeway, or a bike box. Applying a bike box requires an amendment to the law as it is currently against the Road Traffic Law. Although the two-direction bikeway shows a marginal advantage over the one-direction bikeway, considering the concerns of increasing safety risk, it is reasonable to maintain the basic rule to keep the bikeway going one way. A higher e-bike ratio can bring up the efficiency of all bicycles. (3) In a case study for a network model at the community scale, increasing bikeway density may improve cycling efficiency. Intersection treatment can result in relatively more significant improvement than adding bike lanes. Assessing the road network scale can provide a comprehensive knowledge of bicycle-considered space allocation strategies.

The simulation of the community network points out the direction of following Chapter 6 to consider both roads and intersections at a network scale. Meanwhile, parts of the results in this chapter are used in Chapter 6, for example, the movement settings of vehicles in microscopic models; the result is that there is no need to separate conventional and e-bikes. Separating bicycles and cars can give a better performance than mixing, etc.

Inspired by car-free zones and car-free cycle paths, the discussion on car-bicycle interference, especially on narrow streets, the approvement of advantages in bicycle-dedicated facilities, as well as the suggestions from Chapter 5, I considered proposing and evaluating a system with bicycles and cars running on different roads at network scale: In places where no enough area to separate bicycles and cars on a same road, separating them to different roads can be an alternative. More specifically, I wanted to answer in what cases separating bicycles, and cars can be preferred: on which kind of road hierarchy, with low or high traffic volume, with high or low bicycle modal share, in short, or long trips? I designed various scenarios to address these research questions using varying parameters, including traffic volume, modal share, and road hierarchy. I assessed their performance through two key metrics: (1) travel efficiency and (2) the traffic stress imposed on cyclists.

The main findings are as follows. (1) Cars and bicycles have a trade-off relationship in efficiency across network scenarios on separated roads. The only scenario that improves both is to separate bicycles and cars on different middle-class roads when bicycle modal share is 20–30%, traffic volume is at the level of 300–400 vph, and bicycles and cars take 30-minute trips. (2) Regarding the cycling environment, separating bicycles from cars on middle-class and local roads can upgrade the overall cycling environment, including efficiency and comfort on the road and at intersections. The not-as-good but fair scenario is to separate solely on local streets. (3) To reconcile conflicts between motorized speed and cyclists' comfort, the separating strategy provides many alternatives. The main idea is to enlarge high-hierarchy roads for car-dedicated use.

Based on the findings, I discussed the practical implementations of this separation approach. Considering the modal share and trip length at present, separating bicycles from cars systematically out of efficiency reason is radical considering general trip lengths and modal share. Separating middle-class roads in part of the area and gradually transiting to middle and minor streets to provide a cozy cycling environment, especially in some residential areas. For cities with sparsely populated and weak transit systems, cars can be indispensable, and caution is required to promote bicycles as a primary task in a city planning vision.

Chapter 7 summarizes the thesis and discusses the future research that can be done. For example, the main transportation modes in this thesis are bicycles and e-bikes, but the topic remains to be expanded to other micro-mobilities like e-scooters. While pedestrians are excluded from most of this study for simplicity, they must be addressed. They can take part in analysis, especially when discussing shared space where all kinds of road users are involved. Population distribution patterns can be considered part of the bikeway network design.

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1. Introduction

1.1 Usage of different transportation methods

When considering transportation modes in Hanoi City, one probably thinks of motorcycles and mopeds; Copenhagen, bicycles; Tokyo, railways; Curitiba, BRT (Bus Rapid Transit); Nanning, electric bikes—usage of transportation methods various by cities.

The Japanese nationwide modal share changes are recorded in census (Figure 1-1). In the population and employment status survey by place of work or school attendance, the ratios declined from 15.7% in 2000 to 14.6% in 2010 and then to 12.2% in 2020. With the increase in railway usage and decline in buses, public transport, including the two modes, increased from 18% to 20%. Personal car usage increased from 44.8% to 46.5% to 48.2% in 2020, becoming the most often used transportation method for commuting in 2020.

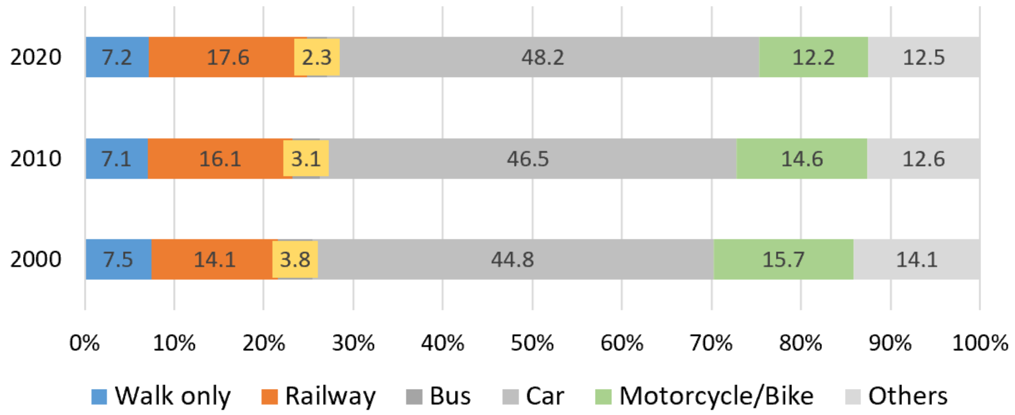


Figure 1-1 Percentages of transportation modes of those aged 15 and older who work or commute to school away from home.

(Revised from Census Report in 2010 (retrieved from https://www.stat.go.jp/data/kokusei/2010/final/pdf/01-11_5.pdf and in 2020 (retrieved from https://www.stat.go.jp/data/kokusei/2020/kekka/pdf/lifestage.pdf)

The details of ratios of commuters by mode of transportation used in each municipality can be visualized using census result data (Figure 1-2, Figure 1-3, and Figure 1-2). It is summarized by the destination the users commute to. Note that the ratios shown in Figure 1-2, Figure 1-3, and Figure 1-4 are summarized in a different way from that of in Figure 1-1. In Figure 1-2, Figure 1-3, and Figure 1-4, if more than one mode of transportation other than walking is used, all modes are counted in the gross. Thus, the total number is different from the population. In Figure 1-1, only the cases when one used only one mode of transportation other than walking are counted; other cases, including using more than two modes, are summarized in the "Others" category.

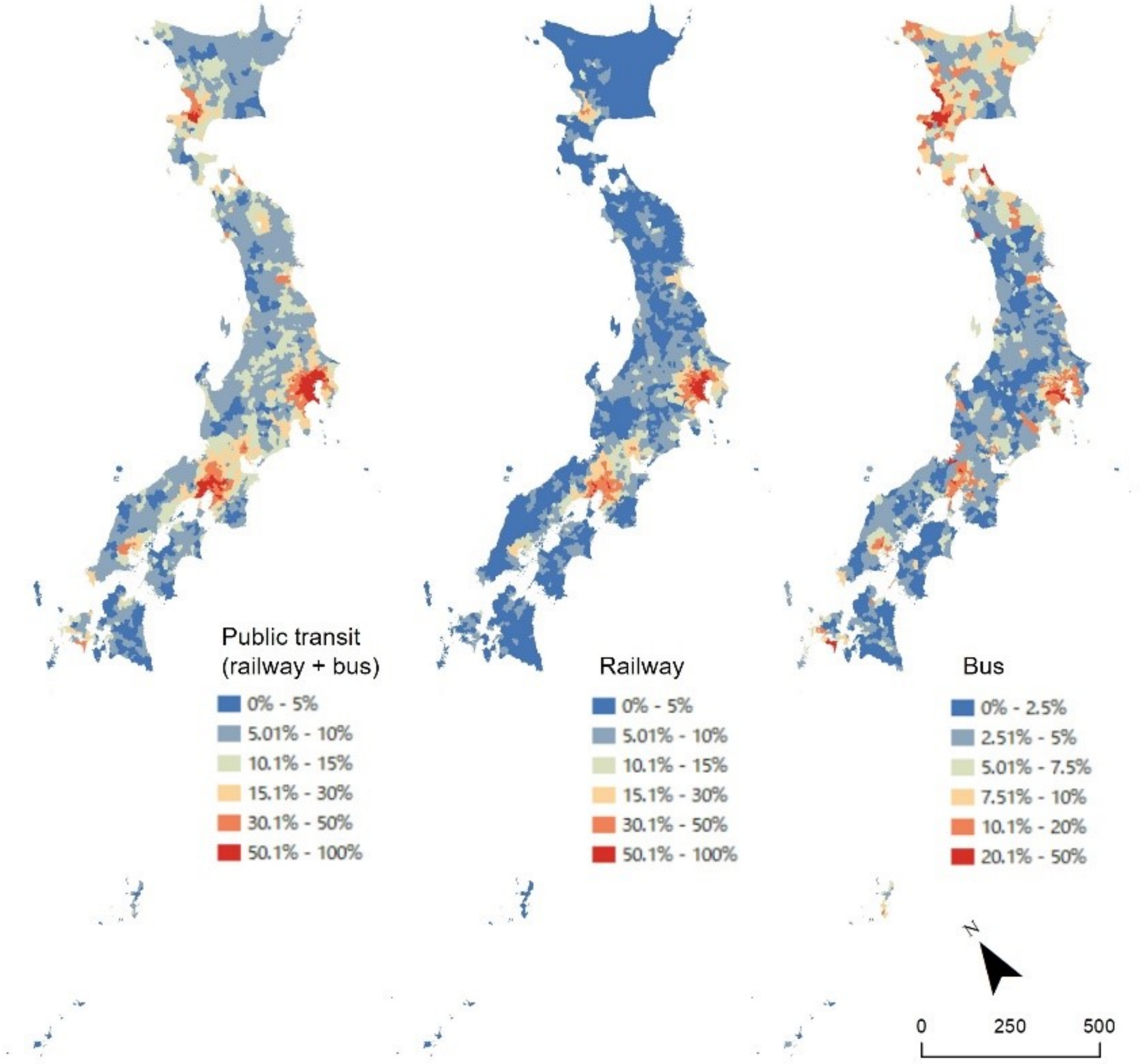


Figure 1-2 Ratios of commuters by public transit (railway or bus).

Usage of different methods of transportation varies by region. The railway users cluster intensely in metropolitan areas like Tokyo, the Keihanshin region (Kyoto, Osaka, and Kobe), and cities like Nagoya, Sapporo, Hiroshima, and Sendai. Buses provide more average service coverage extending outside the centers of metropolitans and large cities. Buses have a relatively high usage in northern Tohoku and Hokkaido regions (Figure 1-2). The ratio of bicycle users is significant, mainly along the Seto Inland Sea and Pacific Ocean seaside in areas of 36 latitude degrees. Motorcycle users comprise a small share and are scattered around the nation. Their distribution pattern is similar to bicycles, but they have a relatively high share in areas northern to 36 latitude degrees (Figure 1-3). Private cars are the most popular commute mode; their usage is frequent almost all over the country, except for the Tokyo and Keihanshin regions, and they are especially popular in mountainous areas. People who go to work or school on foot have a high ratio in Hokkaido prefecture (Figure 1-4).

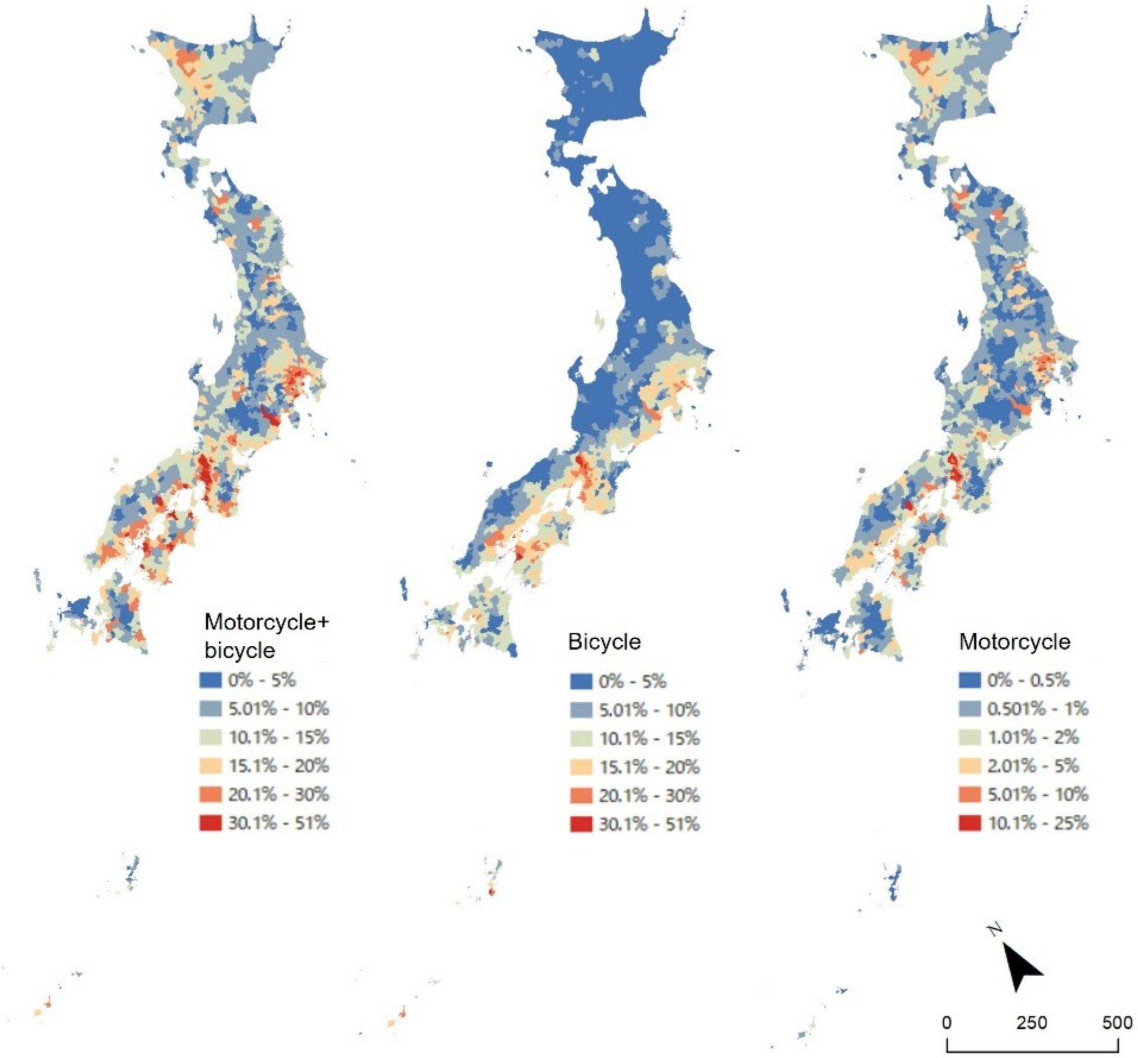


Figure 1-3 Ratios of commuters by motorcycle or bicycle.

Many factors can affect the users' choice. For example, railways are popular when there are dense lines with short headways and high punctuality or when users' origins and destinations are distributed near the lines. Bicycle users are exposed to outdoor. Thus, their usage can be sensitive to weather conditions. They need to paddle on their own feet; thus, they are also easily affected by terrain, the weight of the carriage, and the users' health conditions. The physical energy consumption part can also be one of the reasons for the more scattered distribution of motorcycle usage. Walking is constrained by weather conditions and the distance between where the users are and the places they are visiting. Private cars are easy to use no matter how steep the slopes are and how heavy the carriages are. Still, they require a license to drive, money to buy and pay for tax and fuel, and space to park, so people have to avoid them if they return their license because of the elderly, among the poor population, in a place short of parking area or easily caught up in congestion.

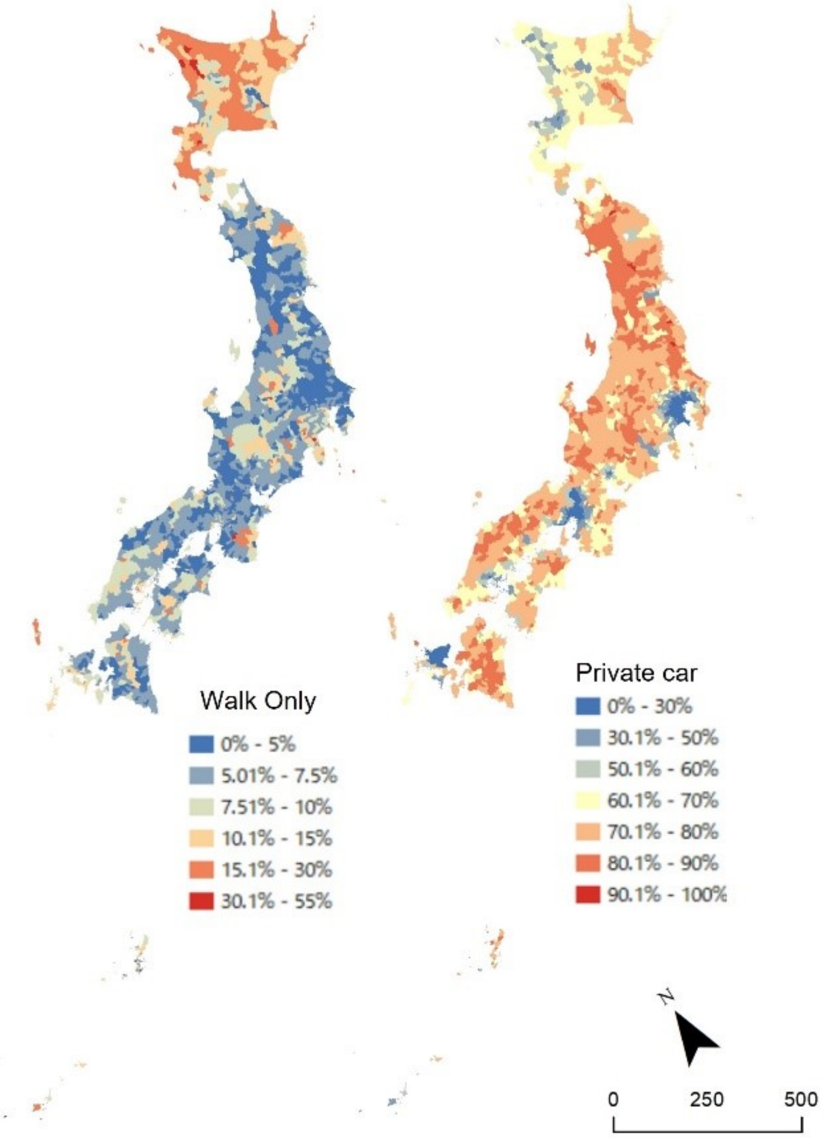


Figure 1-4 Ratios of commuters by walking or private car.

The mode of transportation preference is related to many factors. They include, but are not limited to, climatic conditions, distribution of population and facilities, and level of transportation services. The status quo certainly provides material for understanding the selection mechanism of preferences. Still, from the perspective of urban planners, user preferences are only one aspect to consider in the provision of facility services, and the other is externalities such as safety, environment, congestion, and the impact of overall comfort level.

Before considering the "right" mode of transportation service provision, several emerging means of transportation are to be mentioned.

1.2 Micro-mobilities

1.2.1 E-bikes

One of the relatively new types of vehicles is electric bicycles, or simply e-bikes. Although bearing a similar concept of bicycle-like vehicles with electric motors, their models in different countries can differ. They can be identical to sports bicycles, city bicycles, or even mopeds in their shapes. Their maximum speeds are 25km/h, including pedelecs (pedal cycles with pedal assistance) in the EU, electric bicycles and electrically assisted bicycles in Taiwan, and electric bicycles in Vietnam. In China, a law amendment in 2019 changed the limitation from 20km/h to 25km/h. The electric-power-assisted bicycle in Japan does not have an explicit limitation in speed, but the assistance rate declines as speed increases, and at 24km/h, no assistance is provided. All these e-bikes do not require a license, and their max speeds are lower than license-required two-wheel vehicles.

The public policies regarding e-bikes are varied among cities, seemingly dependent on the quantity and type of e-bikes present. For example, scooter-style e-bikes are completely prohibited in Guangzhou and partially prohibited in Shenzhen and Beijing (Guangzhou Municipal People's Government, 2016; Shenzhen Municipal Public Security Bureau, 2016; The Beijing News, 2016). The policies tend to be moderate for pedal-assisted e-bikes. For example, all e-bikes had been technically forbidden in New York City, but the pedal-assisted type was legalized in 2018 (City of New York, 2018). Tokyo has a relatively lower level of e-bike usage than many Chinese cities and introduced an electric-power-assisted bicycle rental program. Such policies may result in a further increase of e-bikes in the future.

In Japan, the electric-power-assisted bicycle comprise a growing share of bicycle sales volume in the last 15 years, reaching 38.1% in quantity or 72.6% in gross sales in 2017 (Ministry of Economy, Trade, and Industry, 2018) (Figure 1-5). The increase in sales is outstanding against the trend of declining of bicycle usage 2000-2020.

E-bikes are expected to help promote sightseeing and improve the mobility of local citizens, thus e-bike rentals have been introduced into more than 70 cities in Japan. In Tokyo, the e-bike rental system is presented as one of the strategies to make Tokyo more convenient in *The Long-term vision for Tokyo* (Tokyo Metropolitan Government, 2017).

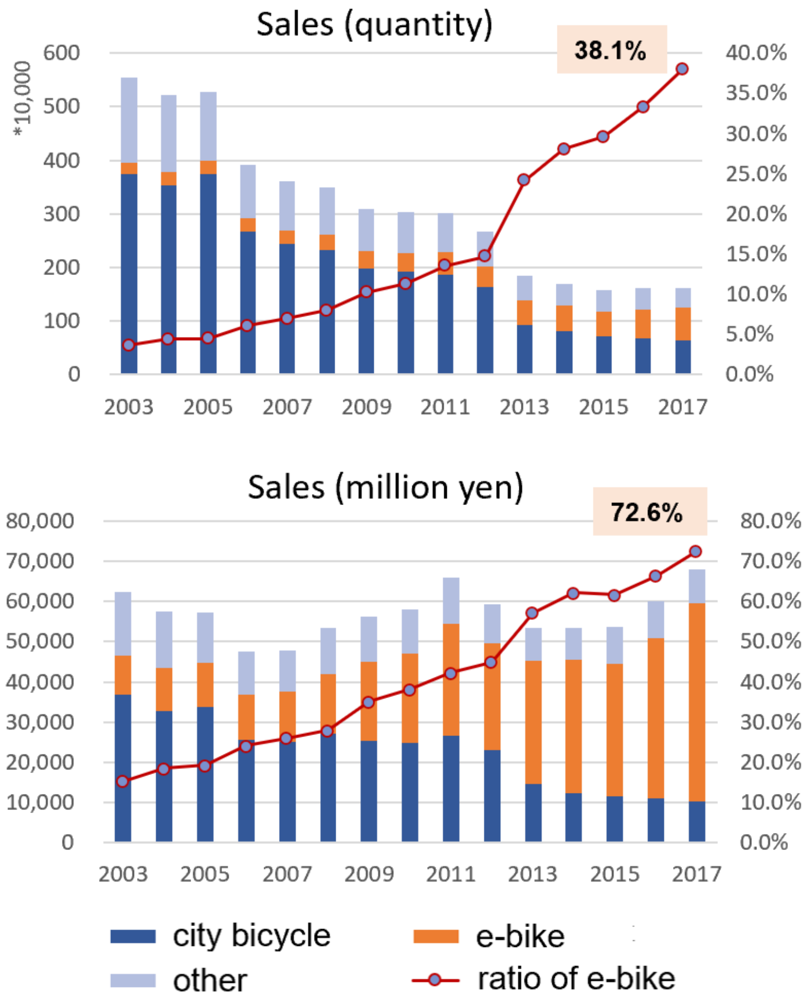


Figure 1-5 E-bike share in bicycle sales.

(Reference: Ministry of Finance, Trade Statistics of Japan)

1.2.2 E-scooter

Not only e-bikes but e-scooters have become popular, too. They are reported to have increased during the COVID-19 pandemic out of the need to maintain social distancing when traveling in European countries. They are also reported to be an alternative to reducing fossil fuel consumption as the mileage consumption is similar to or better than electric cars. The short lifespan of batteries is an obstacle to better performance but can be extended as the technical progresses. They are also seen as an opportunity for a modal shift away from personal cars.

In Japan, with a revision in Road Traffic Law enacted, the National Police Agency announced that new rules for the specified small motorized bicycles be applied starting July 1, 2023. E-scooters are classified as “specified small motorized bicycles”, and no driver’s licenses are required, although people under 16 will be banned from riding them. With a maximum speed of 20 km/h, they can use the left side of the road or in bicycle lanes.

Table 1-1 Before and after the revision of Road Traffic Law regarding electric scooters.

Gray cells are those changed from the previous version of law.

Period	Before July 2023	From July 1st, 2023
Classification	Gendouki tuki jitensha daiisshu [Class 1 motorized bicycle]	Tokutei kogata gendouki tuki jitensha [Specified small motorized bicycles]
Size	≤2.5m (length) and ≤1.3m(width)	≤1.9m (length) and ≤0.6m (width)
Rated output	≤50cc or ≤0.6kw	～0.6kW
Maximum speed	30km/h	20km/h, 6km/h on sidewalks
Transmission	AT	AT
Rear-view mirror	Required	Optional
Saikou sokudo hyoujitou [Warning lamp for max speed]	Optional	Required (always on when using car lane; blink when on sidewalk and max speed to be 6km/h)
Driver's license	Required	Optional, ≥16 years old
Wearing helmet	Required	Duty of effort
Number plate	Required	Required
Location	Car lanes	Same as bicycles (car lanes, bike tracks, paths for bicycles and pedestrians)
Left turn	Blinkers on; lean to left side	Blinkers on; lean to left side
Right turn	One-stage turn: on <3 lane roads, or following traffic signs. Two-stage turn: on ≥3 lane roads, or following traffic signs.	Two-stage turn
Joining automobile liability insurance	Required	Required

They are attracting attention as a point of improved convenience for residents. A company LUUP is providing e-scooter sharing service in 7 cities in Japan, with more than 3,800 ports. Projects to provide the service are being developed, with an increasing number of municipalities experimenting with their introduction.

1.2.3 Diversity

There is a word for vehicles like bicycles, e-bikes, and e-scooters. “Micromobility” is defined as “transportation using lightweight vehicles such as bicycles or scooters, especially electric ones that may be borrowed as part of a self-service scheme in which people hire vehicles for short-term use within a town or city” by Oxford Languages. This term includes popular transportation means, including bicycles and electric bicycles, as well as emerging scooters and electric scooters.

Recently, the development of micromobilities has been progressing and diversifying (Figure 1-6). Regarding speed, some types run at less than 6 km/h, similar to pedestrians, while others have a maximum speed of about 20 km/h. Some standing models can stand independently, like a Segway, while others cannot, like a kickboard. Some sit-on types are walking aids similar to wheelchairs, some take the form of bicycles, and some are kickboards with an additional chair. Others resemble hoverboards or unicycles. In terms of usage, they vary in ease of use, stability, and influence on other users, depending on whether they can be used as a motor at startup, the height of their center of gravity, and other factors.

Figure 1-6 Example of various micromobilities

From left to right and up to down: conventional bicycle, electric assistant bicycle, electric cargo bike, self-balancing scooter, electric scooter, electric wheelchair, hoverboard, electric unicycle, electric skateboard.

These means of transportation bring a variety in vehicle size and fleet characteristics; even under the same name of vehicle species, their features can vary. In the future, I also expect a growing number of species in micromobilities. All these can affect how people use road space and ask for reconsideration from various perspectives, including space allocation, safety issues, fairness in mobility, users' demands, and regulations.

The next chapter will focus on road space allocation considering bicycles.

1.3 Road space allocation considering bicycles

1.3.1 Allocation among multi-modal users

Road space must serve diverse users. As many cities consider car-based transportation systems no longer desirable from environmental and financial perspectives, discussions have been raised about multimodal transportation planning and fair service that road space can provide (Creutzig et al., 2020; Haas, 2018; Nello-Deakin, 2019; Silvano, Koutsopoulos, & Ma, 2016; S. Tsigdinos, Nikitas, & Bakogiannis, 2021). Figure 1-7 are pictures people used to call for a “fair” road space design.

Among the active transportation methods, cycling is promoted in many places as a sustainable and healthy means. In reclaiming space for cyclists, complaints and concerns about cycling facility construction arose. Low-quality bike lanes can impede cycling usage (Duarte, Procopiuck, & Fujioka, 2014). “Bikelash”, an organized controversy against bike lane construction, is being reported among local residents (Wild, Woodward, Field, & Macmillan, 2018).

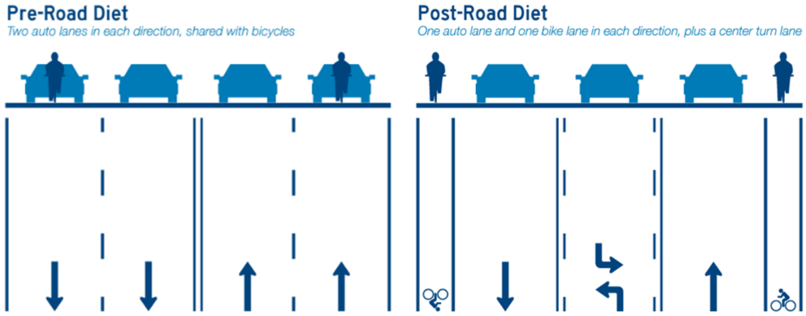
Figure 1-7 Pictures used to call for a “fair” road space allocation.

(a) The phrase “Arrogance of Space” was created to describe car-centric planning (retrieved from: https://colvilleandersen.medium.com/the-arrogance-of-space-93a7419b0278)

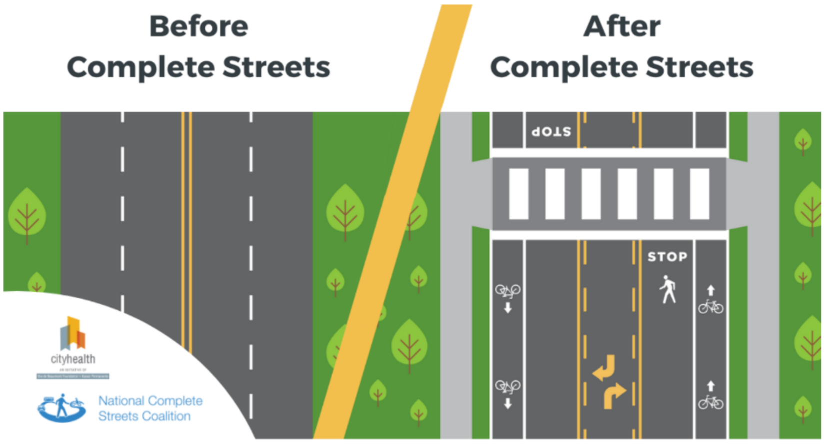
(b) Cyclists with car skeletons in an advocate in Latvia to show a bicycle use less space than car on International Car Free Day of September 14, 2014 (retrieved from: https://www.bloomberg.com/news/articles/2014-10-09/if-bicycles-took-up-as-much-space-as-cars)

(c) A picture to show how the same 3m*25 m strip can be occupied for various uses (retrieved from: https://globaldesigningcities.org/publication/global-street-design-guide/designing-streets-people/comparing-street-users/)

(a)



(b)



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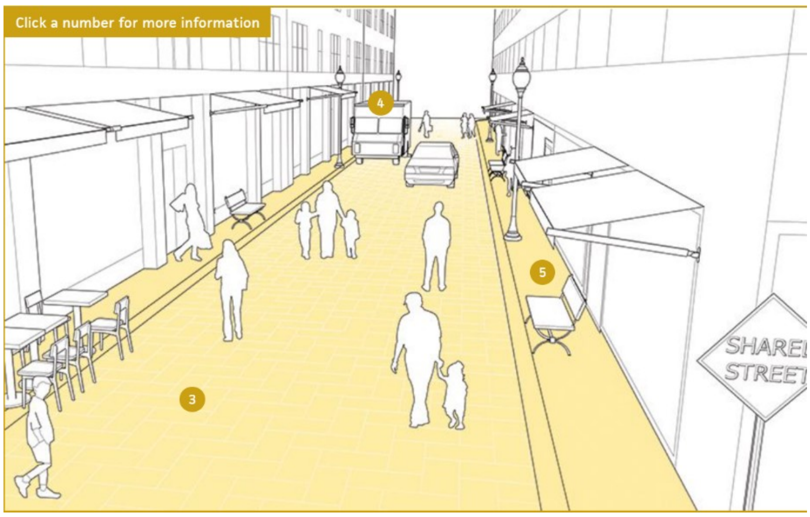


Figure 1-8 Schematic diagram of road space re-allocation methods.

(a) Road diet reversion to change two directions of two auto lanes design to two directions of one auto lane and one bike lane and one center turning lane. (retrieved from https://nacto.org/docs/usdg/yorkblvd_mccormick.pdf).

(b) Complete streets to consider pedestrians, bicycles, and cars (retrieved from https://smartgrowthamerica.org/what-are-complete-streets/).

(c) A commercial shared street design example is where pedestrian activity is high, and vehicle volumes are either low or discouraged. Although permitting cars and pedestrians, it includes street furniture, pedestrian-priority pavement, and truck-loading areas that do not block sidewalks. (retrieved from https://nacto.org/publication/urban-street-design-guide/streets/commercial-shared-street/)

Some new methods for re-allocating road space between multi-modal modes have recently appeared. “Car-free zone” is becoming a trend in cities driven by sustainable motives through reducing car dependence. In car-free projects in Bogota, Jakarta, New York, Paris, and Groningen, cars are restricted in the streets for all or part of the day. There is also discussion on making these schemes to be the norm.

“Road diet” is one of the unified approaches to implementing bicycle infrastructure and modifying the roadway space. It re-allocates part of the auto lanes center turn lanes, enlarging bike lanes, widening sidewalks, and/or adding on-street parking.

“Complete street” is a concept that streets are for everyone. It is an approach to planning streets that enables safe access for all people who need to use them, including pedestrians, bicyclists, motorists, and transit riders of all ages and abilities.

“Shared space” encourages sharing road space between all road users based on social protocols while eliminating physical barriers.

1.3.2 Road space allocation considering bicycles

When allocating road space for transportation modes, bicycles are hard to ignore. Among the active transportation methods, cycling is promoted in many places as a sustainable and healthy means. Cities such as Copenhagen, London, Paris, and Beijing are working to develop cycling infrastructure. Not only do they have cycle tracks alongside car lanes, but Copenhagen is also building completely car-free cycle paths. These include cycle superhighways for long-distance commuters that span municipal borders and green cycle routes through parks and residential areas.

There are various approaches to allocating road space between bicycles and cars (Figure

1-9). The methods can be summarized as follows in a continuum of mixed-use to total separation with different routes.

(1) Mixed-use without intended separation or bicycle and car traffic mixture.

(2) Shared space intended to mix all kinds of road users, including pedestrians, bicycles, and cars, but car traffic is expected to be low volume or restricted.

(3) Bicycle boulevards are for shared use of low-volume traffic but reinforce that they prioritize bicycle use.

(4) Sharrow or shared bicycle lane markings painted on the road to indicate where bicycles can share the road.

(5) Bike lane adjacent to car lane that uses clear painted pavement or line markings to confirm the place for cycling use but without physical separation.

(6) Bike lanes along car lanes have physical separation, like poles, fences, street plants, blocks, and parking lots.

(7) A bike path or bicycle highway that is basically separated from car lanes for bicycle-dedicated use, especially for long-distance cycling, and usually chooses a different route from auto lanes.

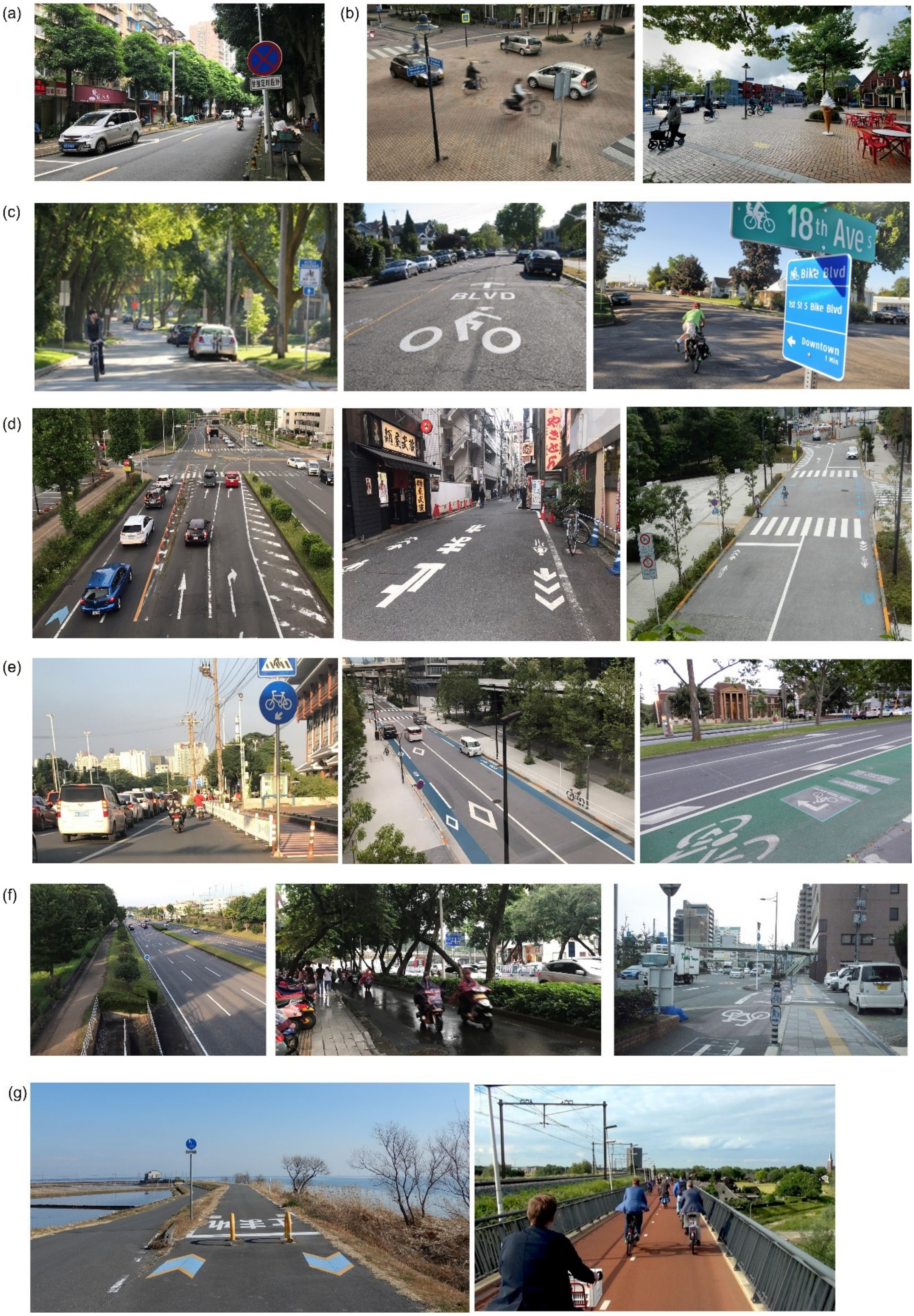


Figure 1-9 Road allocation methods considering bicycles in real world

(a) Mixed use of car and bicycle without intended separation or mixture (taken in Nanning, China)

(b) Shared space in Drachten, Netherland (retrieved from https://worksthatwork.com/1/shared-space).

(c) Bicycle boulevard (retrieved from https://nacto.org/publication/urban-bikeway-design-guide/bicycle-boulevards/signs-and-pavement-markings/).

(d) Sharrow, or shared bicycle lane marking (photos from left to right taken in Tsukuba, Japan in May 2023; in Tokyo, Japan in June 2021; in Tokyo, Japan in August 2023).

(e) Bike lane adjacent to car lane using clear painted pavement or line markings but without physical separation (photos from left to right taken in Nanning, China in September 2018; in Tokyo, Japan in August 2022; and in Melbourne, Australia in November 2019)

(f) Bike lanes along car lanes with physical separation (photos from left to right taken in Tsukuba, Japan in July 2023; in Nanning, China in September 2018; and in Kyoto, Japan in March 2017)

(g) Bike path or bicycle highway (Photo on the left: taken in Rinrin road in Tsutiura, Japan in February 2019; photo on the right: retrieved from https://www.bloomberg.com/news/articles/2017-06-22/this-dutch-cycling-superhighway-connects-commuters).

1.3.3 Guidelines on bicycle-considered roads and intersections

Among these road space allocation methods, there are guidelines for selection between them.

In Japan, there is a guideline for building cycling network, *Anzen de kaitekina jitensha riyou kankyou soushutu gaido rain* [*Guideline for building safe and comfortable cycling environment*] (Ministry of Land, Infrastructure, Transport and Tourism [MLIT] and National Police Agency [NPA], 2016). It provides the guidance on selecting physically, visually, or not separate bicycles and cars based on traffic conditions (Figure 1-10). It advises physical separation on roads when car speed is higher than 50km/h, mixed traffic when car speed equals or lower than 40km/h and the average daily traffic equals or lower than 4,000, visually separation in other cases.

(a)

	A 自動車の速度が高い道路	B A,C以外の道路	C 自動車の速度が低く、 自動車交通量が少ない道路
自転車と自動車の分離	構造的な分離	視覚的な分離	混在
目安※	速度が50km/h超	A,C以外の道路	速度が40km/h以下、かつ 自動車交通量が4,000台以下
整備形態	自転車道	自転車専用通行帯	車道混在（自転車と自動車を 車道で混在）

※ 参考となる目安を示したものであるが、分離の必要性については、各地域において、
交通状況等に応じて検討することができる。

(b)

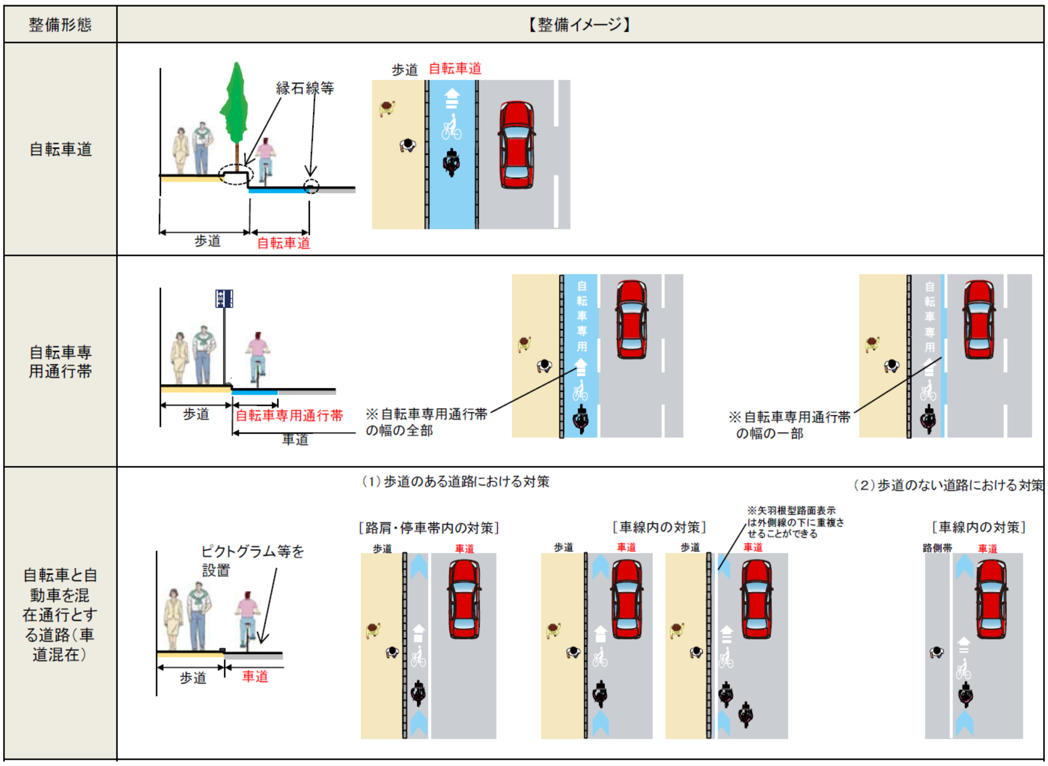


Figure 1-10 Bikeway selection matrix (MLIT and NPA, 2016)

(a) Advised selection of bikeway form based on traffic conditions;

(b) The images of completion forms of bikeway designs shown.

There are no global common criteria for separating or mix bicycles and cars. The criteria seem different by cities. Figure 1-11 shows the cycling facility pre-selection nomograph in *Ontario (Canada) Traffic Manual Book 18: Cycling Facilities* (MTO, 2021). As the first step in the selection, the more detailed criteria considered contextual conditions. It advices physical separation when car speed higher than 40km/h or average daily traffic is over 4,000, which is more strict than Japanese guide.

District Department of Transportation (DDOT) summarized the criteria for cycling facilities from American Association of State Highway and Transportation Officials (AASHTO) and National Association of City Transportation Officials (NACTO) (DDOT, 2020) (Figure 1-12). As a comparison, on local streets with car speed lower than 40km/h (25mph in the table) and daily traffic volume to be 1500-3000, the preferred facility is dedicated bicycle lane. Which is also a higher standard than Japanese standard.

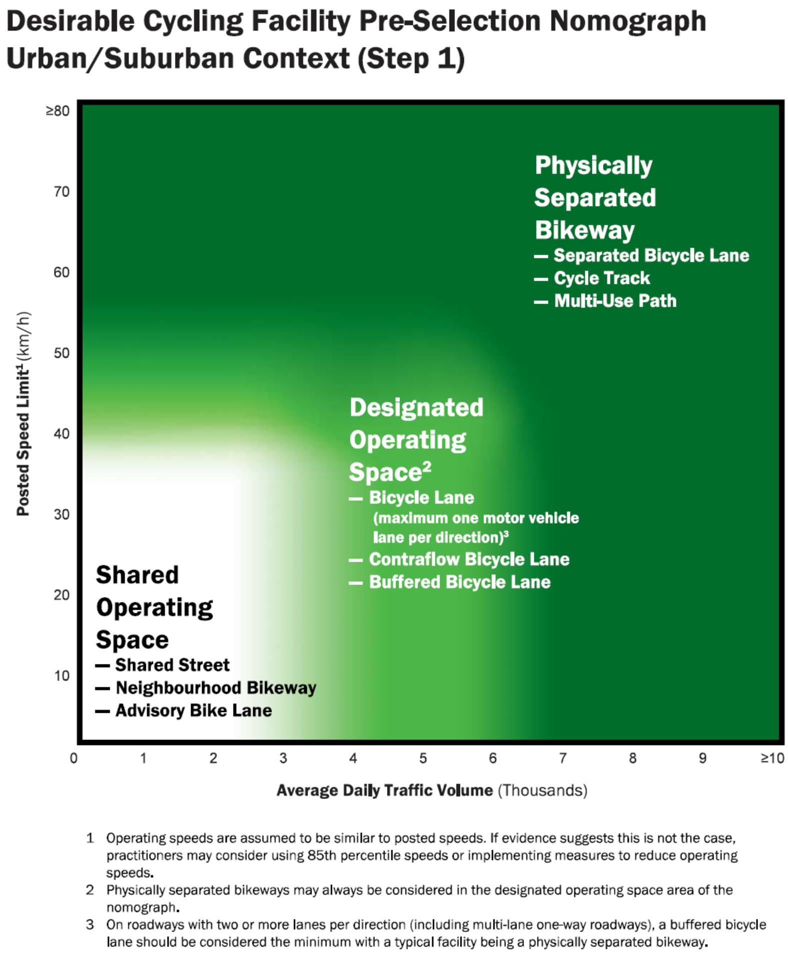


Figure 1-11 Desirable cycling facility pre-selection nomograph for urban or suburban context

(MTO, 2014)

Speed Limit	Traffic Volume (vehicles per day)	Existing Facility Type	Existing Lane Configuration	Cross Section[2]	Preferred Treatment[3]	Alternative Treatment	Other Considerations
<15 mph	n/a	Shared Street[1]	n/a	Any	Shared Markings Additional Signs	None or Signs Only	• Roadway design should limit the vehicular speed
<20 mph	<3,000	Local (neighborhood)	No Centerline Single Lane, One-way	<30′	No Markings	Shared Lane Marking Advisory Bicycle Lane	• Use a contraflow bicycle lane to establish bidirectional bicycle traffic on one-way streets
≤25 mph	<500-1,500	Local (commercial)	One or Two Lanes Parking lane(s)	<34′	Shared Lane Marking	Advisory Bicycle Lane	• Locate Bicycle Lane between curb and parking lane with buffer for door swing clearance • Use a contraflow bicycle lane to establish bidirectional bicycle traffic on one-way streets
≤25 mph	<1,500-3,000	High-Volume Local	One or Two Lanes Parking lane(s)	<38′	Dedicated Bicycle Lane	Shared Lane Marking	• Consider pairing the facility with an adjacent one-way local road in the opposite direction
≤25 mph	<3,000-9,000	Collector	Two Lanes Parking Lane(s)	<44′	Buffered Bicycle Lane or Protected Bicycle Lane[4]	Dedicated Bicycle Lane	• Locate Bicycle Lane between curb and parking lane with buffer for door swing clearance • Use a contraflow bicycle lane or buffered bicycle lane to establish bidirectional bicycle traffic on one-way streets
≤25 mph	<9,000-12,000	Collector – Multi-Lane	Two to Four Lanes Parking Lane(s) Peak Period Parking	<44′	Buffered Bicycle Lane or Protected Bicycle Lane[4]	Protected Bicycle Lane[4]	• Locate Bicycle Lane between curb and parking lane with buffer for door swing clearance • If facility is one-way, create 2-directional pairing with adjacent one-way street
≤30 mph	<12,000-15,000	Minor Arterial	Two to Four Lanes Parking Lane(s) Peak Period Parking	<50′	Protected Bicycle Lane[4]	Buffered Bicycle Lane	• Use an adjacent parking lane to provide enhanced bicycle facility buffer and protection if possible
≤35 mph	>15,000	Principal Arterial	Two to Six Lanes Parking Lane(s) Peak Period Parking	>50′	Raised Protected Bicycle Lane	Protected Bicycle Lane[4]	• Consider dedicated bicycle facilities when motorized vehicle volume is high

References: *AASHTO Guide for the Development of Bicycle Facilities, Fourth Edition Table 2-3; DDOT DEM 30-12,30-13,30-14; NACTO Urban Bikeway Design Guide, Contextual Guidance for Selecting All Ages & Abilities Bikeways*

Notes:

[1] Shared streets are not defined by the DDOT Design and Engineering Manual

[2] Cross section widths are provided as reference only. Actual application of a facility type is dependent on field conditions and should be discussed with the DDOT project manager.

[3] The preferred treatments indicated in the table represent the minimum preferred treatment for bicycle protection and accommodation. In locations where a continuous bicycle network is advantageous, a higher-class bicycle facility may be used for connectivity.

[4] Protected bicycle lanes may be one-way or two-way facilities, dependent on the overall bicycle network, available right-of-way, and other user access factors.

Figure 1-12 Facility Treatment Selection Matrix (DDOT, 2020)

Intersection design for cyclists are considered as a vital part in bikeway. The typical intersection advised in guideline (MLIT and NPA, 2016) is in Figure 1-13.

Meanwhile, there are emerging treatment regarding bicycles. Protected intersection is a design method to make cyclists easily seem by cars while separated from pedestrians and cars. The main features include refuge island at the turning curb to separate bicycles and cars; the waiting zone for bicycles are in front of that for cars to increase bicycles visibility; clear marking at waiting zones and roads to separate pedestrians, bicycles and cars (NACTO, 2019) (Figure 1-14).

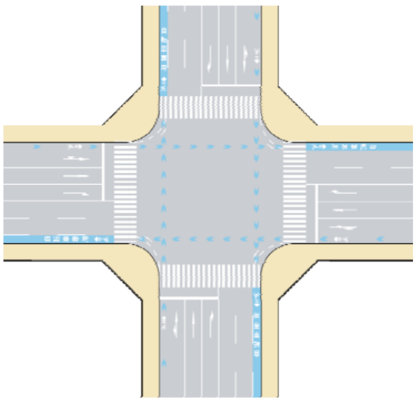
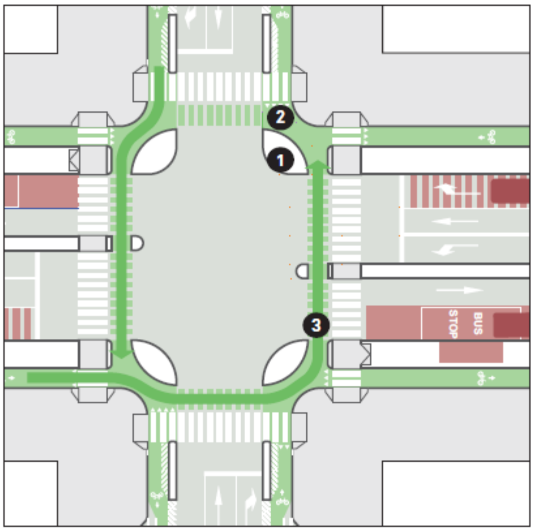


Figure 1-13 Intersection design with bike way (MLIT and NPA, 2016)

(a)



(b)

(c)

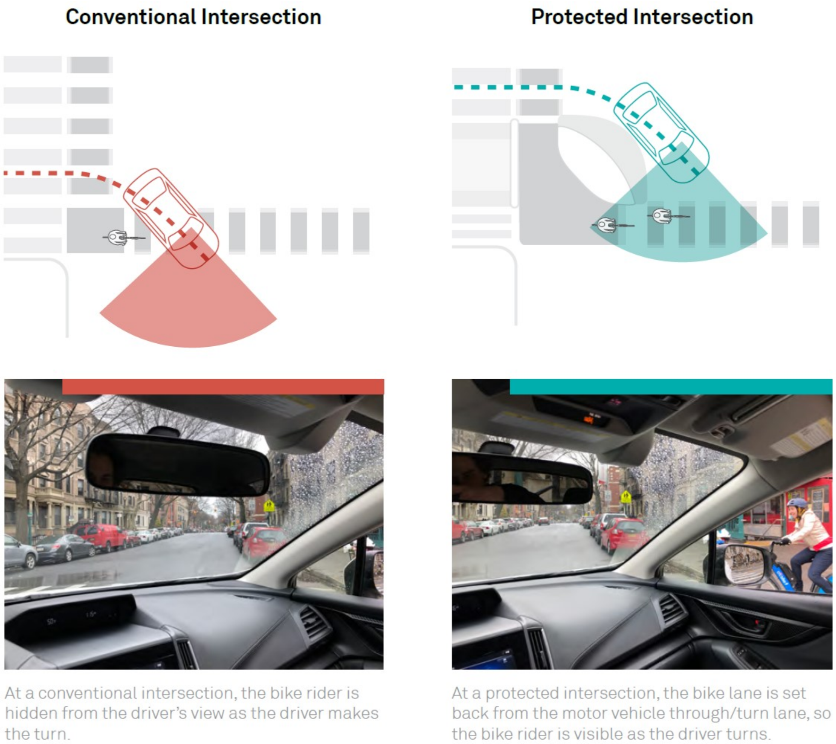


Figure 1-14 Examples of protected intersections

(a) Protected intersection design (Design National Association of City Transportation Officials [NACTO) and Global Designing Cities Initiative [GDCI],2016) p.102

(b) Protected intersection in Chicago, USA (retrieved from https://www.flickr.com/photos/24858199@N00/26125689470/)

(c) Comparing the visibility of cyclists in conventional and protected intersections (NACTO, 2019)

Bike box is a place ahead of motorized traffic for cyclists to line up during the red signal phase. An example of bike box is shown in Figure 1-15. It can help with a speedy start for waiting bicycles, as well as a better bicycle visibility from drivers, thus a safer cycling environment.

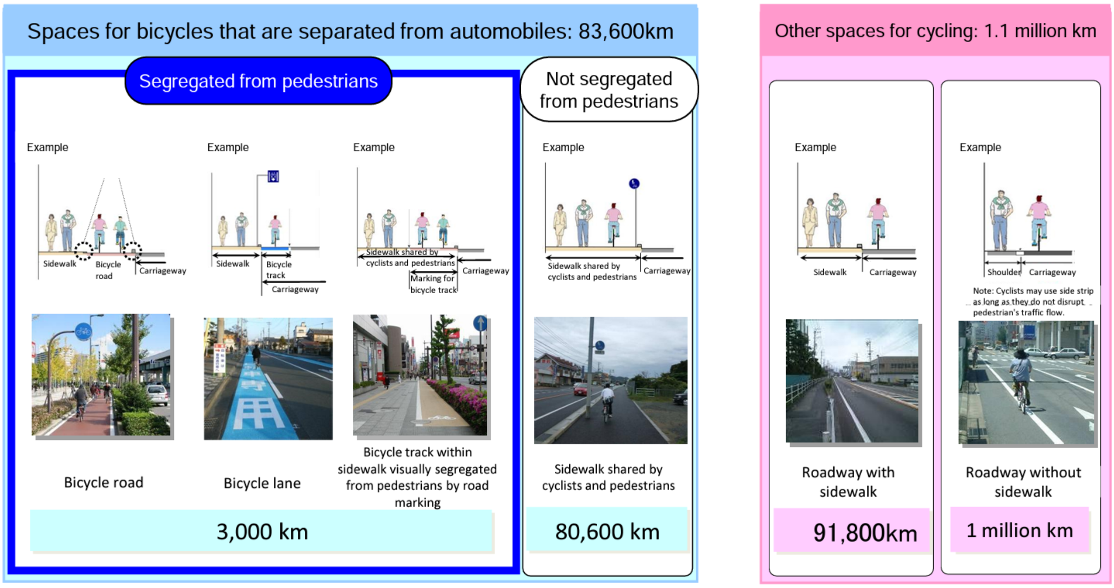
Note that bike box is against the Japanese traffic rules. According to the 19^{th} article and the 5^{th} paragraph of the 63^{th} article in *Road Traffic Act* (2015), bicycles are not allowed to ride side by side unless there is any signs that allows two bicycles progressing parallelly. Although it does not against the law to parallelly park bicycles or wait in front of signal lights, when they start to move in group from the bike box when traffic light turn green, it is inevitable to move side by side. Therefore, these articles forbid the apply of bike box virtually although there is no code forbid bike box directly.

Figure 1-15 A bike box in Portland, USA

(retrieved from https://nacto.org/publication/urban-bikeway-design-guide/intersection-treatments/bike-boxes/)

1.3.4 Conflicts involving bicycles

In Japan, bicycles are an important mode of transportation, accounting for 20% of the traffic that travels distances less than 5km. Bicycles are classified as vehicles and is regulated to use left side of car lane in general. A traffic regulation on this relaxed in 1970s an cyclists can use designated sidewalks. Cycling facilities of various kinds is summed up to be 1.2 million km. the Bicycle Use Promotion Act was enacted in 2017, and the Bicycle Use Promotion Plan was adopted in 2018.



Note: "length" refers to road length as of Mar 2010. Source: MLIT documents and NPA documents.

Figure 1-16 Length of different kinds of bicycle facilities

(MLIT, n.d.)

Since bicycles are regulated to use car lanes, car-bicycle conflicts occur in mixed traffic. They can hinder car speed and raise cycling safety concerns, especially on narrow roads in urban areas (*The Tokyo Shimbun*, 2021).

According to the *Traffic Accidents in 2022* (National Police Agency, 2023), the number of fatalities, seriously injured, and slightly injured cyclists tend to decline from 2012 to 2022. The only exception is the injuries in 2020 and 2021, which may be related to limited outgoing during the pandemic.

Although this decline, conflicts between bicycles and cars can occur in daily life (Figure 1-17). Although the rule is that on roads where sharrows exist, cyclists should ride on the markings instead of on sidewalks, the cars driving on the markings can make the cyclists reluctant to cycle on sharrows. Trucks and cars can park on the side for loading for a short time. They force cyclists to overtake and thus push them into the center of the car traffic. In a study by the National Police Agency in May 2023, reported by NHK, on bicycle-dedicated lanes in Tokyo, they studied parking cars blocked 85% of the lanes (Figure 1-18). Although driving on sharrows and parking for a short time on bicycle-dedicated lanes is not against the law, the high frequency of their occurrence can make the cycling environment unfriendly and stressful. Therefore, cycling promotion requires a road space allocation that considers cars.

Figure 1-17 Conflicts between cyclists and cars

Photo on the left taken in Chofu, Japan in October 2023; right: taken in Fujisawa, Japan in February 2021.

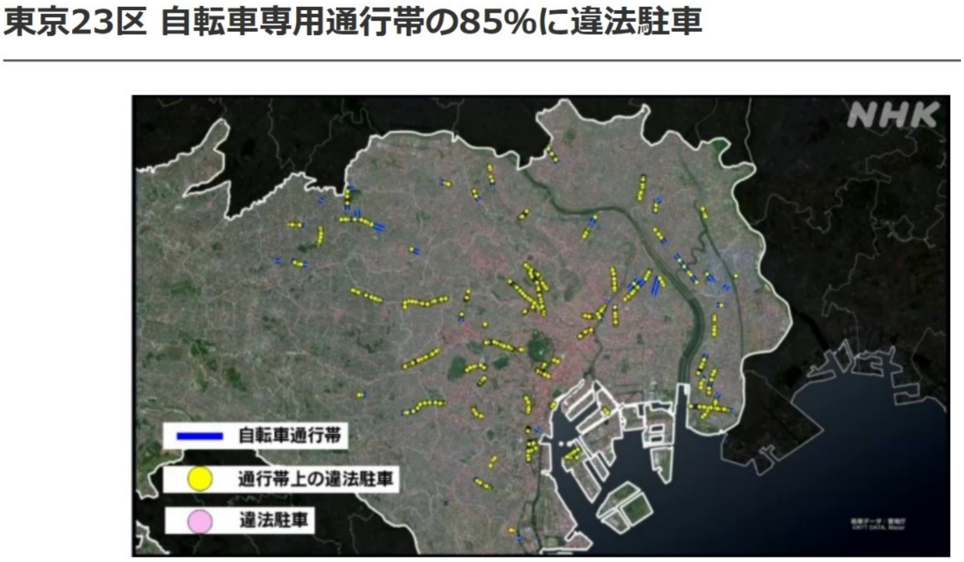


Figure 1-18 85% of bicycle-dedicated lanes are blocked by parking cars

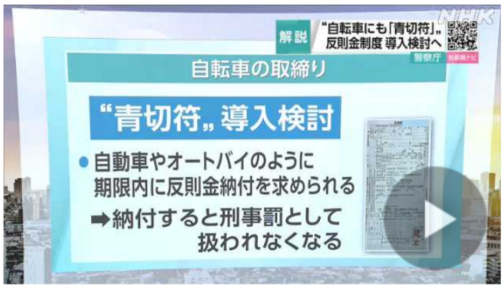
(retrieved from https://www.nhk.or.jp/shutoken/newsup/20230530b.html)

In bicycle-pedestrian conflicts, bicycles can be dangerous. The numbers of pedestrian fatalities and serious injuries in bicycle versus pedestrian accidents did not decline from 2012 to 2022, and was 312 in 2022 (National Police Agency, 2023). A "blue ticket" system is being discussed that minor traffic violations to be dealt with in the form of a fine payment, especially for cyclists using sidewalks cause accidents with pedestrians (Figure 1-19).

As electric scooters are employed, safety concerns are raised again. Traffic accident statistics began to be recorded in reports from 2020; the accident numbers increased from 4 to 41, and the injuries from 5 to 41.

自転車の悪質な交通違反 反則金制度の導入検討へ 警察庁

08月03日　11時12分



自転車の悪質な交通違反が後を絶たないことから、警察庁は、自動車やオートバイのようにいわゆる「青切符」による取締りを行う反則金制度の導入を検討することになりました。
実効性のある取締りにつなげるのが狙いで、導入されれば、身近な交通手段のあり方の大きな転換点

Figure 1-19 Length of different kinds of bicycle facilities

(retrieved from https://www3.nhk.or.jp/shutoken-news/20230803/1000095497.html)

1.4 Objectives

I would like to contribute to the topic of providing mobility services for residents. It is a complicated topic that contains many factors to consider. The usability of the transportation network differs by place; places with high density and connectivity of a specific transportation means can be especially friendly to their users. For example, city centers with frequent and high-density transit networks can provide effective service for transit users; places with wide and green sidewalks may attract pedestrians; places with exclusive bike tracks can be fascinating for cyclists. The distribution pattern of population and facilities pattern can affect the property of the mobility service. For example, walking can be suitable for places with both population and facilities immensely compactly distributed; bicycles are for places slightly compactly distributed and in-between the transit coverage; cars are for places with population and facilities scarcely distributed. Other factors can affect the mobility provision, needs, and preference matches of the provision and needs in the short and long run, including demographic features, socio-economic status, culture, and weather conditions. For example, older people choose ones that do not consume physical energy; young generations welcome emerging vehicle types; in developing countries, bikes and autocycles are for working-class while car ownership comes with a status symbol; showers can limit walking and cycling.

These factors that affect mobility provision and needs are dynamic. Population distribution can change with urbanization, migration, aging, and declining fertility rates. Facilities open and close responding to demographic changes. New mobility alternatives emerge following technological innovations, like e-bikes, e-scooters, other types of micro-mobilities stated in this chapter, and autonomous cars. Road facilities that are newly built and deteriorated can change the existing transportation network. Other unexpected incidents may change usage; for example, micromobilities are reported to be widely used during the COVID-19 pandemic for keeping social distance.

While providing better mobility services for residents is a comprehensive topic, I chose to pay attention to bicycles and e-bikes rather than other means of transportation. Because they are active modes that are promoted as sustainable and healthy means of transportation, and other productions in micromobility industry innovation that answer users' demands for mobility share similar features with (e-)bicycles. In the analyses, I tried not to neglect transportation means other than cyclists, including cars, public transit, and pedestrians, considering them essential parts of road users.

I also chose to focus on road space because the growing ridership and various vehicle sizes and fleet characteristics can be problematic in terms of safety, convenience, and traffic fairness if there is no understanding of their advantages and disadvantages, proper regulation design, or transportation system plan to integrate them into the whole system.

In the first step to provide background information on mobility service provision, I analyzed population distribution patterns. I aimed to classify the urban form by population distribution patterns and find the correlation between them and the usage of pedestrians, bicycle or bicycle-like means, transit, and cars. By investigating the long-term dynamics of the population distribution, I tried to understand the status quo of modal shares and how they will possibly change in the future. These are in Chapter 3.

After summarizing the overall trends in the modal share changes of multiple transportation means in Chapters 3 and 4, I tried to understand their comparative advantages and disadvantages. I analyzed travel time and physical energy consumed by conventional bicycles, electric assistant bikes, and public transportation.

After realizing bicycles can have advantages over transit in some places in Chapter 4, I considered maximizing their strengths while reconciling the conflicts between road users in the scope of multi-modal transportation design in the following Chapters 5 and 6.

Chapter 5 focuses on space allocation strategies between multiple types of transportation methods, including bicycles, e-bikes, cars, and buses at road links, to explore the knowledge of how traffic efficiency is affected by allocation. Then, it turns to several intersection treatments, considering bicycles and comparing them with status quo design.

Using the vehicle settings in Chapter 5, Chapter 6 proposes a system in which bicycles and cars are assigned to different roads at a network scale. The proposed system is assessed in terms of cycling environment and traffic efficiency.

Chapter 7 summarizes the conclusions in each chapter and points out the possible future research topics.

2. Literature review

2.1 Concept and measurement of "compact city"

With the objective to classify the compactness in the population distribution patterns and find the correlation between them and the usage of each kind of transportation method, I need to clarify the concept of "compact city" and how the "compactness" is quantified in the previous studies.

The concept of the "compact city" arose after the discussion on the issue of global warming at the UNCED in 1992. Then the European governments began to consider the compact city as one of the major urban construction goals, and many efforts are spent on its investigation. The OECD (the Organization for Economic Co-operation and Development) also considers the compact city as an illustration of ideal future cities in terms of environmental and economic sustainability (OECD, 2012a).

In Japan, the concept of "compact plus network" is the focus of future city ideal plans to create more comfortable urban areas under strict constraints of space, environment, and finance. The compact and networked concept has been put into practice, symbolized by enacting revisions of two Acts on urban reconstruction and local public transportation systems in 2014.

Despite the intense attention on the compact city, there is no quantified standard for its definition. Currently, the OECD identifies the key characteristics of a compact city as "dense and proximate development patterns; urban areas linked by public transport systems; and accessibility to local services and jobs" (2012a: 27–28). Among these, urban form is a crucial aspect of defining a compact city.

As ends of urban form development continuums, compactness and sprawl are usually described as two antonyms.

Conceptually, compactness is described as employment concentration, housing clustering, and mixed land-uses (Ewing, 1997), being distinguished from sprawl form with a low-density, strip, scattered, and leapfrog urban development pattern in United States (Gordon & Richardson, 1997). Recently, the OECD identified the key characteristics of a compact city as "dense and proximate development patterns; urban areas linked by public transport systems; and accessibility to local services and jobs" (2012a: 27–28).

To measure compactness and sprawl quantitatively, metrics have been operationalized from the one-dimension variable of density to multi-dimensional systems, which compose of metrics from the perspectives including density, mix land-use, activity centering, and street connectivity (Arribas-bel, Nijkamp, & Scholten, 2011; Ewing, Pendall, & Chen, 2002;

Galster et al., 2001; Hamidi, Ewing, Preuss, & Dodds, 2015). Facing the tendency of increasing amount of factors to capture urban form characteristics, the necessary arouse to summarize the similar indicators and to create standardized protocols are pointed out, and efforts are put in indicator comparison and selection (Clifton, Ewing, Knaap, & Song, 2008; J. H. Lowry & Lowry, 2014; Schwarz, 2010).

Finding the relative associations between urban form and transportation pattern has long been a topic to investigate (Frank, Bradley, Kavage, Hapman, & Lawton, 2007; Kaplan, Nielsen, & Prato, 2016; Kaza, 2020; Miller & Badoe, 2000; Shim, Rhee, Ahn, & Chung, 2006). While some studies show a marginal impact from urban form to transportation usage, some studies concluded that urban densities, traditional neighborhood design, land-use mix, have an impact on auto ownership; and some confirmed the effectiveness of contiguous and compact urban form on energy consumption in the transportation sector.

2.2 Urban form metrics and international comparison

Trying to choose the metrics to measure compactness, I compared the metric pool for quantifying “urban form”, because the sprawl and compactness concepts are in the urban form development continuums.

The quantitative and time series analysis of urban form has been researched to investigate its relation to transportation mode choice, travel pattern, energy consumption, emission, and resilience (Anderson et al., 1996; Crane, 2000; Sharifi, 2018). Meanwhile, studies on urban form metrics are also in progress. The metrics can be classified into two types: landscape metrics and socio-economic indicators (Schwarz, 2010). The former focuses on the physical structure of urbanized areas, measuring each urban patch and the difference and distance between patches. The socio-economic indicators consist of demographic, social, and economic measurements, studying population, household, GDP, and their density and distribution.

Landscape metrics are usually combined with remotely sensed land cover data, which play a substantial role in urban form investigation (Guérois & Pumain, 2008; Huang, Lu, & Sellers, 2007a; Inostroza, Baur, & Csaplovics, 2013; Kasanko et al., 2006; Schneider & Woodcock, 2008; Sun, Wu, Lv, Yao, & Wei, 2012; Wu, Zhao, Zhu, & Jiang, 2015). Such metrics measures urban land patches by the means of the size, quantity, regularity, and morphology. While can provide environmental information, they may lack the perception to reveal the urban activity inside patches, especially when land cover do not match land use. For example, built-up lands are not demolished to return to grasslands when residents moved out; in rapid urbanization in developing cities, facility provision cannot match population large amount of move-in, capacity increased by per capita.

Exceptions include research conducted by Schneider and Woodcock (2008), and Guérois and Pumain (2008). Their method was to draw concentric circles around city centers and investigate the built-up area ratio in each circles area at regular distances from the city center. shorten

One of the methods to address the limitation in landscape metrics by investigating the intra-city population distribution structure is a socio-economic method employed by Tsai (2005). Urban form is quantified at the metropolitan level through four dimensions: size, density, the degree of equal distribution (Gini coefficient), and degree of clustering. To assess the degree of population clustering, Tsai (2005) used Moran’s I coefficient, a spatial autocorrelation measure. Defining spatial clusters as unlikely concentrations that occurred by chance, Moran’s I identifies clusters based on the conjecture that there is a correlation among variables in nearby units (Getis, 2010). Tsai (2005) test on Moran’s I coefficient using hypothesized population distribution models shows that it can distinguish monocentric, polycentric, and decentralized urban form with high, middle, and low values, respectively. It is reported more useful than Geary's C, another spatial autocorrelation measure, and can also be preferable than some methods that require combining several indices into one using arbitrary weights. In recent studies, the Moran's I is adopted as a spatial centering indicator, quantifying clustering of urban development activities using data of employment (Hamidi *et al.*, 2015), land cover types (Wang *et al.*, 2019), urban land development (H. Liu et al., 2021), and residents and workplace (Rahman, Islam, & Neema, 2022).

Tsai (2005)'s compactness metric of Gini and Moran's I using population distribution is attractive out of two reasons: (1) It focuses on socio-economic but not environmental features, thus suitable for analyzing transportation usage; (2) It is simple with only two metrics and the data required for the calculation is accessible.

As I planned to check the compactness of cities all over the world, I reviewed the studies on international comparison.

Many inter-city urban form comparison studies have emerged in recent years. Studies conducted in Europe (Guérois & Pumain, 2008; Kasanko et al., 2006; Schwarz, 2010; Siedentop & Fina, 2012), Latin America (Inostroza et al., 2013), and China (Wu et al., 2015), revealed city types and urban growth patterns within these regions. A global point of view is also adopted in some studies (Huang, Lu and Sellers, 2007; Schneider and Woodcock, 2008; Dong *et al.*, 2019). Findings show that sample cities outside the US do not display the large and dispersed form present in the US (Schneider and Woodcock, 2008; Dong *et al.*, 2019), and the cities in developing countries in Asian and Latin America are more compact and dense than those in Europe or North America (Huang et al., 2007a). Despite revealing insights into the regional diversity of urban form, the number of target cities is restricted by the lack of international comparative data and heterogeneity of data sources (Siedentop & Fina, 2012); thus, research on urban form at the global scale is rare.

2.3 Bicycling convenience evaluation

Aiming to provide mobility services for residents. I reviewed the studies to assess the performance of transportation modes. I found there are various of them, including convenience, environmental impact, cost, traffic safety, and public health. Among these, convenience is one of the most crucial factors because it can influence a user's basic transport choice behavior (Burns & Golob, 1976).

Because I chose to pay attention to bicycles and e-bikes as active modes that are promoted as sustainable and healthy means of transportation, and the innovation in micro-mobility industries can answer users' demands for mobility. I focused on the bicycle convenience evaluation.

There have been many methods proposed since 1987 for evaluating bicycling convenience, which focused on the bikeway sections of a cycling network. These methods share a similar form, in which each bikeway section is graded according to its perceived safety and comfort to cyclists, then the scores are combined (Lowry et al., 2012).

Different from the previous studies focused on linear network sections, Lowry et al. (2012) and McNeil (2011) considered the convenience throughout the network to measure the potential accessibility of cyclists. Lowry et al. (2012) first evaluated the bikeways based on bicycle level of service (LOS) considering attributes of physical infrastructure and traffic volume, and then measured the convenience of the network, derived from accessibility to commercial destinations. McNeil (2011) developed a scoring criterion by counting the public destinations of home-based utilitarian trips within service areas in distance thresholds from the origin. When calculating the service areas, the road segment suitability was evaluated by assigning a new length accounting for traffic, cycling infrastructure, and arterial class.

Winters et al. (2013) presented another method to pinpoint areas with high bicycling convenience, in which a district is divided into 10-m diameter cells and the convenience score of each cell is given based on components within a 400-m radius circular buffer area. The relevant importance of each component is derived from opinion surveys, travel behavior studies, and focus groups. Built environment components, such as bicycle facilities and land use features, are also considered. Similar analyses are conducted in (Krenn et al., 2015) and (Larsen et al., 2013).

The commercial Bike Score® service measures whether a location is convenient for biking based on four weighted components: presence of bike lanes, terrain severity, destinations and road connectivity, and bike commuting mode share (Walk Score, n.d.). Nikolaos et al. (2009) evaluated a city's cycling convenience based on a rating scale questionnaire.

2.4 Positives and negatives of e-biking

To help myself narrow down the scope of assessing the advantages and disadvantages of deploying e-bike, I reviewed the studies on their perspectives of environmental friendliness and risk on urban streets.

Electric bikes (e-bikes) present to be a relatively sustainable and healthy transportation mode. Their emissions are less than motorcycles and cars, and similar to those of a bus on a per passenger per kilometer basis (Cherry et al., 2009). E-bikes can overcome the required level of physical effort and physical barriers, such as rough terrain, compared to manually-powered bicycles, being friendly to people with physical limitations (Dill and Rose, 2012). Riding pedal-assisted e-bikes can cause a sufficiently high energy expenditure, leading to positive physiological change, which can be considered an active transportation mode (Gojanovic et al., 2011; Langford et al., 2017; Louis et al., 2012; Simons et al., 2009; Sperlic et al., 2012).

However, there remain concerns about e-bike riders' higher ratios of risk-taking behavior and higher conflict rates than riders of conventional bicycles (Bai et al., 2013; Schepers et al., 2014), widely used lead-acid batteries in e-bikes (Cherry et al., 2009), and the hesitation of promoting public transportation use for the fear that it will decrease transit ridership.

As I decided to focus on the benefits from the e-bike users' side when assessing the suitability of employing e-bikes, I noticed that one of the differences between conventional bicycles and e-bikes lie in the physical energy consumption. I reviewd the papers for metrics that can be used in my assessment.

Studies have been conducted on the physiological demand in pedal-assisted e-biking for scenarios including hilly and flat terrain, fixed and self-selected speeds, and light and high levels of motor support (Gojanovic et al., 2011; Langford et al., 2017; Louis et al., 2012; Simons et al., 2009; Sperlich et al., 2012). The two primary perspectives to evaluate physical energy expenditure in e-biking are benefits and costs. In terms of benefits, all of the published research reports that e-biking can contribute to at least moderate intensity physical activity (i.e., 3-6 metabolic equivalent of task (MET)), being sufficient to meet physical activity guidelines (Table 2-1). In terms of cost, a comparison to conventional bicycling shows that electrical assistance can reduce intensity and the perceived exertion level of cycling, help overcome terrain barriers, and lower the perceived need to shower after bicycling.

Although these studies confirmed the advantages of e-biking for saving physical energy consumption, there is no complete set of data of e-biking corresponding to different slopes, especially the Japanese style electrical assistant bicycle. I developed my own methods of calculation in Section 4.3.4.

Table 2-1 Reported physical activity values in bicycling and e-biking.

Source	Activity	Physical Activity Metabolic Equivalent of Task (MET)		
		Bicycling	E-biking	
			Light support	High support
Simons et al. (2009)	4.3 km, almost flat, self-selected speed	6.1 (19.6 km/h)	5.7 (21.1 km/h)	5.2 (23.4 km/h)
Gojanovic et al. (2011)	5.1 km, uphill, average grade: 3.4%	8.2 (10.3 km/h)	7.3 (15.1 km/h)	6.1 (16.5 km/h)
Ainsworth et al. (2011)	leisure, 8.9 km/h	3.5		
	leisure, 15.1 km/h	5.8		
	leisure, commuting, for pleasure, <16.1 km/h	4.0		
	leisure, light effort, 16.1-19.2 km/h	6.8		
	general	7.5		
Louis et al. (2012) [a b]	16 km/h	6.5 (5.6)	5.8 (4.9)	4.2 (3.9)
	free chosen speed (≈18 km/h)	6.7 (6.5)	6.2 (5.6)	4.3 (4.2)
	21 km/h	7.9 (7.3)	7.1 (6.4)	5.0 (4.6)
Sperlich et al. (2012)	uphill (compact gravel)	7.2	5.2	
	downhill (compact gravel)	6.5	4.8	
	uphill (compact gravel)	5.8	7.7	
	flat (pavement)	5.1	7.3	
Ministry of Health, Labour and Welfare (2013)	commuting, ≈16 km/h	4.0		
	general		3.0	
Langford et al. (2017) [a]	1.6 km, downhill, (net elevation change: -33.2 m)	3.9	3.7	
	1.8 km, flat, (net elevation change: -0.3 m)	5.2	4.5	
	1.0 km, uphill, net elevation change: +33.5 m).	7.6	6.6	

a: Converted from oxygen consumption rate.

b: for participants regularly practicing endurance sports in parentheses.

2.5 Cycling dedicated facility design

2.5.1 Preference for car-free bike path

As shown in the last chapter, there is a wide variety of approaches to allocate road space between bicycles and cars. In a mix-separate continuum, there are shared space, bicycle boulevard, sharrow, bike lane, bike path or bicycle highway. I reviewed to find is there any kinds of allocation methods preferred by cyclists. Cycling dedicated facilities show their importance to reduce the impact of intervening with motorized vehicles to provide a comfortable and safe ride.

In stated preference survey, commuter bicyclists value travel time most, the following important items include presence of a bicycle facility, especially a bike lane or separate path, and the level of automobile traffic (Stinson & Bhat, 2003). Samples from European cities show the determinants of overall cycling satisfaction are most related to limited hindrance from other transportation modes and smoothness (Susilo & Cats, 2014). GPS tracking data shows that cyclists value off-street bike paths most, followed by bicycle boulevards (Broach, Dill, & Gliebe, 2012). Regarding safety perspective, an international survey with respondents from 17 countries on self-reported bicycle collisions show that motor-bicycle accidents are more severe and than bicycle-bicycle and single bicycle crashes (Shinar et al., 2018).

Excluding cars from road space is raised as an option to reconcile conflicts between active and motorized transportation. Car-free projects, where cars are restricted in streets, are becoming a trend in many cities driven by sustainable motives through reducing car dependence (Glazener, Wylie, van Waas, & Khreis, 2022). (Bagloee, (Avi) Ceder, Sarvi, & Asadi, 2019) confirm that road closure can improve congestion developed a method to identify no-car roads dedicated for exclusive bicycle use based on Braess Paradox. Although the advantages in separating bicycles and cars, there is no discussion on a systematical strategy to separate them to different road at network scale.

2.5.2 Intersection design

Intersection design for cyclists is considered as a vital part in bikeway.

Regarding intersection treatments for cycling, research primarily focused on safety issues, exploring the effectiveness in reducing vehicle-bicyclist conflicts by pre- and post-evaluations. Solutions are proposed to improve cyclist safety at the intersections in geometric design and pavement markings (Carter, Hunter, Zegeer, Stewart, & Huang, 2006; Jensen, 2008; Weigand, 2008). In addition to the layout and pavement design, research on signal timing treatments also appeared. Bicycle specific signals, exclusive bicycle phases, leading bike intervals, are explored in (Kothuri *et al.* 2018). Some designs combining geometric and signal timing treatments were proposed to improve capacity and eliminate vehicle-bicycle conflicts at in specific intersections, continuous flow intersections and tandem intersections (J. Zhao, Gao, & Knoop, 2019; J. Zhao, Yan, & Wang, 2019).

However, to what extent can intersection treatments affect transport efficiency performance in network scale, and consideration of e-bikes is absent in these studies. In the Japanese case, bike box and protected intersection require insights as they are not adopted in reality.

2.6 Bicycle-car mix traffic flow simulation

Considering simulation as one of my research methods, I reviewed papers on bikeway design modeling when considering traffic on road. Previous research has been conducted with different approaches.

2.6.1 Cellular automata models

Cellular automata model is a kind of temporal and spatial discrete traffic flow model. Figure 2-1 is an example of a CA model to depict how spatial discreate model is like and how vehicles with different sizes can be expressed.

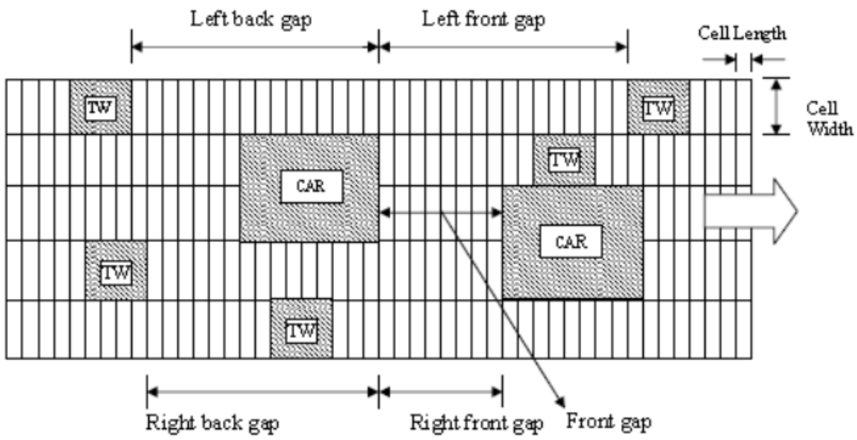


Figure 2-1 An example of CA model

(Mallikarjuna & Rao, 2009)

Much effort has been devoted to improving the model performance to reflect the real traffic flow(Li et al., 2014; Luo et al., 2015). The Nagel-Schreckenberg (NaSch) (Nagel & Schreckenberg, 1992) CA model and the multi-value CA (MCA) model are two categories of CA model widely used to simulate nonmotorized traffic. While (D. Zhou, Jin, Ma, & Wang, 2015) indicated that MCA model exhibits more stable and closer results than a 2-lane NaSch model to field observations, NaSch model is also used in bicycle mixed bicycle traffic flow simulation, and can well match empirical data when lateral movement is considered. Though the cellular automata modeling reported being well-performed in mixed traffic simulation on road segments, it is difficult in nature to apply for simulation at crossings, which can be critical in bikeway design. However, there remain issues to address about road space reallocation corresponding to e-bike number.

Table 2-2 Overview of mixed traffic flow simulation using CA models.

References	Vehicle	Simulated scenarios	Model prototype	Cell size	Description
(Luo et al., 2015)	car, bicycle	3.5 car lane +3.5 bike lane	NaSch	1.0m × 0.5m	Building linear regression of passing cars speed and lateral distance with bicycles
(Zhang, Ren, & Yang, 2013)	bicycle, e-bike	3 bike lane	NaSch, gas dynamics	2.0m (length)	Comparing speed-density diagram between empirical data with NS model or gas dynamics model.
(Li et al., 2014)	bicycle, e-bike	2~4 bike lane	NaSch	2.0m (length)	Counting passing events in mixed traffic. Randomization probability validated. Lateral distance considered.
(Jin, Qu, Xu, Ma, & Wang, 2015)	bicycle, e-bike	2~4 bike lane	MCA	2.0m (length)	Extending the speed in previous model to simulate the high speed in e-biking. Validated.
(Ding et al., 2015)	car, bicycle, bus	Near bus stops	NaSch + MCA	/	Simulating car and bicycle mixed traffic near bus stops. Lateral distance considered. Used passenger transport capacity to assess the bus stop design.
(Zhou et al., 2015)	bicycle, e-bike	2 bike lane	NaSch + MCA	1.25m × 1.25m	Comparing performance of NaSch and MCA models. M-CA model more stable than the two-lane NS model.

2.6.2 Microscopic models

Microscopic simulation methods are applied recently. Different from cellular automata model that simulates traffic flow in a spatially and temporally discrete way, microscopic model that simulates space continuously, is reported to be a useful tool, providing another option to simulate traffic flow.

There are studies tried to apply car-following models that originally designed for car traffic to reproduce bicycle traffic in the real world, and calibrated the variables considering bicycle reactions and road conditions (Castro *et al.*, 2022; COWI, 2013; Kaths *et al.*, 2021). Microsimulation is also used for simulating bicycle considered intersection treatments, which is an important part in cycling traffic design. In a study on delimiting right-turn confliction using bicycle-specific intersection treatments, microsimulation tool is used to model three signal timing strategies, and to compare car and bicycle delays with current timing (Kothuri et al., 2018). Grigoropoulos *et al.*(2022) used microscopic simulation to investigate traffic characters when in high bicycle traffic volume. Microscopic models are used as decision support tools to assess projects where cycling areas are enlarged based on original road space allocation (Boyle, Faghri, & Gomes, 2023; del Carmen Almanza Mendoza et al., 2018;

Grigoropoulos et al., 2021; B. Liu et al., 2021; Noland, Gao, Gonzales, & Brown, 2015). These studies select target streets consisting of several continuous road segments and intersections where a specific pilot project is conducted. Then scenarios are simulated in microscopic models based on road section re-design, traffic volume, and signal control data. The simulated results are compared with the empirical or baseline scenario in terms of travel-time delay, pollutant emissions, and cost-benefit, to assess the outcome of the projects.

(a)

(b)

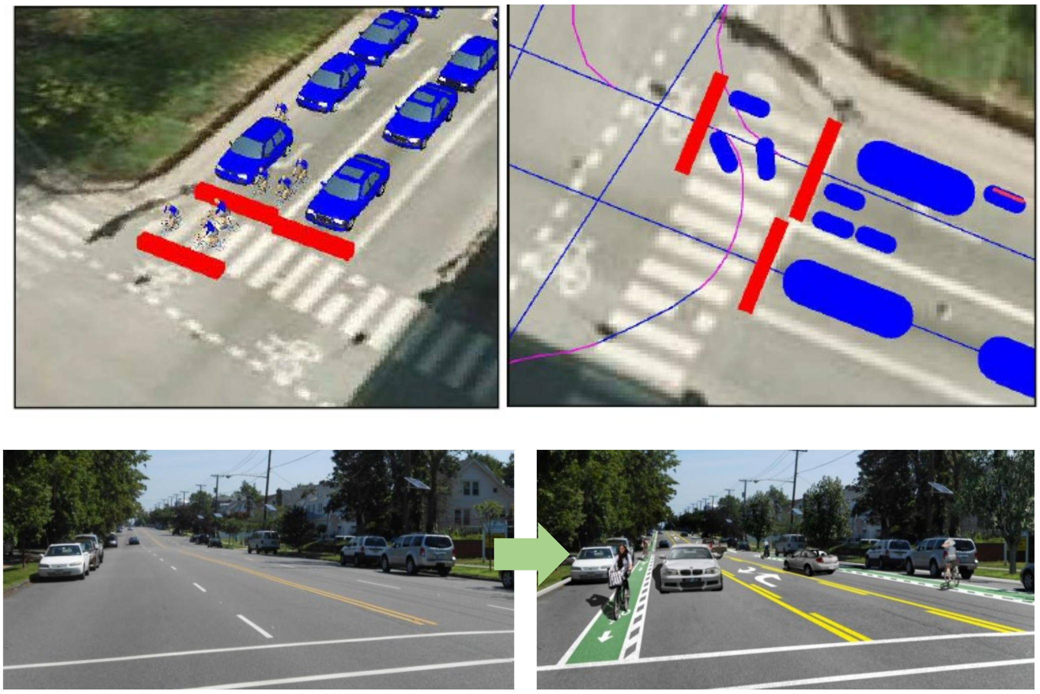


Figure 2-2 Examples of microscopic model.

(a) 3D and simplified view in the simulator Vissim (COWI, 2013)

(b) A road diet design to be simulated in microscopic model (Noland et al., 2015)

While some microscopic models themselves are comprised of a local road network (del Carmen Almanza Mendoza et al., 2018; B. Liu et al., 2021), traffic characters in road space allocation scenarios can be applied to data at road network scale for further analysis. In bikeway network design studies that discuss methods to prioritize roads to build bicycle facility, adding on-road bike lane facilities is assumed to reduce car capacity. Such reduction is expressed as usable road ratio deduction (Burke & Scott, 2016), and as an exact change in upper limit value of vehicle per hour in bike-lane adding scenario (Mesbah, Thompson, & Moridpour, 2012). The trade-off of road space between road users is also quantified in the form of passenger car equivalent/unit considering 1 bike as 0.2 car (Asadi, Sarvi, & Wallace, 2016). Other than these approximate methods to describe overall travel-time impacts from road space allocation, microscopic simulation results at road and intersections can be input into a wide network for bikeway network design studies.

2.7 Summary

With the overall objective of analyzing and improving mobility services for residents. To provide the background information on the topic, I am investigating the long-term dynamics of the population distribution; I tried to understand the status quo of modal shares and how they will possibly change in the future. Among various transportation methods, I chose to pay attention to bicycles, e-bikes, and other transportation means. Road space is also in my scope because the growing ridership and various vehicle sizes and fleet characteristics can be problematic regarding safety, convenience, and traffic fairness.

Corresponding to the objectives, I reviewed studies on urban form metrics, bicycle convenience evaluation, cycling considered facilities, and bicycle-car mix traffic simulation. Research gaps are summarized as follows.

Regarding the classification of urban form, research on urban form at the global scale is rare. While the previous studies have revealed insights into the regional diversity of urban form, the number of target cities is restricted. Among urban form metrics, I chose Tsai's (2005) compactness metric of Gini and Moran's I using population distribution because it focuses on socio-economic but not environmental features, thus suitable for analyzing transportation usage, and its simplicity with only two metrics and the data required for the calculation is accessible.

Regarding bicycle convenience, while previous studies on bicycle convenience focused on the cycling environment, they are not specified to consider a new transport mode like e-bikes, which requires insights into their potential and limitations. Regarding e-biking, though studies confirmed the advantages of e-biking for saving physical energy consumption, there is no complete set of data on e-biking corresponding to different slopes, especially the Japanese-style electric assistant bicycle.

Regarding bicycle-considered road space and intersection design, cellular automata and microscopic models have proved useful tools for simulating bicycles. Although the studies simulate mixed traffic and road space re-allocation, a research gap also exists in comparing how different road space allocations affect efficiency involving e-bikes, and there is no discussion on a systematical strategy to separate them into different roads at a network scale.

I tried to fill these research gaps mentioned above in the studies in the following chapters.

3. Dynamics of intra-city population distribution and modal shares

3.1 Introduction

In this chapter, I tried to provide background information on mobility services by analyzing population distribution patterns. I aimed to classify the compactness in the population distribution patterns and find the correlation between them and the usage of different modes.

The concept of the "compact city" arose after the discussion on the issue of global warming at the UNCED in 1992. In Japan, the concept of "compact plus network" is the focus of future city ideal plans to create more comfortable urban areas under strict constraints of space, environment, and finance. The quantitative and time series analysis of urban form has been researched to investigate its relation to transportation mode choice, travel pattern, energy consumption, emission, and resilience (Anderson et al., 1996; Crane, 2000; Sharifi, 2018).

Despite the intense attention on the compact city, there is no general standard for its definition. As ends of urban form development continuums, compactness and sprawl are usually described as two antonyms. To measure compactness/sprawl quantitatively, metrics have been operationalized from the one-dimension variable of density to multi-dimensional systems, which compose of metrics from the perspectives including density, mix land-use, activity centering, and street connectivity (Arribas-bel et al., 2011; Ewing et al., 2002; Galster et al., 2001; Hamidi et al., 2015). The urban form metrics can be classified into two types: landscape metrics and socio-economic indicators (Schwarz, 2010). One of the methods to address the limitation in landscape metrics by investigating the intra-city population distribution structure is a socio-economic method employed by Tsai (2005).

Many inter-city urban form comparison studies have emerged in recent years. Studies conducted in Europe (Guérois & Pumain, 2008; Kasanko et al., 2006; Schwarz, 2010; Siedentop & Fina, 2012), Latin America (Inostroza et al., 2013), and China (Wu et al., 2015). Despite revealing insights into the regional diversity of urban form, the number of target cities is restricted by the lack of international comparative data and heterogeneity of data sources (Siedentop & Fina, 2012); thus, research on urban form at the global scale is rare.

3.2 Objective

With the overall objective of this thesis to finding ways to provide mobility services for residents. This chapter aims to provide background information that how are the intra-city population distributed, and how the distribution patterns of population can correlate with the usage of mobility services.

With the hope to fill the research gap in global urban form comparison, I conducted a comparison among cities worldwide, including Asia, Africa, Latin America and the Caribbean, Northern America, Europe, and Oceania, to provide insights into differences and similarities among worldwide urban form.

I analyzed the population distribution inside urbanized areas by applying four indices: population size, population density (pop/km2), the degree of equal distribution (Gini coefficient) and the degree of clustering (Moran coefficient). Cities were classified based on the indices. Next, I explored the regional distribution characteristics of these classifications, the relationship between classification and city population scales and the differences and similarities among regions. Then I looked at the long-term dynamics in urban form change.

Although the primary methodology is based on Tsai's (2005) work, I extends the number of target cities as well as the time range by using a global coverage population dataset, Global Human Settlement Layer (GHSL) (Schiavina et al., 2019). A latest urban area definition endorsed by UN Statistical Commission is employed as the data source. Cities in developing countries in Asia, Africa, Latin America and the Caribbean, which are rarely mentioned in previous studies are shed light on together with those in Northern America and Europe, thus bridge the gap in global city comparison and help to deepen the understanding of the urban forms.

In addition to the global comparison, I also zoomed in on the Japanese municipalities. Based on the Japanese cities, I analyzed the correlation between modal share and population distribution as detailed data on modal share is available.

Other than the goal to confirm the interaction between transportation and urban form, a comparison of urban form can help define the “compact city” and help with setting and assessing a city’s growth goal for compactness considering its own context.

3.3 Indices for urban form measurement

With the purpose to commit a global comparison, I attempted to find methods with small requirement of dataset that a global dataset can cover. Methods in (Tsai, 2005) stands out due to its simplicity of four indices required, the population size, population density (pop/km^2), the Moran's I for the degree of clustering, and the Gini coefficient to represent the degree of equal distribution.

Population density (*D*) expressed in Eq. (3.1), where *n* is the number of grid-cells in the urban area, p_i is the population in grid-cell *i*, and *A* is the total area in an extracted city. Density can be one of the most intuitive and factor in urban form (Churchman, 1999), and is widely used to measure compactness/sprawl (Ewing & Hamidi, 2015).

$$D = \frac{\sum_{i=1}^{n} p_i}{A} \tag{3.1}$$

The Global Moran's I statistic (*M*) is a measure of spatial autocorrelation. *M* is used to show how much densely (or sparsely) populated areas are accumulated. The *M* is expressed as Eq.(3.2) according to (Tsai, 2005),

$$M = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(p_i - \bar{p})(p_j - \bar{p})}{\sum_{i=1}^{n}(p_i - \bar{p})^2} \tag{3.2}$$

where *n* is the number of grid-cells in the urban area. w_{ij} denotes the spatial weighting between grid-cell *i* and *j*. p_j is the inhabitant in grid-cell *i*, and $\bar{p}$ is the average population within the city. Values of *M* are bounded by -1 and 1, where a complete dispersion is -1, and a unipolar concentration is 1. The Moran's I describes the spatial distribution pattern of population, single-center concentration, multinuclear concentration, or dispersion can lead to high, intermediate and low M values, and strip or discontinuous development can bring down the value, according to simulation analysis in (Tsai, 2005). Despite the capability of *M*, it alone cannot differentiate leapfrogging (a form of sprawl) from polycentric (compact). While both of them involve discontinuous centers, the former occurs among sparsely but the latter among rather densely populated surrounding area. Such cases require *D* and Gini coefficient (*G*) to cooperate in distinguishing leapfrog and polycentric.

The spatial weighting w_{ij} is calculated as reciprocal of the Euclidean distance between grid-cell centroids. I used distance-based criteria rather than contiguity-based ones after confirming the former works better to classify different clustering city forms in virtual samples. Euclidean distance is chosen here for morphology analysis, rather than Manhattan distance, which imitates network distance for analyzing functional features. For each city, all grid-cells are set to be a neighbor of all other cells without threshold distance, considering all cells in the applied urban boundary affect the morphology of urban center, thus and think of no rationale to weighting some distance of grid-cells in a different criterion. Although the scale effect, variability of results due to different sizes of spatial units, occurs when calculating *M* (Tsai, 2005). The effect can be diminished by using grid-cell dataset. Moran's I is calculated using ArcGIS 10.6.1.

The Gini coefficient (*G*), a commonly used measure of income or wealth inequality, is used as the degree of population distribution equality in this chapter. The *G* is expressed as Eq.(3.3) according to (Tsai, 2005), where *n* is the number of grid-cells in the urban area, a_i and p_i are respectively the cumulative ratio of area and population of grid-cell *i* to the whole urban area. The value range of the *G* is 0≤*G*≤1, when 0 is for most equal and 1 is for most unequal situations.

$$G = \frac{1}{2}\sum_{i=1}^{n}|a_i - p_i| \quad \textbf{(3.3)}$$

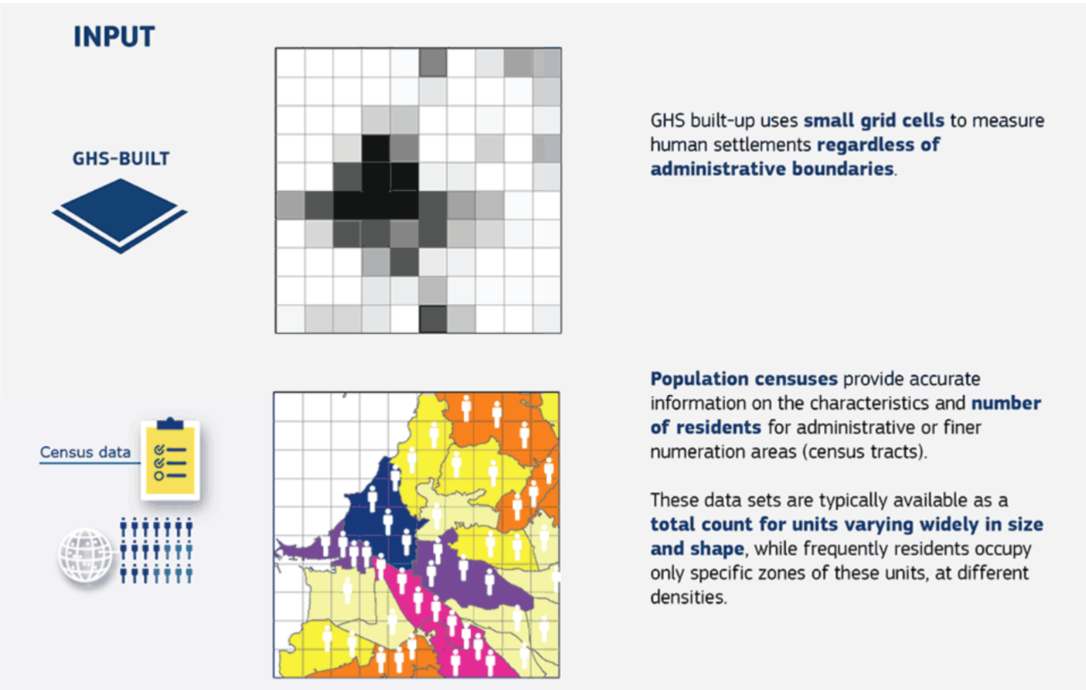
Although the concept of compact city refers to comprehensive characteristics of development patterns composing of aspects in population, land-use, transit systems, and distribution of job and service, in this work I mainly consider the population distribution characteristics. Considering compactness identify a dense and proximate development pattern, I consider high values of *D* (high density), *M* (monocentric, polycentric, continuity in development), and low values of *G* (evenly distribution) are in line with the concept of compactness to an extend.

3.4 World cities in 2015

In this chapter, the cities complying with the latest definition of urban centers in the OECD report are explored regarding their spatial characteristics, similarities, and differences using the population size, population density (*D*), degrees of equal distribution (*G*) and clustering (*M*) and the classification based on the *G* and *M* indices.

3.4.1 Data source and data processing

Using the population distribution to indicate human activity distribution, I applied population dataset to capture the urban form. To accomplish this comparison on a global scale, I exploited 1km^2 population grid-cell data for 2015 from the Global Human Settlement Layer (GHS-POP) (Schiavina et al., 2019). The data were generated by disaggregating the population census data for administrative areas in built-up areas extracted from satellite imagery (Figure 3-1). With its worldwide coverage, this dataset provides a chance to look at cities from a global point of view.



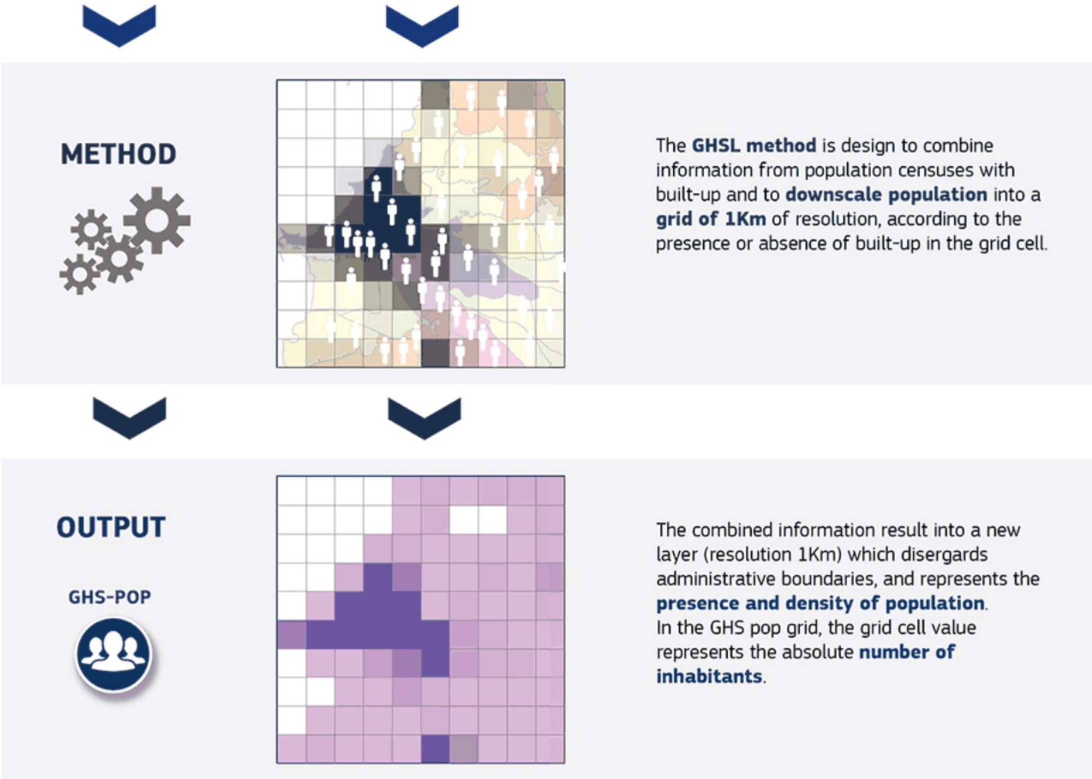


Figure 3-1 Data process by GHSL

(retrieved from https://ghsl.jrc.ec.europa.eu/data.php)

Clear criteria are necessary to delineate the urban boundary from the grid-cell dataset. Though some research used political boundaries (Sun et al., 2012; Tsai, 2005; Wu et al., 2015), the weakness of this approach is that such boundaries probably do not coincide with the real geographical limits of urban areas when the built-up area extends into the periphery suburban area, or the city authority claims agricultural area within its boundary, or adjacent cities converge into one urbanized area. The United Nations (2018: 4) endeavored to use the boundary of "urban agglomeration" rather than administrative ones. However, the residential density criteria remained debatable, as urban land consumption per person varies greatly by region. While average built-up land per person in sample cities in south and central Asia was 47 m^2 in 2014, the value in their counterpart in land-rich developed countries was 426 m^2 (Bertaud, 2018). Despite the diversity, in a cross-nation study on functional urban areas in 29 countries and 1,179 urban areas, the population density threshold for city core is set to 1,000 inhabitants/km^2 for the United States and Canada, and 1,500 for other countries (OECD, 2012b: 26). Recently, the UN Statistical Commission endorsed a methodology to classify degree of urbanization for international and regional comparison purpose (OECD et al., 2021). Three grid cell classifications are urban centers (high-density clusters), urban clusters (moderate density clusters), and rural grid cells (mostly low-density cells).

Here, I used this latest definition of urban centers in this report as our study target areas. Urban centers are defined to have population of at least 50,000, consisting of contiguous dense grid cells with population density over 1,500 inhabitants/km2. In the resulted clusters gaps are filled and edges are smoothed, and 50% built-up grid-cells can be added when necessary. Applied the degree of urbanization classification, GHSL released urban centers database (GHS-UCDB) (Florczyk et al., 2019) to their baseline data.

Data processing procedure based on GHS-POP and GHS-UCDB for extracting cities is as follows (Figure 3-2).

(1) For further data processing, every grid-cell in GHS-POP data (raster data) is converted into a point (vector data) at each cell's centroid.

(2) Points within urban centers in GHS-UCDB are extracted.

(3) Areas equal or larger than 30 km^2 were selected for analysis because I considered the GHS data likely to contain errors due to wrongly downscaling the total population of a large area to small grid-cells. To exclude areas where such errors are relatively large, and to consider the reliability of the calculation result of the Moran's I, the threshold of an urbanized area of 30km^2 (30 grid-cells) was set.

(4) Naming of the extracted cities follows that in GHS-UCDB dataset. For visualization, each city is represented by a mean center point of the group of extracted GHS-POP points and weighted by population.

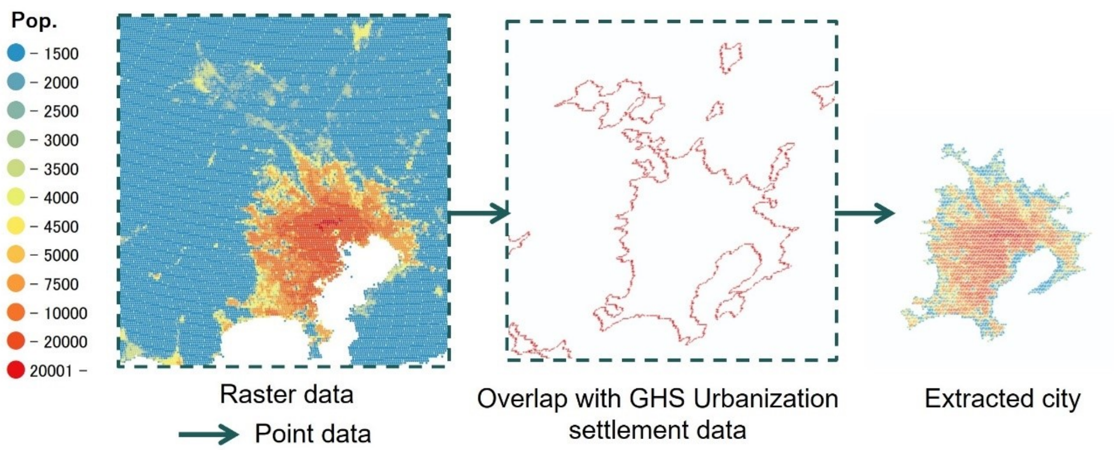


Figure 3-2 Process to extract a target city

Four thousand and eighty-eight urban areas were extracted. Figure 3-3 depicts the 2015 population distribution of some sample cities. The continuous area standard is applied regardless of political boundaries. For example, the city polygon labeled Guangzhou crosses several administrative cities including Guangzhou, Foshan, Dongguan, and Shenzhen, while the area labeled Hong Kong excludes Sha Tin, which is administratively a district in Hong Kong, because the mountainous area in between does not meet the density standard.

Pattern differences in coverage, population density, equal distribution, and clustering, among cities can be seen visually. There are cities like Guangzhou and Jakarta have a wide territory, as well as relatively small coverage ones like Haifa and Fez. While Cairo, Sao Paulo, and New Delhi have overall high population density, residents in Dallas, Oslo, and Melbourne sparsely distribute. While inhabited and less populated cells in New York and Manila, have obvious variation, population distributes evenly in Riyadh, Berlin, and Prague. While there is one explicit center in Tokyo, Mombasa, Hong Kong, and Guadalajara tend to have several clusters throughout the cities. The classification methods labeled below each city name will be explained in next section.

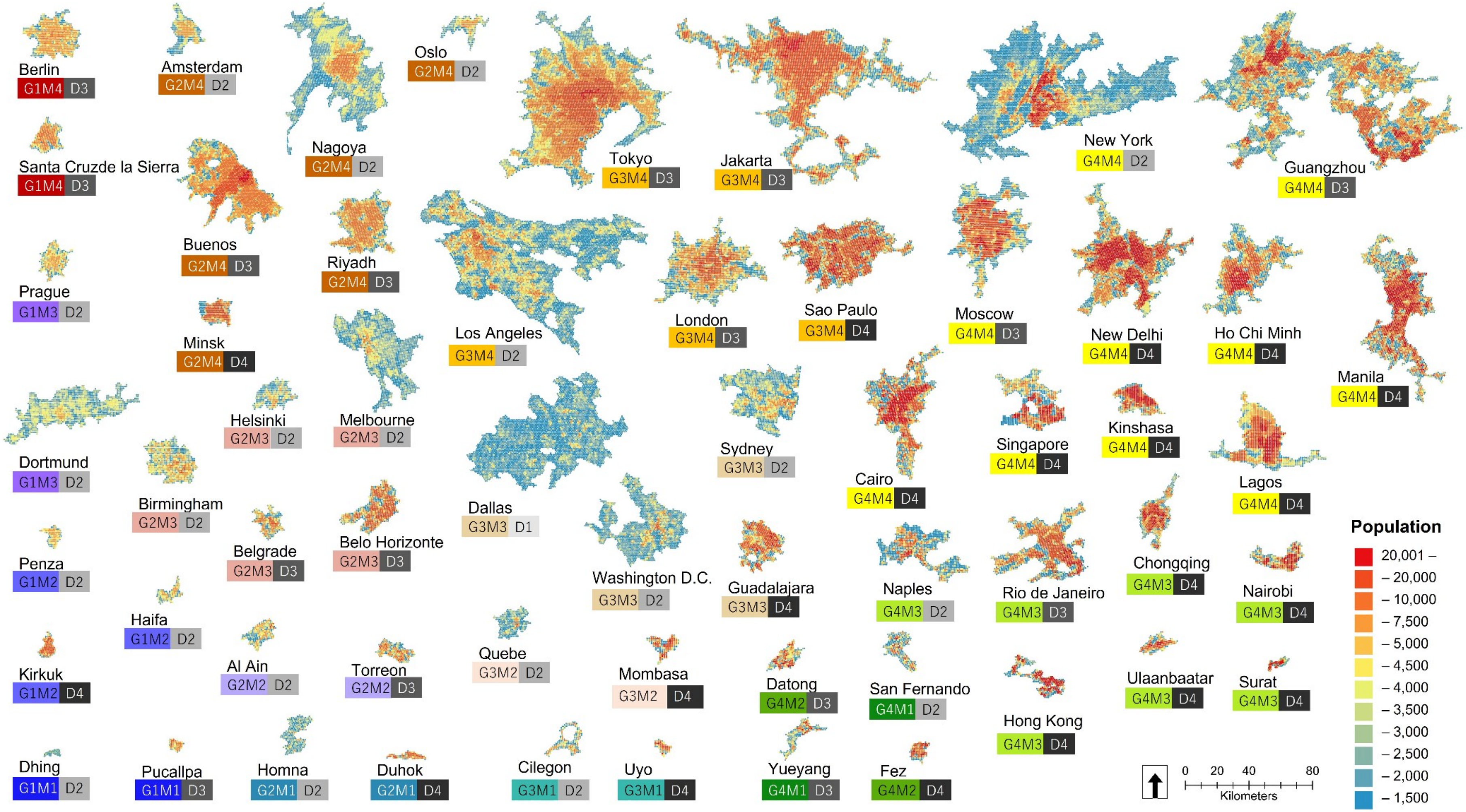


Figure 3-3 Population distribution in sample cities in 2015

(together with the classification results).

Table 3-1 Sample of extracted major worldwide cities, in population size descending order.

Name	Pop. (k)	Area (km^2)	Density ($pop./km^2$)	Moran	Gini	Class	
Guangzhou (China)	40,575	6,592	6,155	0.721	0.536	G4M4	D3
Jakarta (Indonesia)	36,309	5,001	7,260	0.812	0.438	G3M4	D3
Tokyo (Japan)	33,025	5,318	6,210	0.887	0.385	G3M4	D3
New Delhi (India)	26,632	2,474	10,765	0.826	0.518	G4M4	D4
Shanghai (China)	24,468	3,309	7,394	0.802	0.557	G4M4	D3
Dhaka (Bangladesh)	23,942	3,248	7,371	0.812	0.646	G4M4	D3
Mumbai (India)	21,751	1,060	20,520	0.720	0.552	G4M4	D4
Manila (Philippines)	21,691	2,023	10,722	0.627	0.565	G4M4	D4
Kolkata (India)	21,613	2,816	7,675	0.820	0.644	G4M4	D4
Seoul (South Korea)	21,597	2,438	8,859	0.742	0.500	G4M4	D4
Cairo (Egypt)	19,730	1,585	12,448	0.827	0.628	G4M4	D4
Mexico City (Mexico)	19,560	2,114	9,253	0.650	0.433	G3M4	D4
São Paulo (Brazil)	19,114	2,005	9,533	0.631	0.406	G3M4	D4
Beijing (China)	17,980	2,115	8,501	0.742	0.545	G4M4	D4
New York (US)	15,951	5,337	2,989	0.742	0.629	G4M4	D2
Osaka (Japan)	15,689	3,158	4,968	0.840	0.387	G3M4	D3
Bangkok (Thailand)	14,721	2,568	5,733	0.816	0.425	G3M4	D3
Los Angeles (US)	14,282	5,608	2,547	0.674	0.446	G3M4	D2
Istanbul (Turkey)	14,106	1,300	10,851	0.842	0.535	G4M4	D4
Moscow (Russia)	14,075	1,882	7,479	0.790	0.484	G4M4	D3
Buenos Aires (Argentina)	13,901	1,965	7,074	0.819	0.337	G2M4	D3
Karachi (Pakistan)	13,144	751	17,502	0.822	0.507	G4M4	D4
Tehran (Iran)	12,493	1,382	9,040	0.770	0.446	G3M4	D4
Lagos (Nigeria)	11,566	1,196	9,670	0.852	0.511	G4M4	D4
Ho Chi Minh (Vietnam)	11,488	1,467	7,831	0.891	0.565	G4M4	D4
Bengaluru (India)	10,625	628	16,918	0.796	0.590	G4M4	D4
Jieyang (China)	10,441	2,448	4,265	0.638	0.466	G3M4	D2
Lahore (Pakistan)	10,130	955	10,607	0.721	0.466	G3M4	D4
Chennai (India)	9,991	939	10,640	0.722	0.501	G4M4	D4
Rio de Janeiro (Brazil)	9,798	1,349	7,263	0.546	0.488	G4M3	D3
Paris (France)	9,711	1,638	5,929	0.898	0.467	G3M4	D3
London (UK)	9,610	1,863	5,158	0.747	0.421	G3M4	D3
Chengdu (China)	9,320	1,326	7,028	0.680	0.503	G4M4	D3
Lima (Peru)	9,264	874	10,600	0.721	0.456	G3M4	D4
New Taipei (Taiwan)	8,872	1,013	8,758	0.749	0.536	G4M4	D4
Suzhou (China)	8,627	1,893	4,557	0.658	0.497	G4M4	D3
Bogota (Colombia)	8,608	538	16,001	0.627	0.401	G3M4	D4
Surabaya (Indonesia)	8,342	1,751	4,764	0.797	0.473	G3M4	D3
Bandung (Indonesia)	8,183	1,014	8,070	0.870	0.511	G4M4	D4
Hyderabad (India)	8,131	874	9,304	0.744	0.487	G4M4	D4
Nagoya (Japan)	7,664	2,651	2,891	0.845	0.351	G2M4	D2
Hangzhou (China)	7,526	1,679	4,483	0.639	0.521	G4M4	D2
Wuhan (China)	7,340	838	8,759	0.717	0.611	G4M4	D4
Singapore(Singapore)	6,913	857	8,067	0.687	0.578	G4M4	D4
Chicago (US)	6,780	3,830	1,770	0.720	0.510	G4M4	D2
Luanda (Angola)	6,760	757	8,930	0.848	0.445	G3M4	D4
Ahmedabad (India)	6,672	363	18,379	0.836	0.519	G4M4	D4
Pune (India)	6,659	634	10,503	0.748	0.539	G4M4	D4
Tianjin (China)	6,640	698	9,513	0.704	0.658	G4M4	D4
Johannesburg (South Africa)	6,516	1,638	3,978	0.654	0.547	G4M4	D2
Kuala Lumpur (Malaysia)	6,333	1,327	4,772	0.745	0.328	G2M4	D3
Santiago (Chile)	6,330	720	8,792	0.675	0.418	G3M4	D4
Comilla (Bangladesh)	6,171	2,491	2,477	0.517	0.366	G2M3	D2
Toronto (Canada)	6,036	2,019	2,990	0.599	0.475	G3M4	D2
Khartoum (Sudan)	5,845	750	7,794	0.666	0.424	G3M4	D4
Hong Kong (China)	5,707	331	17,243	0.415	0.655	G4M3	D4
Yangon (Myanmar)	5,685	521	10,912	0.585	0.434	G3M4	D4
Riyadh (Saudi Arabia)	5,656	1,016	5,567	0.697	0.277	G2M4	D3
Kinshasa (Congo)	5,621	383	14,675	0.720	0.529	G4M4	D4
Alexandria (Egypt)	5,532	586	9,441	0.753	0.624	G4M4	D4
Baghdad (Iraq)	5,357	787	6,807	0.681	0.341	G2M4	D3
Dar es Salaam (Tanzania)	5,346	660	8,100	0.807	0.514	G4M4	D4
Madrid (Spain)	4,894	781	6,266	0.755	0.427	G3M4	D3
Dubai (UAE)	4,888	763	6,406	0.665	0.416	G3M4	D3
Abidjan (Côte d'Ivoire)	4,551	431	10,560	0.714	0.484	G4M4	D4
Tijuana (Mexico)	4,437	1,755	2,528	0.663	0.480	G3M4	D2
Accra (Ghana)	4,406	844	5,221	0.838	0.455	G3M4	D3
Kabul (Afghanistan)	4,383	321	13,655	0.698	0.457	G3M4	D4
Colombo (Sri Lanka)	4,303	1,151	3,739	0.659	0.404	G3M4	D2
Casablanca (Morocco)	3,987	391	10,197	0.651	0.519	G4M4	D4
Nairobi (Kenya)	3,986	337	11,828	0.486	0.578	G4M3	D4
Algiers (Algeria)	3,856	713	5,408	0.673	0.494	G4M4	D3
Santo Domingo (Dominica)	3,847	510	7,542	0.663	0.395	G3M4	D4
Addis Ababa (Ethiopia)	3,833	392	9,779	0.747	0.455	G3M4	D4
Sydney (Australia)	3,745	1,345	2,785	0.534	0.377	G3M3	D2
Amman (Jordan)	3,670	542	6,772	0.757	0.426	G3M4	D3
Kathmandu (Nepal)	3,529	271	13,023	0.755	0.575	G4M4	D4
Kampala (Uganda)	3,484	528	6,599	0.635	0.378	G3M4	D3
Yaounde (Cameroon)	3,463	251	13,798	0.828	0.438	G3M4	D4
Dortmund (Germany)	3,443	1,315	2,618	0.516	0.239	G1M3	D2
Dakar (Senegal)	3,355	269	12,470	0.667	0.381	G3M4	D4
Athens (Greece)	3,315	431	7,691	0.797	0.414	G3M4	D4

Berlin (Germany)	3,271	686	4,769	0.655	0.242	G1M4	D3
Naples (Italy)	3,168	882	3,591	0.571	0.589	G4M3	D2
Kuwait City (Kuwait)	3,162	472	6,699	0.745	0.353	G2M4	D3
Tashkent (Uzbekistan)	3,154	504	6,257	0.634	0.610	G4M4	D3
Caracas (Venezuela)	3,104	330	9,405	0.622	0.459	G3M4	D4
Mbuji-Mayi (Congo)	3,024	134	22,566	0.712	0.431	G3M4	D4
Bamako (Mali)	2,971	332	8,948	0.587	0.461	G3M4	D4
Port-au-Prince (Haiti)	2,769	279	9,925	0.749	0.522	G4M4	D4
Kyiv (Ukraine)	2,736	518	5,282	0.697	0.376	G3M4	D3
Guayaquil (Ecuador)	2,734	301	9,085	0.686	0.432	G3M4	D4
Damascus (Syria)	2,706	321	8,429	0.763	0.461	G3M4	D4
Ouagadougou (Burkina Faso)	2,704	345	7,837	0.605	0.352	G2M4	D4
Guatemala City (Guatemala)	2,670	411	6,496	0.552	0.411	G3M3	D3
Sana'a (Yemen)	2,542	198	12,836	0.677	0.503	G4M4	D4
Conakry (Guinea)	2,469	297	8,314	0.641	0.448	G3M4	D4
Beirut (Lebanon)	2,463	252	9,775	0.810	0.661	G4M4	D4
Pyongyang (North Korea)	2,439	252	9,677	0.612	0.423	G3M4	D4
Maputo (Mozambique)	2,428	418	5,808	0.714	0.452	G3M4	D3
Lusaka (Zambia)	2,384	309	7,714	0.670	0.412	G3M4	D4
Tel Aviv (Israel)	2,361	477	4,949	0.709	0.441	G3M4	D3
Antananarivo (Madagascar)	2,148	258	8,326	0.419	0.582	G4M3	D4
Lomé (Togo;Ghana)	2,143	313	6,848	0.578	0.381	G3M3	D3
Minsk (Belarus)	2,007	265	7,572	0.668	0.353	G2M4	D4
Asuncion (Paraguay)	1,968	442	4,452	0.630	0.296	G2M4	D2
Baku (Azerbaijan)	1,960	328	5,976	0.681	0.375	G3M4	D3
Lisbon (Portugal)	1,959	435	4,502	0.421	0.471	G3M3	D2
Harare (Zimbabwe)	1,932	486	3,976	0.572	0.312	G2M3	D2
Rotterdam (Netherlands)	1,914	658	2,908	0.719	0.348	G2M4	D2
San José (Costa Rica)	1,861	431	4,318	0.620	0.361	G2M4	D2
Vienna (Austria)	1,857	392	4,736	0.747	0.333	G2M4	D3
Havana (Cuba)	1,839	432	4,256	0.537	0.432	G3M3	D2
Phnom Penh (Cambodia)	1,815	263	6,901	0.734	0.557	G4M4	D3
Warsaw (Poland)	1,789	425	4,209	0.668	0.353	G2M4	D2
Bucharest (Romania)	1,773	252	7,037	0.656	0.350	G2M4	D3
Budapest (Hungary)	1,758	433	4,061	0.770	0.386	G3M4	D2
Cotonou (Benin)	1,752	296	5,919	0.760	0.428	G3M4	D3
Almaty (Kazakhstan)	1,730	318	5,441	0.711	0.303	G2M4	D3
Gaza (Palestina)	1,706	271	6,294	0.706	0.439	G3M4	D3
El Alto [La Paz] (Bolivia)	1,700	253	6,721	0.614	0.332	G2M4	D3
San Salvador (El Salvador)	1,674	287	5,832	0.469	0.399	G3M3	D3
Brazzaville (Congo)	1,633	134	12,184	0.728	0.556	G4M4	D4

Santa Cruz de la Sierra (Bolivia)	1,554	281	5,532	0.623	0.265	G1M4	D3
Doha (Qatar)	1,554	372	4,178	0.700	0.500	G4M4	D2
Jerusalem (Israel)	1,514	272	5,566	0.735	0.510	G4M4	D3
Monrovia (Liberia)	1,420	252	5,636	0.529	0.403	G3M3	D3
Campinas (Brazil)	1,397	333	4,194	0.367	0.384	G3M2	D2
Brussels (Belgium)	1,381	266	5,193	0.810	0.464	G3M4	D3
Ulaanbaatar (Mongolia)	1,315	166	7,924	0.582	0.490	G4M3	D4
Montevideo (Uruguay)	1,311	231	5,674	0.613	0.389	G3M4	D3
Stockholm (Sweden)	1,305	360	3,624	0.626	0.399	G3M4	D2
Manama (Bahrain)	1,247	315	3,959	0.604	0.409	G3M4	D2
Copenhagen (Denmark)	1,226	375	3,269	0.766	0.469	G3M4	D2
Fez (Morocco)	1,194	113	10,563	0.336	0.488	G4M2	D4
Managua (Nicaragua)	1,144	210	5,450	0.704	0.391	G3M4	D3
Yerevan (Armenia)	1,133	191	5,930	0.540	0.406	G3M3	D3
Tripoli (Libya)	1,132	419	2,701	0.680	0.239	G1M4	D2
Prague (Czech)	1,126	295	3,818	0.408	0.246	G1M3	D2
Panama City (Panama)	1,119	221	5,062	0.440	0.412	G3M3	D3
Kigali (Rwanda)	1,118	215	5,201	0.492	0.402	G3M3	D3
Bishkek (Kyrgyzstan)	1,118	156	7,167	0.821	0.557	G4M4	D3
Nouakchott (Mauritania)	1,116	134	8,331	0.504	0.435	G3M3	D4
Niamey (Niger)	1,112	113	9,841	0.552	0.366	G2M3	D4
Belgrade (Serbia)	1,106	237	4,669	0.538	0.371	G2M3	D3
Tbilisi (Georgia)	1,078	132	8,164	0.517	0.392	G3M3	D4
Dushanbe (Tajikistan)	1,064	144	7,387	0.773	0.476	G3M4	D3
Angeles (Philippines)	1,056	263	4,016	0.223	0.527	G4M1	D2
Mombasa (Kenya)	1,034	132	7,836	0.391	0.478	G3M2	D4
Auckland (New Zealand)	1,034	451	2,293	0.465	0.333	G2M3	D2
Bangui (Central Africa)	1,024	103	9,942	0.545	0.480	G3M3	D4
Kingston (Jamaica)	1,017	233	4,366	0.603	0.321	G2M4	D2
Dandong (China)	1,006	110	9,148	0.501	0.573	G4M3	D4
Dublin (Ireland)	1,004	291	3,451	0.566	0.337	G2M3	D2
Tegucigalpa (Honduras)	995	141	7,058	0.655	0.324	G2M4	D3
San Juan (Puerto Rico)	970	373	2,599	0.514	0.377	G3M3	D2
Sofia (Bulgaria)	927	205	4,524	0.531	0.288	G2M3	D2
Helsinki (Finland)	907	337	2,691	0.498	0.363	G2M3	D2
Bujumbura (Burundi)	900	104	8,659	0.447	0.528	G4M3	D4
Huangshi (China)	896	201	4,459	0.223	0.511	G4M1	D2
Kirkuk (Iraq)	833	109	7,638	0.402	0.252	G1M2	D4
Bukavu (Congo)	825	64	12,888	0.343	0.575	G4M2	D4
Ashgabat (Turkmenistan)	803	119	6,749	0.659	0.368	G2M4	D3
Lilongwe (Malawi)	792	127	6,235	0.486	0.459	G3M3	D3
Oslo (Norway)	782	240	3,258	0.644	0.321	G2M4	D2
Al Ain (UAE)	779	224	3,477	0.371	0.335	G2M2	D2

Sambhal (India)	740	32	23,137	0.293	0.626	G4M2	D4
Zurich (Switzerland)	732	257	2,850	0.652	0.426	G3M4	D2
Serrekunda (Gambia)	728	124	5,868	0.613	0.367	G2M4	D3
Tirana (Albania)	719	106	6,783	0.691	0.418	G3M4	D3
Zagreb (Croatia)	660	203	3,253	0.596	0.308	G2M4	D2
Cúcuta (Colombia)	652	80	8,151	0.448	0.333	G2M3	D4
Asmara (Eritrea)	644	46	13,997	0.511	0.495	G4M3	D4
Uyo (Nigeria)	619	67	9,239	0.061	0.477	G3M1	D4
Cilegon (Indonesia)	618	191	3,234	0.141	0.377	G3M1	D2
Duhok (Iraq)	589	78	7,551	0.150	0.325	G2M1	D4
Quebec (Canada)	582	285	2,042	0.380	0.427	G3M2	D2
Homna (Bangladesh)	571	269	2,121	0.080	0.330	G2M1	D2
Riga (Latvia)	556	165	3,373	0.522	0.317	G2M3	D2
Port Louis (Mauritius)	545	144	3,783	0.400	0.366	G2M2	D2
Bacolod (Philippines)	540	96	5,624	0.204	0.451	G3M1	D3
Libreville (Gabon)	536	115	4,664	0.547	0.363	G2M3	D3
Bissau (Guinea-Bissau)	501	61	8,220	0.374	0.333	G2M2	D4
Bakhtiyarpur (India)	494	59	8,377	0.414	0.501	G4M3	D4
Djibouti (Djibouti)	475	32	14,831	0.287	0.546	G4M2	D4
Juba (South Sudan)	468	75	6,235	0.479	0.312	G2M3	D3
Chişinău (Moldova)	460	120	3,837	0.494	0.237	G1M3	D2
San Juan (Argentina)	442	98	4,506	0.238	0.262	G1M2	D2
Seeb (Oman)	439	103	4,264	0.453	0.327	G2M3	D2
Dhing (India)	436	205	2,129	0.111	0.256	G1M1	D2
Haifa (Israel)	429	125	3,430	0.258	0.268	G1M2	D2
Skopje (Macedonia)	427	112	3,817	0.499	0.400	G3M3	D2
Thiès (Senegal)	425	43	9,887	0.207	0.294	G2M1	D4
Shibin Al-Kom (Egypt)	419	53	7,911	0.329	0.487	G4M2	D4
Vientiane (Laos)	407	122	3,336	0.284	0.361	G2M2	D2
Windhoek (Namibia)	366	80	4,574	0.661	0.483	G4M4	D3
Gembongan (Indonesia)	358	166	2,159	0.185	0.215	G1M1	D2

3.4.2 Results by indices in 2015

D, *G* and *M* were calculated for each extracted urban agglomeration. Table 3-1 shows the details of some sample cities ranked by population in 2015. To confirm that the indices reflect different aspects of the urban structure, the correlation coefficients were tested pairwise. Most of the results, correlation coefficients of M and G (0.313), M and D (0.253), M and P (0.343), G and P (0.231), D and G (0.260), G and D (0.514), are smaller than 0.35 with one exception smaller than 0.67. Such results present weak or moderate correlations between indicators, suggesting their independence. Table 3-2 summarizes the statics of counts and ratios in categories.

Table 3-2 Summary of city counts and ratios in categories by indicators, population size, population density, Gini, and Moran's I.

Region classifications are according to GHS-UCDB dataset.

		P						D				G				M			
		P1	P2	P3	P4	P5	P6	D1	D2	D3	D4	G1	G2	G3	G4	M1	M2	M3	M4
Africa	N	12	176	160	42	20	2	1	127	164	120	31	145	141	95	65	135	150	62
	%	3%	43%	39%	10%	5%	0%	0%	31%	40%	29%	8%	35%	34%	23%	16%	33%	36%	15%
Asia	N	227	1105	668	179	62	20	18	1276	619	348	290	651	806	514	398	645	831	387
	%	10%	49%	30%	8%	3%	1%	1%	56%	27%	15%	13%	29%	36%	23%	18%	29%	37%	17%
Europe	N	115	335	145	34	10	1	9	573	54	4	243	276	87	34	89	180	267	104
	%	18%	52%	23%	5%	2%	0%	1%	90%	8%	1%	38%	43%	14%	5%	14%	28%	42%	16%
Latin America and the Caribbean	N	10	192	127	39	13	3	2	174	168	40	34	214	124	12	80	140	124	40
	%	3%	50%	33%	10%	3%	1%	1%	45%	44%	10%	9%	56%	32%	3%	21%	36%	32%	10%
Northern America	N	146	131	43	21	12	2	228	127	0	0	49	177	109	20	45	124	153	33
	%	41%	37%	12%	6%	3%	1%	64%	36%	0%	0%	14%	50%	31%	6%	13%	35%	43%	9%
Oceania	N	16	13	3	2	2	0	13	22	1	0	9	20	7	0	11	11	14	0
	%	44%	36%	8%	6%	6%	0%	36%	61%	3%	0%	25%	56%	19%	0%	31%	31%	39%	0%

World maps in Figure 3-4, Figure 3-5 and Figure 3-6 depict the results of *D, G,* and *M* of all sample cities in circles, with their centers represent the population-weighted mean centers, and circle areas proportional to population size. Regarding *D* (Figure 3-4), the densest cities cluster in Indian subcontinent, appear in African tropical zone, western coastal in South America, while the cities with lowest density are in North America, Europe, Oceania, and Japan. Regarding *G* (Figure 3-5), cities with low values tend to cluster in Europe, Japan, northern China, and Bangladesh, suggesting that the population is relatively evenly distributed. In contrast, cities in China and South Asia, large cities in Africa and around Mediterranean Sea tend to have unequal urban spatial structures. Cities in North and South

America, Mesoamerica, Middle East, and Southeast Asia are in between. Regarding the results of *M* (Figure 3-6), among cities nearby, populated cities tend to show a relatively higher degree of clustering than ones with fewer inhabitants.

3.4.3 Classification based on indices in 2015

The classification methods are as follows. The mean of *D* is 4,550 pop/km^2 with a standard deviation of 2,936 pop/km^2, and that of *G* and *M* are 0.374 (0.106), and 0.405 (0.180) respectively. The average density is similar to the threshold of Densely Inhabited District (DID) in Japanese cities that DID should contains continuous areas with population density of 4,000 pop/km^2 or denser, and the total population should be over 5,000. Using the values of two indices *G* and *M*, cities are plotted in a scatter diagram along two axes of *G* and *M* (Figure 3(a)). Each axis is divided into four parts at mean and mean ± standard, creating 16 types. The four parts in *G* and *M* are nominated respectively as G1-G4 and M1-M4 from small to large values. Using the same method to group *G* and *M, D* is divided into four groups nominated as D1-D4. In the dimension of population size, 6 groups are divided according to Table 3-3. The type of P0 with range of less than 50,000 persons/km^2 is absent because the threshold of urban centers is set to have population of at least 50,000.

Table 3-3 City groups by population size

Type	Range (persons/km^2)
P6	10,000,000 -
P5	3,000,000 - 10,000,000
P4	1,000,000 - 3,000,000
P3	300,000 - 1,000,000
P2	100,000 - 300,000
P1	50,000 - 100,000

To capture general statistical characteristics between indicators, M-G plots for 6 population classes and those for the 4 density classes are shown in Figure 3-6(b) and (c), which also show the difference of *M* and *G* mean (± standard) between classes. On average, *G* and *M* tend to be large in cities with large population size (Figure 3-6 (b)). In Figure 3-6 (c), as density increases from D2 to D4, M and G increase as well. Results suggest that more concentrated, and unequal population distribution appear correlated with larger population size and density.

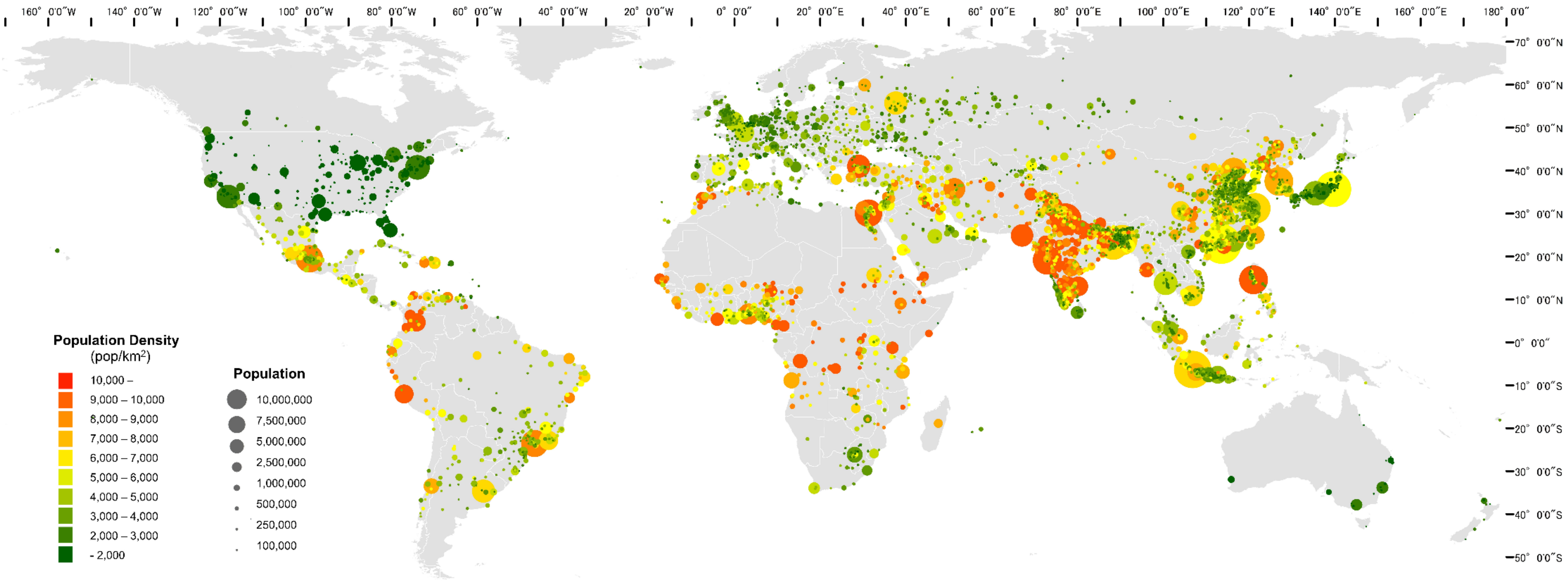


Figure 3-4 Population density in major cities in 2015

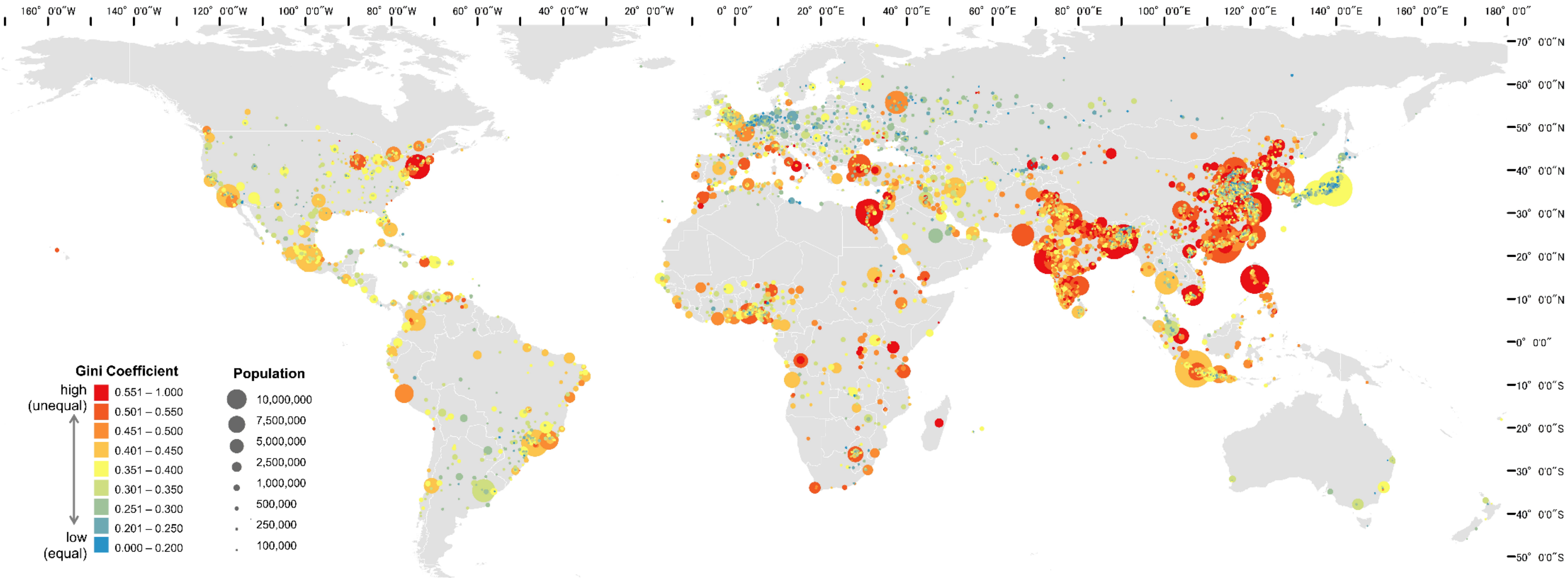


Figure 3-5 Gini coefficients for major cities in 2015

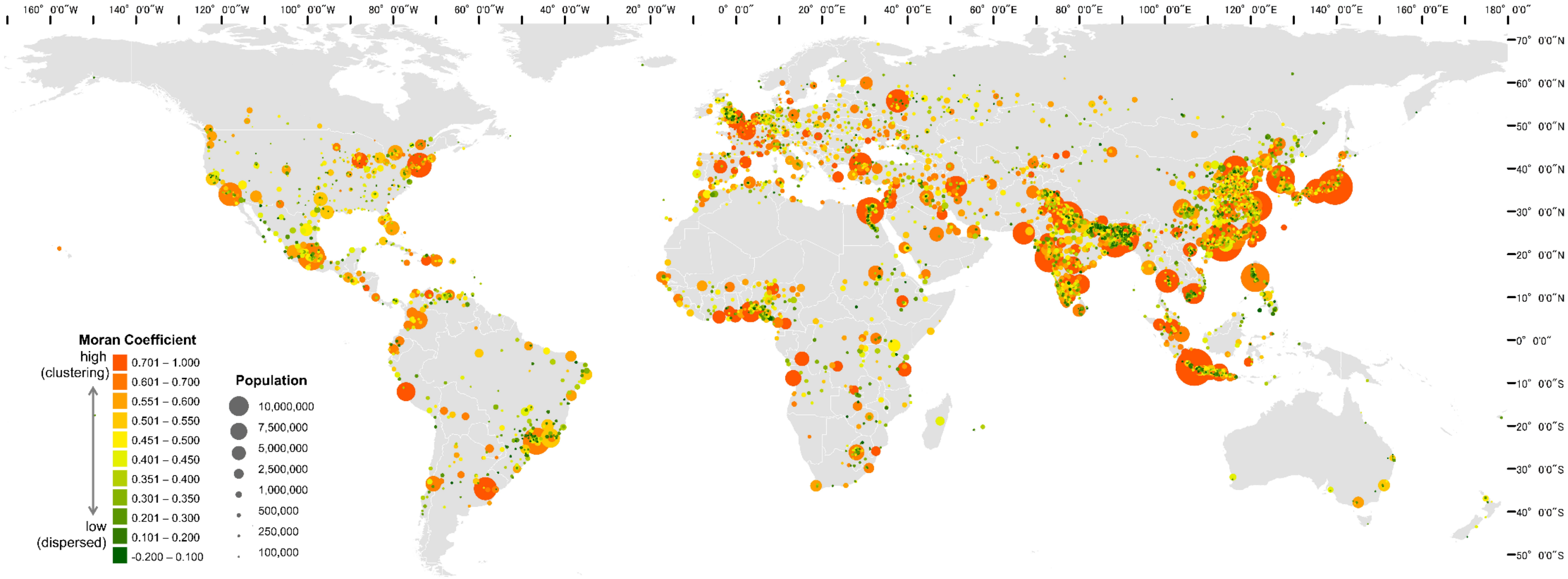


Figure 3-6 Moran coefficients for major cities in 2015

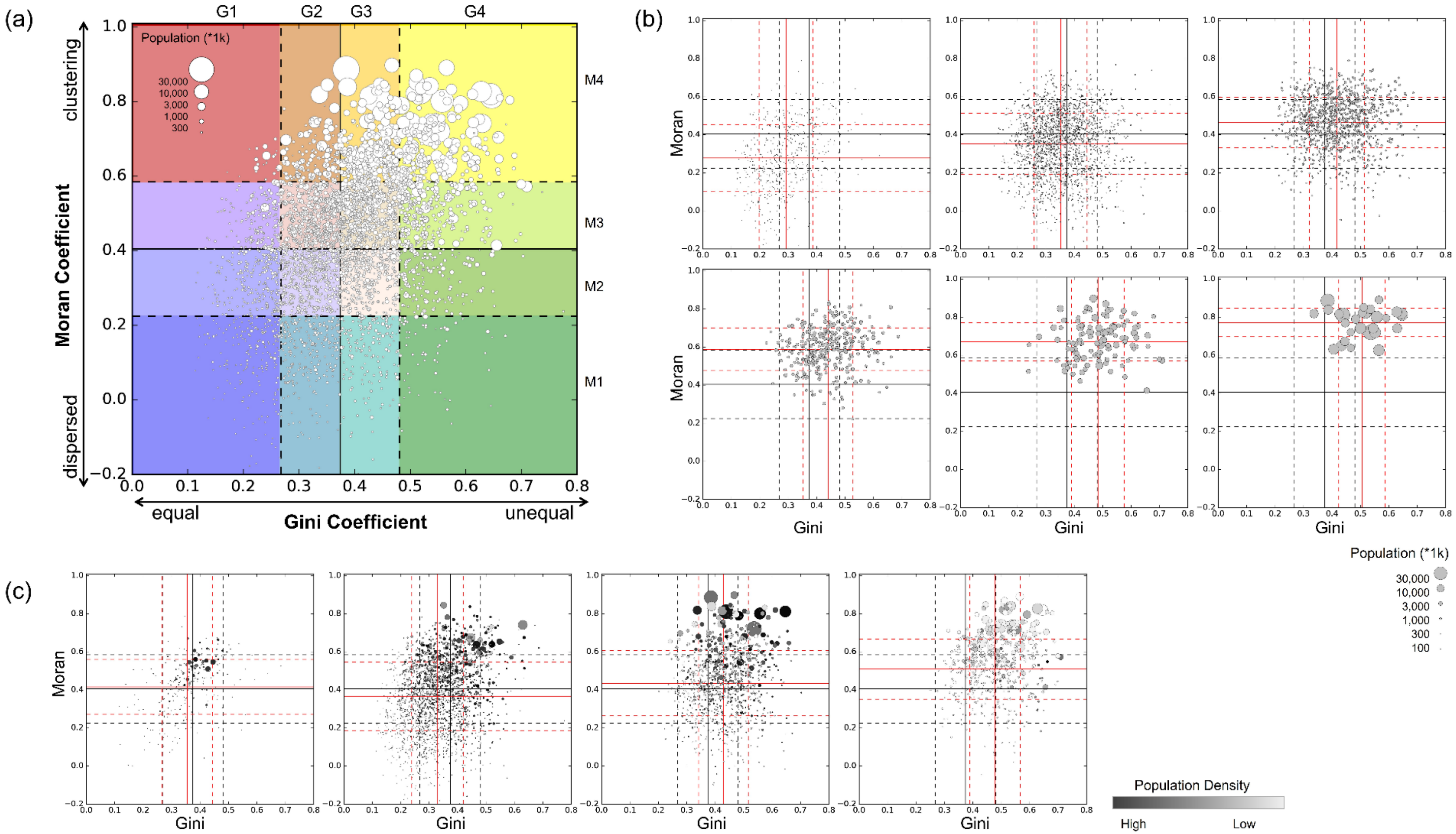


Figure 3-7 Scatter plot diagram for Gini and Moran coefficients based on the population of cities in 2015.

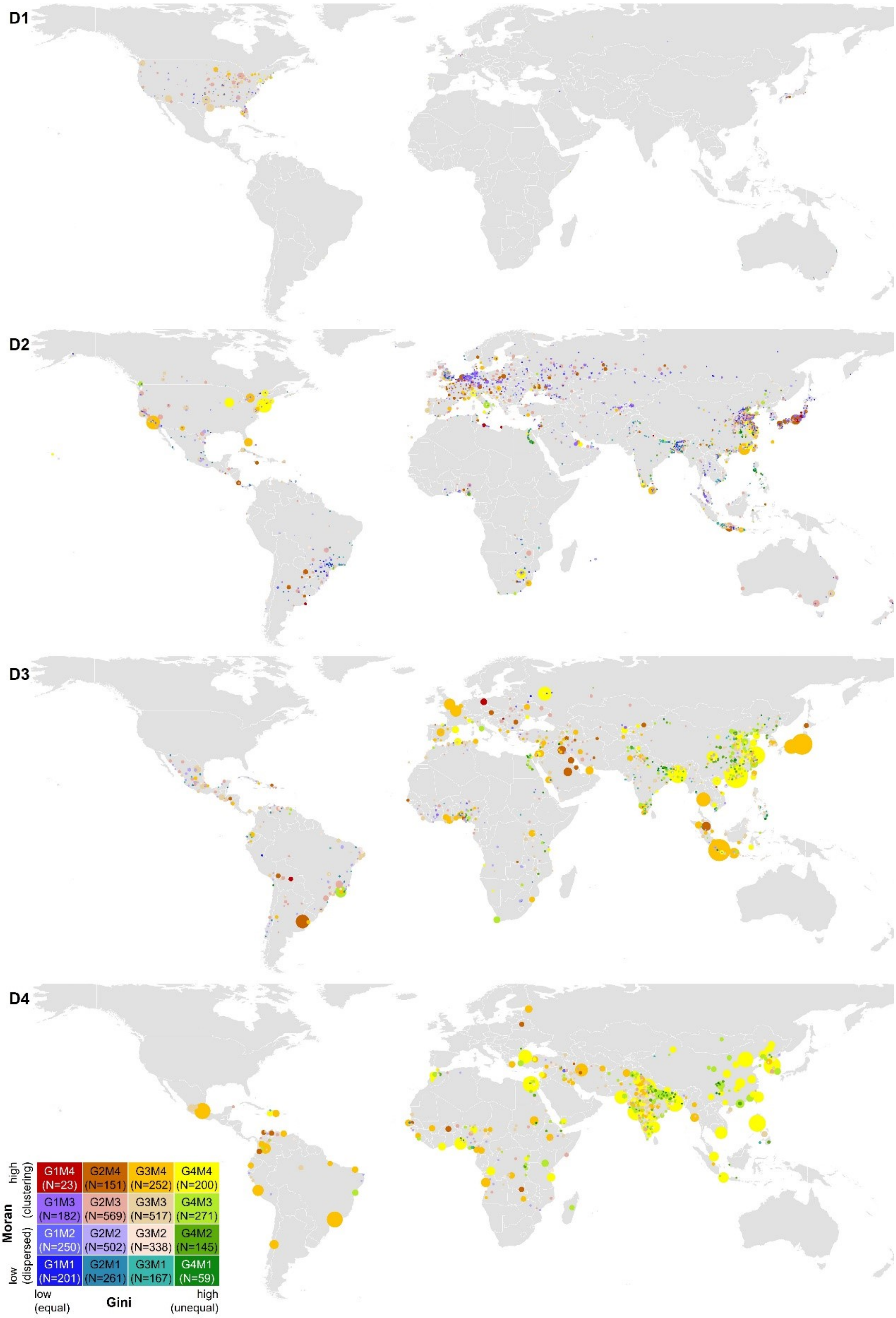


Figure 3-8 Mapping urban form classifications by population density.

Figure 3-9 shows the city composition ratio among the 6 population groups in each urban form class, indicating that a large M (strong agglomeration tendency) is related to a high ratio of large cities. Among cities with a large M, large G values tend to connect to a larger proportion of large and middle size cities. Such results are in line with the positive correlation coefficient between P, D, G, and D shown in previous section.

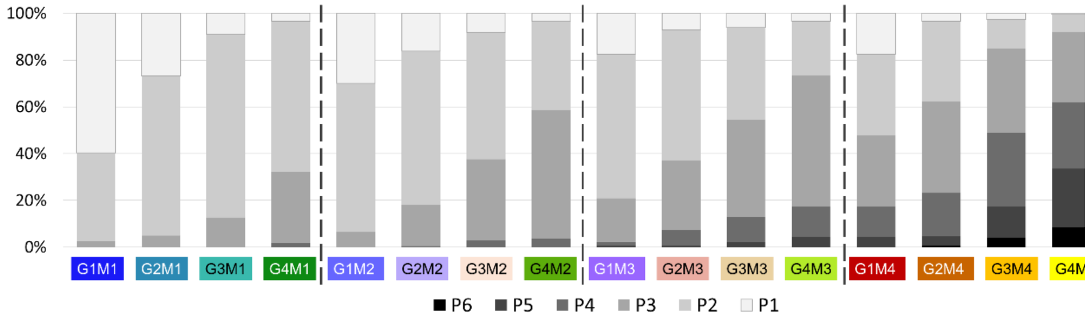


Figure 3-9 Population groups and classification

To visualize regional comparison, Figure 3-8 locates the M-G classifications of all sample cities in different D groups onto four panels. It is visualized that in a specific region, cities of similar size tend to have similar urban form, which similarity can be shared among in different regions. For example, P1~P2 cities locating in Eastern Europe, Central and Eastern China, Japan, Middle East, and Southeast Africa are D2, G1~G2 and M2~M3, a small population size, low density, evenly and clustering fashion. While P1~P2 ones gathering across China, South Asia, and Nile River Delta are classified as D3~D4, G4, M2~M3, high density, unequally and clustering urban form. Differences between regions also illustrated. While the P3~P4 cities in South Asia are G3~G4 and M3~M4, their counterparts categorized in G2~G3 and M3, more evenly distributed and less clustering, and those in Europe tend to be G1~G2 and M3~M4, in a more equal fashion. While the largest cities are dominated by G3M4 and G4M4, the most populated ones in Japan, Latin America, Middle East, and Europe are mainly G2~G3 and M4, in South and East Asia are G4M4, in Southeast Asia, Africa, and Northern America, the most crowded cities are of these types.

I tried to select compact cities from samples using the indicators from the point of view of urban form (Figure 3-10). Based on the discussion in previous chapters that compactness is characterized of dense and continuously clustering development pattern, I chose cities categorized as D3 or D4 (density higher than average), and M3 or M4 (clustering level higher than average), and G1 or G2 (population distributes more evenly than average). The resulted cities are mainly located in Latin America and the Caribbean, Africa, Eastern Europe, and Middle East.

At the end of this section, I have to admit that I worried that I did not fully deal with problematic feature in the metric Moran’s I. The metric has the feature in its nature that for samples with more subdivided units (grid-cell in this section), the results tend to be large. That is to say that when the grid-cell size is decided, which is the case in this study, larger the city, larger the Moran’s I. This feature weakens the conclusion that large cities tend to be more clustering. I tried to minimize the negative impact of the correlation between Moran's I and total city area size. I tried to minimize the negative impact of the correlation between Moran's I and total area size. I used a range of values rather than exact numbers for categorization, and I used four values, M, G, D, and P, in the categorization. These treatments do not completely eliminate the negative effects of correlation. The most thorough treatment would be to modify Moran's I equation or to compare only cities with the same number of grid cells. I was not able to complete such a treatment, and it will be a part of future work.

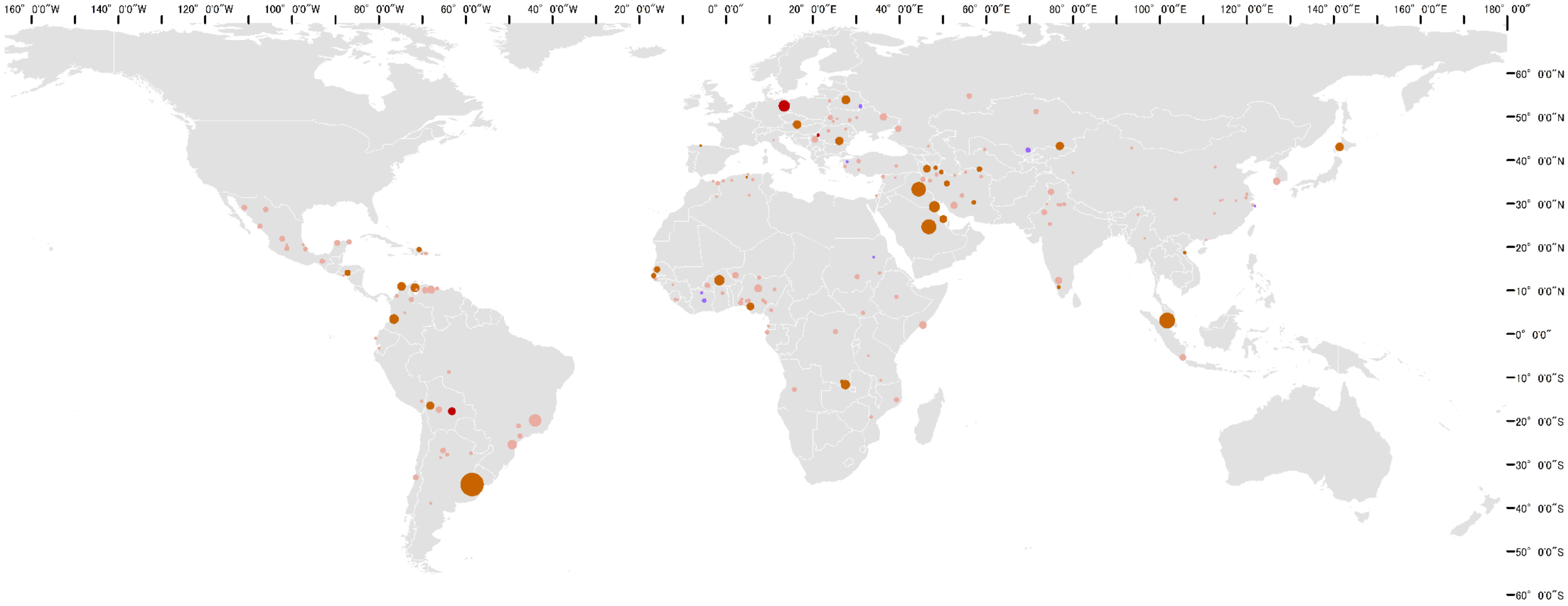


Figure 3-10 Compact cities selected based on classification results.

3.5 Long term changes

3.5.1 In world cities

Using the same dataset and same methodology in Section 3.3, classification analysis is conducted for 1975-2020 with an interval of 5 years. Then, the average of Gini, Moran's I, population, and population density are depicted in Figure 3-11, Figure 3-12 and Figure 3-13.

In Figure 3-11(a), cities with different population sizes tend to be equal and clustering distributed. Cities with small population sizes tend to be dispersed initially. From 1975, all size types became more and more evenly distributed. While all types became clustering gradually, the largest cities clustered fastest. Regarding population density and population size (Figure 3-11(b)), all kinds have become denser, but the larger the size, the denser and larger they became.

Cities with different densities also have a general trend to be equal and clustering distributed (Figure 3-12(a)). Regarding population density types, three groups, other than the most sparsely populated type, share a similar trend that cities with low-density levels tend to be dispersed initially and then become clustering and evenly distributed since 1975. The clustering rate between 1975 and 1985 was fast; then, it went into a period of slow growth, and from 2015 to 2020, the clustering rate became fast again. But the sparsest cities became dispersed 1975-1985, and then clustered fast, while the change in evenly distribution level did not change much. Regarding population density and population size (Figure 3-12 (b)), all types have become denser and larger, but the higher the density, the denser and larger they became. The D2 and D3 types decreased in density from 2015 to 2020.

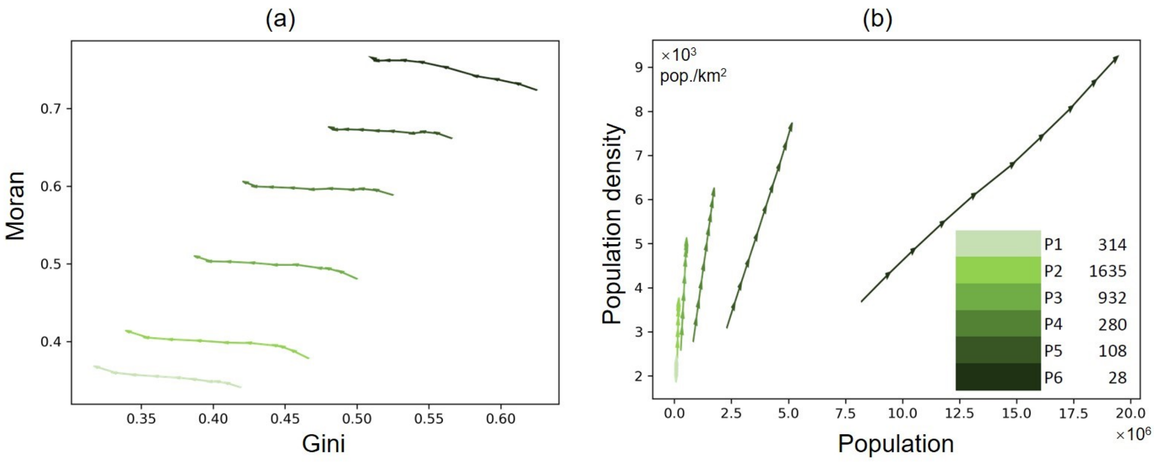


Figure 3-11 Dynamics of average of (a) Gini and Moran, and (b) population and density by population types

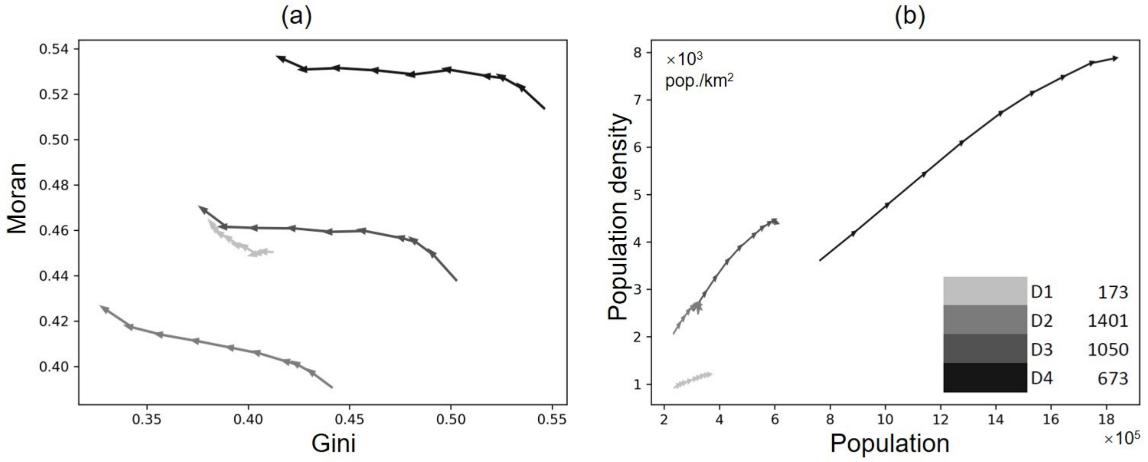


Figure 3-12 Dynamics of average (a) Gini and Moran, (b) population and population density by population density types.

When looking at long-time dynamics in each region (Figure 3-13(a)), Asian cities stand out from the other areas with their intense trend to be clustering and even. African and European cities went through a pattern of being more and more equally distributed continuously while also becoming more dispersed than clustering. Latin America became dispersed from 1975 to 2015 but clustered slightly recently. Northern American cities did not see any vast change in the period. Cities in Africa, Latin America, Northern America, and Oceania tend to be both populated and dense throughout 1975-2020. European cities are different from the overall trend that they have a downward in density and little increase in population. Asian cities had a slower growth in density increase than African and Latin American peers and turned to decrease in the 2015-2020 period.

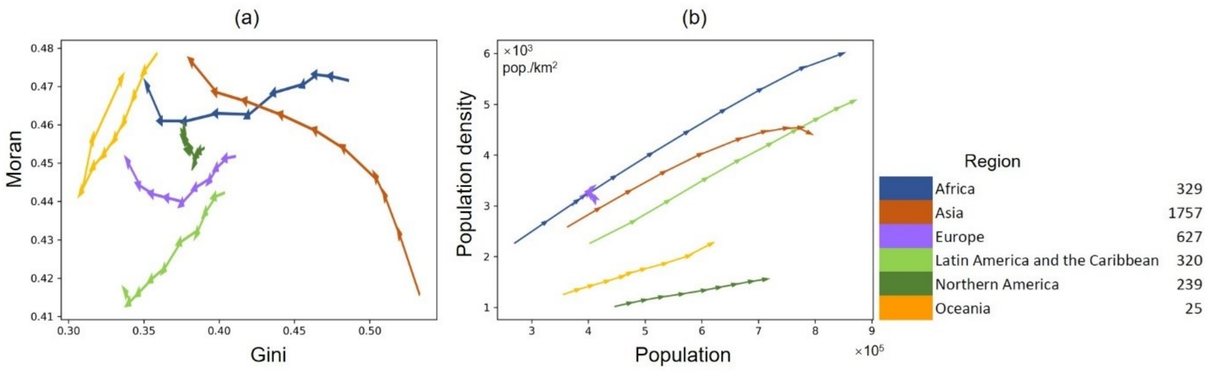


Figure 3-13 Dynamics of average (a) Gini and Moran, (b) population and population density by regions.

3.5.2 In Japanese cities

Additional to the global comparison, in this section I zoomed in the Japanese municipalities. Based on the Japanese cities, I analyzed the correlation between modal share and population distribution as the detailed data on modal share is available.

Municipalities are used as the basic spatial unit. Note that the unit is different from that when analyzing global cities, where the agglomerations of urbanized area are used without considering political boundaries. Three-year population data are used: 1km-grid-cell data for 1980 and 2015, and the 1km-grid-cell data of future population estimates for 2050 (estimated by the Director-General Planning Division, Land Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism in 2009). The administrative boundaries are calculated using the National Land Survey Data for Administrative Districts (2017) in order to standardize the spatial units for all three years. The number of target municipalities is 1,891 cities, wards, towns, and villages (wards are the 23 wards of Tokyo and ordinance-designated cities), and the number of grid-cell is 365,320. The following places are excluded: the Northern Territories, the hard-to-return areas, and Tadaoka Town, Osaka Prefecture, where the number of corresponding grid-cell is too small to define indicators. The population of each grid is assigned to the municipality in which the center point of the mesh is located. Note that the mesh is not strictly limited by municipal boundaries.

Figure 3-14 shows the distribution of population density and its changes. The population density in the period from 1980 to 2015 (referred to "the past") increased in large cities, their fringe areas, and prefectural capitals, while it decreased in many rural areas. The period 2015-2050 (referred to as "the future") will see a decrease except for a small portion. The range of change is larger in densely populated urban areas.

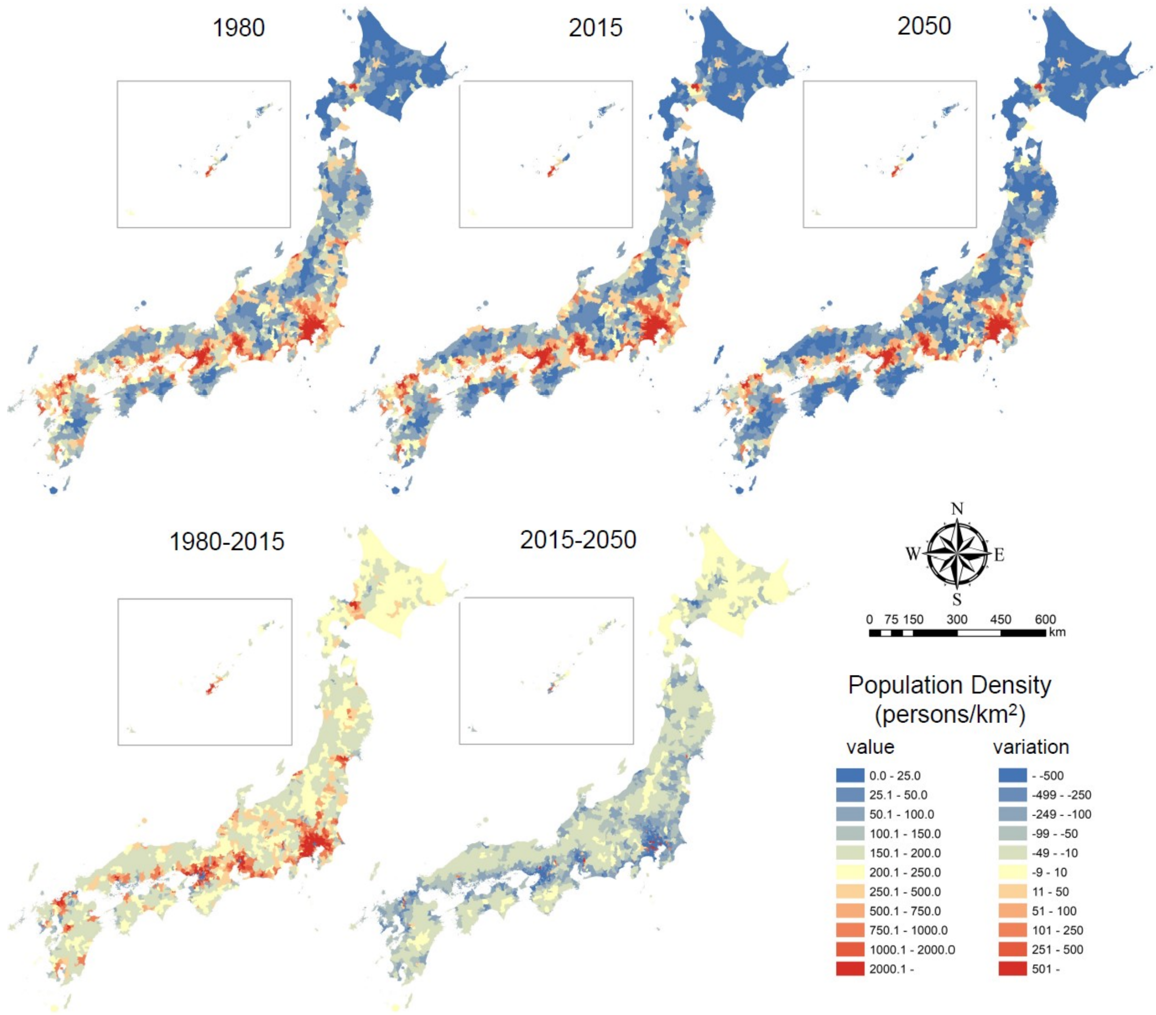


Figure 3-14 Distribution and variation of population density by municipality,

Figure 3-15 shows the distribution of the Gini coefficient and its variation. The distribution of the Gini coefficient is low and even in urban areas, especially in metropolitan areas, where the areas inside the boundary urbanized in a uniform way. Different from the urban area, the values are high, suggesting an uneven pattern, in suburban, rural, and mountainous areas. The average change of the past is almost stable at -0.003, while the future change is +0.026, indicating an overall trend toward greater inequality. However, the trend of increase is weaker in urban areas than in rural areas, indicating a relatively more even distribution.

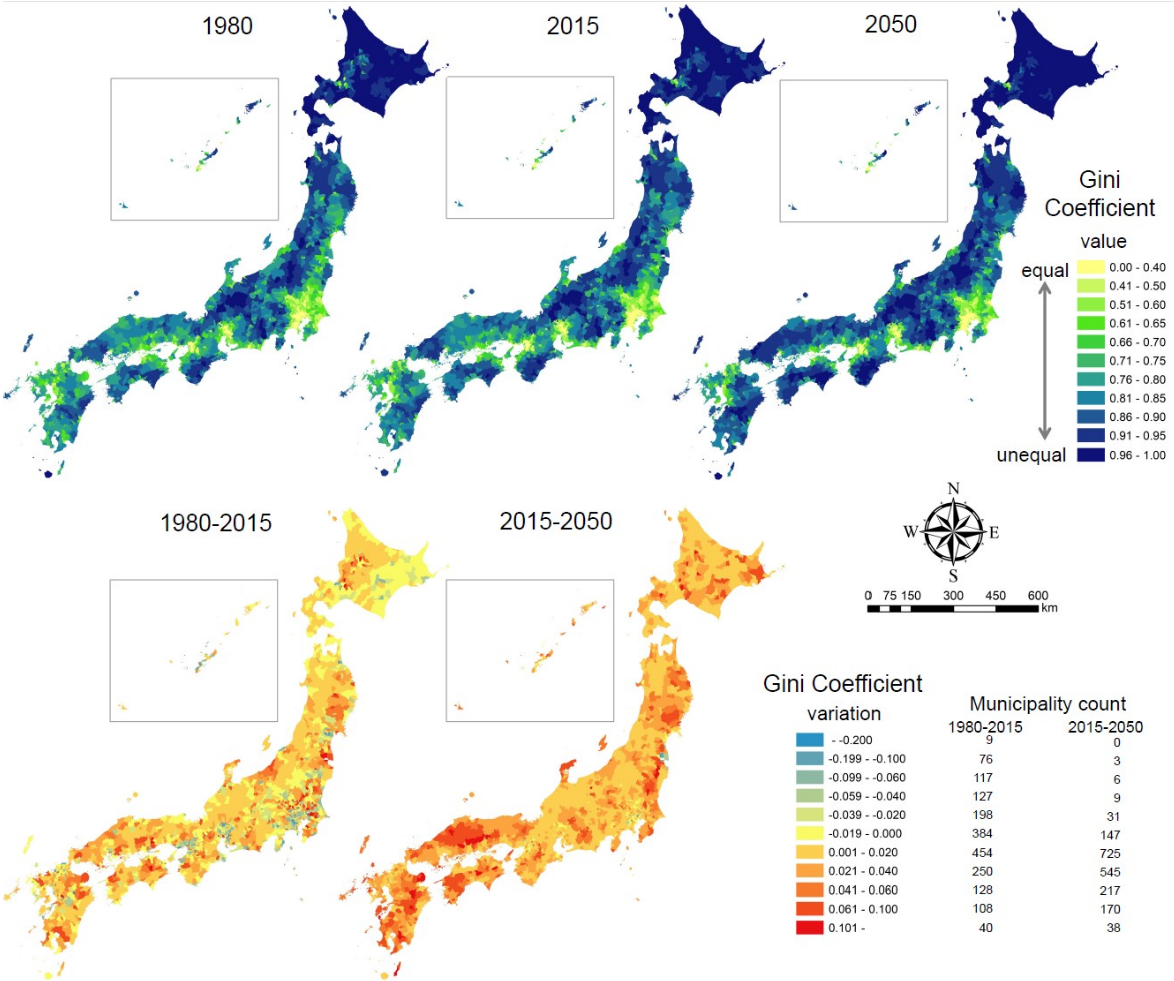


Figure 3-15 Distribution and variation of Gini coefficient by municipality.

Figure 3-16 shows the distribution of the Moran coefficient and its variation. Most of the municipalities have positive values. In big cities, the values are relatively low, which means dispersed, due to urbanization within the boundaries. In urban areas in local cities, the values are higher, showing the trend to be concentrated in some areas within the municipality boundaries. In the mountainous areas, the values are relatively low (dispersed) in mountainous areas due to the scattering of settlements. Although it is difficult to read spatial trends from the map because the trends vary from municipality to municipality, it can be seen that the number of municipalities has increased in the past in 1,391 municipalities, and the average change is +0.069, indicating that the population is generally becoming more concentrated, while the average change is -0.012, indicating that the population will become slightly more dispersed in the future.

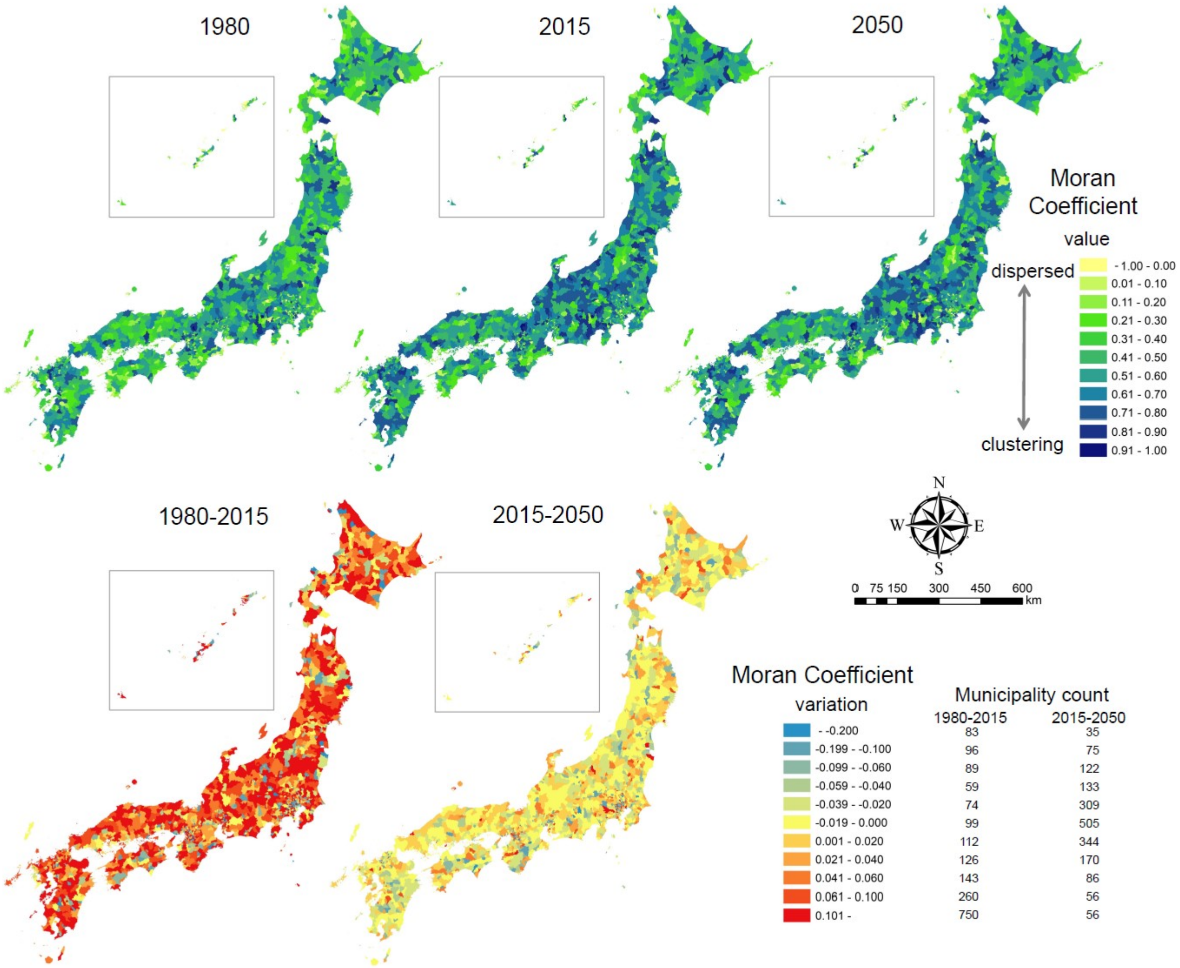


Figure 3-16 Distribution and variation of Moran coefficient by municipality.

3.6 Modal shares and urban form

I calculated the correlation coefficients between modal shares and urban form indices, Gini, Moran's I, population density, and population size. The data of modal shares in 2010 is that in Section 1.1, and the urban form index results are those in 2015. Although the years of the two datasets do not perfectly match, there is no data for the number of commuters by transportation modes in each municipality in 2015, and I considered that resident composition and their commuting patterns did not abruptly change during 5 years; the difference in years of the data source was acceptable.

I joined the two datasets by the city codes, which belong to the same system. A city included in this analysis must (1) exist in transportation data, (2) exist in the dataset for urban form analysis, and (3) have a commuter count in 2010 that is larger than 0. Thus, some municipalities are excluded if they are merged and disappear, excluded in urban form data out of too small area coverage, or if no commuter exists. T-test is performed for all pairs, p-value<0.005; thus, the results are considered statistically significant.

Results are showed in Figure 3-17. The public transit, railway, and bus ratios share similar features: a high ratio has a positive relationship with density and gross population size, a negative one with Gini (evenly distributed), and a slightly negative one with Moran's (dispersed distribution). Private car has the opposite result of public transit relative to uneven, slightly clustering, low density, and low population size. Motorcycles and bicycles have similar features with transit, but the relationship strengths with urban form indices are moderately weaker than railways and stronger than buses. The ratio of walk-only has a positive relationship with Gini (uneven distribution), a negative one with Moran and population size (scattered and small population), and a weak one with population density.

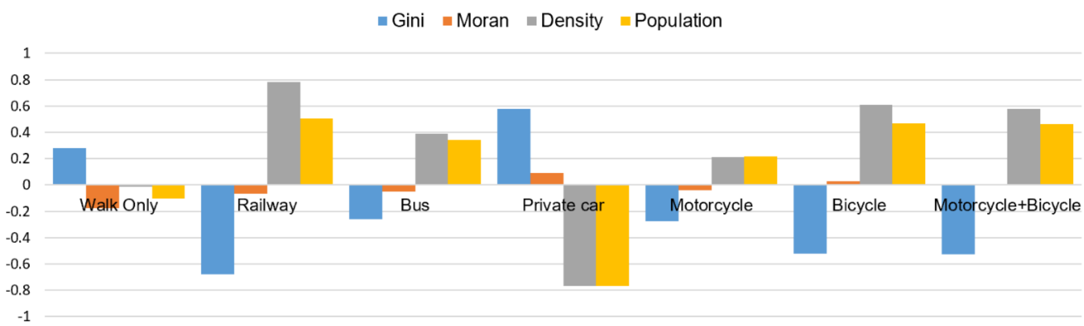


Figure 3-17 Correlation coefficient between modal shares with Gini, Moran's I and population density

In Section 3.4.3, I chose cities with high population density, concentrated and evenly distributed (high density, low Gini, high Moran's I) as the compact cities. Part of the criteria (high Moran) seems inconsistent with results in Figure 3-17 , which show that cities with low Moran agree with public transit and cycling. The inconsistencies stem from the difference in the city unit for analysis. In Section 3.4.3, the agglomerations of urbanized areas are used without considering political boundaries; here, the municipalities are used as the unit. Thus, the Japanese "cities" being talked about here are much smaller (in cases like Nagoya or Tokyo) or bigger (in cases where a city political boundary covers suburban areas) than those in "cities" for worldwide city analysis.

Regarding cycling and public transportation, in terms of the other two compactness criteria (high density, low Gini), there is no contradiction with the intuition that in a compact city, people choose public transit and bicycles. The essential difference between cycling and public transportation is in Moran's I. Bicycling is positively correlated, i.e. (in subdivided urban areas) people tend to prefer bicycling where there is a clear center. Public transportation is negatively correlated, i.e., people choose public transportation with no clear center (in a subdivided urban area). The suppose is consistent with the fact that public transportation can reach farther places more quickly, making users less tied to getting to the center of the subdivided urban area. The stronger positive correlation between transit and population density can be attributed to the fact that regions with larger agglomerations are more likely to pay for transit operations. The stronger negative correlation between public transit and Gini may be attributed to the fact that the service areas of public transit routes are more likely to be strip-like or area-like. Thus, the service in an area tends to be averaged.

The differences between railways and bus can be interpreted as railways are faster and more costly, so the characteristics abovementioned are stronger than the bus system.

Bicycles and motorcycles are different in that motorcycles are for less compact cities with uneven and scattered distribution and lower density and gross population than bicycles.

I assumed that in a highly compact city, people would walk to work and school. However, the results surprisingly seem to disagree with the assumption. I suppose it could be for the following reasons.

First, walking is a relatively slow mode of transportation, and commuting has a punctuality requirement, so people tend to use faster transportation, thus avoiding walk-only as a mode of commuting. So, the urban form characteristics that apply to walk commuters are particular compared to other commuters.

Second, walking also depends on the distance between the place of residence and the place of work. In larger cities, service industries are highly concentrated in limited areas, and residents choose where to live based on the neighborhood, commuting distance, rent, etc., which makes it less likely that they will live in the immediate vicinity of their place of work. As a result, smaller cities are more likely to have a higher proportion of walkable commuters. This is confirmed by the fact that the ratio of walk-only is negatively correlated with population size.

Third, a high ratio of walk-only may be related to mixed land use; the population does not concentrate on some specific places, and the communities tend to be traditional with mixed use of residential and commercial without a particular city center. These may result in the high Gini and low Moran's I, which are the characteristics of a non-compact city, i.e., the population distribution is relatively decentralized. Whether the consideration is correct is unknown because the facility and land-use feature were not included in this correlation analysis. Compared to walk-only, private car use featured a positive relationship with Moran's I, indicating that cars are for small towns with low population density but a clear city center.

3.7 Discussion

The overall objective of this thesis is to find ways to provide mobility services for residents. This chapter aims to provide background information on how the intra-city population is distributed and how the distribution patterns of the population can correlate with the usage of mobility services. The urban form quantification method used in this chapter was initially proposed in (Tsai, 2005) by applying four indices: population size, population density (pop/km2), the degree of equal distribution (Gini coefficient), and the degree of clustering (Moran coefficient).

There are three analysis parts in this chapter: Part (1): I conducted a comparison among cities worldwide in 2015 at the global scale, to fill the research gap in global urban form comparison. Part (2): I summarized the trends in population distribution dynamics over the long term in the global agglomerations and Japanese municipalities. Part (3): I analyzed the correlation between modal share and population distribution in Japanese municipalities.

As results of Part (1) in Section 3.4, in the 4,088 sample world cities extracted, the mean of D is 4,550 pop/km2 with a standard deviation of 2,936 pop/km2, and that of G and M are 0.374 (0.106), and 0.405 (0.180) respectively. In general, populated city areas tend to have more concentrated and unequal population distribution patterns than less populated cities. Among cities near by, cities of similar size tend to have similar urban form. Sometimes the similarity can be shared among in different regions. The main results are in line with those in previous research on global comparison that US cities have more dispersed form than those outside of US, and those in developing countries in Latin America and Asia have more compact urban form (Huang, Lu and Sellers, 2007; Schneider and Woodcock, 2008).

The long-term dynamics analysis in Part (2) in Section 3.5 reveals that the most populated cities have been growing fastest with the highest levels of density and agglomeration. Asian cities have an intense trend to be clustering and even while growing larger, but slowed down to be denser recently. Regarding Japanese municipalities, population distribution in large cities became dense, even, and dispersed in the past but otherwise in suburban areas. In the future, municipalities will see a major trend to be sparse, unequal, and concentrated.

As Part (3), Section 3.6 connected the urban form indices to the usage of transportation modes in Japanese municipalities. Railway, bus, bicycle, and motorcycle users have similarities in correlation with equal and dense distribution and large population size. Bicycle's difference among these is that it correlates with clustering municipalities or those with clear centers. Private car has the opposite result with the modes above relative to uneven, slightly clustering, low density, and low population size. Surprisingly, walking correlates with unequal and dispersed distribution and small population size, with little relation with population density. This was against my assumption that walking for work is popular in highly compact areas with dense and equal distribution.

If viewing the results of Parts (2) and (3) against each other, as the Japanese municipalities will see a major trend to be sparse, unequal, and concentrated, private cars seem to be the natural choice for most future urban commuters. In contrast, there appears to be a dim future for active modes and public transportation.

However, it is too early to conclude that there is no hope for any increase in the percentage of bicycle and transit use. The reasons for this are as follows.

(1) Different from the shrinkage in some Japanese cities, large cities keep growing. Developing countries are in the process of urbanization, following which is the trend of growth, agglomeration, and even distribution in African, Latin American, and Asian cities. Suppose the correlation between modal usage and urban form in Japanese cities can also be applied to other cities. In that case, such trends in urban form make it possible to have a higher proportion of use of public transportation systems and bicycle-like vehicles.

(2) While both railways and bicycles show strong correlations with indicators of urban form, motorcycles, which are similar to bicycles, show relatively weak correlations. This suggests that motorcycles are adaptable to a broader range of urban forms.

(3) The relationships above are trends that may change in more specific and subdivided areas.

(4) The relationship between usage rates and urban form is a static status quo, while the factors affecting mobility provision are variable. While changes in urban form are the main focus of the discussion in this chapter, changes in transit systems, road space design, distribution of facilities, innovation of the vehicle industry, etc., all have the potential to alter this modal usage-urban form correlations.

(5) This relationship showed the users' choice of transportation modes, as opposed to urban planners' or transportation service providers' point of view of whether the current situation is suitable for providing a particular mobility service. There are many aspects of transportation infrastructure, demographic characteristics, cost, and benefit, especially the externality, such as the impacts on health, safety, and the environment.

4. Comparing ranges of applicable time and physical energy cost for bicycles, e-bikes, and public transportation

4.1 Introduction

In the Chapter 3, I summarized the correlation between modal share and urban form in Japanese municipalities. While the overall trends in future urban form dynamics is likely to be friendly for private car usage, bicycles and public transit are likely to be welcome in dense, large, evenly population distributed cities. Motorcycles can adjust to wider range of urban form than bicycles. Compared to a general trend, specific subdivided areas, like communities, requires further investigations. The point of view from provider of mobility service or urban planners is also required when consider transportation infrastructure, especially about the suitability of providing some new kinds of transportation modes, and about the externality like impacts of health, safety, and environment.

Considering that electric vehicles can contribute to environmentally friendly lifestyle, and answering to the discussion that motorcycles may fit more various urban form than bicycles, I focused on a vehicle that in-between bicycle and motorcycle, electric bikes (e-bikes) in this chapter. E-bikes refer to the electric-power-assisted bicycles that are legally defined as bicycles according to Japan law (*Road Traffic Act*, 2015). They use motors to supplement human power, and the assist rate to human force has a maximum of two when the speed is less than 10 km/h, and the rate gradually decreases as the speed increases and becomes 0 at 24s km/h (*Regulation for Enforcement of the Road Traffic Act*, 2018). They present to be a relatively sustainable and healthy transportation mode. Their emissions are less than motorcycles and cars, and similar to those of a bus on a per passenger per kilometer basis (Cherry et al., 2009). E-bikes can overcome the required level of physical effort and physical barriers, such as rough terrain, compared to manually-powered bicycles, being friendly to people with physical limitations (Dill and Rose, 2012).

I tried to inform policy decisions for integrating e-bikes into urban transportation systems, especially on their advantages and limitations when compared with public transportation system. Because Chapter 3 revealed motorcycle and bicycles share similarities in urban forms of the areas they serve. For further understanding the limitation and advantages between them, I chose case study cities to investigate subdivided areas at community ("chouchomoku" in Japanese) scale.

4.2 Objective

this chapter aims to evaluate e-bike convenience for local users when introduced into the existing urban transportation system. While previous studies on bicycle convenience focused on the cycling environment itself, assessment of a new transport mode like e-bikes requires insights into their potential and limitations, which can be obtained by comparing it to existing transportation modes. Therefore, I define e-bike applicability as the change of convenience due to the introduction of e-bikes into the existing urban transportation system, and I propose an assessment methodology based on the comparisons.

This chapter aims to explore e-bike's applicability in the transportation system within the urban environment, specifically by answering two questions. (1) Whether and where can e-bikes improve resident mobility compared to bicycles and transit (community-wide scale)? (2) What are the ranges of applicable time and physical energy cost for e-bikes (city-wide scale)?

The two alternative transport modes selected for comparison are: (1) conventional bicycles, the antecedent of e-bikes, and the mode to possibly be replaced by e-bikes in terms of ownership (Kroesen, 2017); (2) public transit, defined here as a combination of walking, bus, and railway, considered as another mode that users will shift from (Cherry et al., 2016; Kroesen, 2017) possibly due, in part, to public transit deficiencies. Conventional bicycles and e-bikes are simplified to be privately owned. The comparison components applied here are travel time and energy expenditure.

This work will expand the body of literature on bicycling convenience from three perspectives: (1) applying an evaluation to e-bikes, (2) using a comparative evaluation against other modes of transportation, and (3) quantitatively considering the physical energy expenditure.

4.3 Methods

This study mainly proposes three indices: overall convenience index (Section 4.3.1), index of e-bike convenience on a community ("chouchomoku" in Japanese) scale (Section 4.3.5), and on a city-wide scale (Section 3.6). The data source and processing of the base map are presented in Section 4.3.2. The two evaluation components, travel time and physical energy expenditure, will be explained in Sections 4.3.3 and 4.3.4, respectively.

4.3.1 Overall convenience index

To denote the convenience of a transport mode for a user in a community, a service area is used in this study. The service area is the area of a region encompassing all accessible streets from a departure point at a specified cost. In this study, the departure point is the center of a community. The two types of cost are travel time and energy expenditure, which are the components used for comparison. These two components are chosen since e-bikes' higher speeds and quicker acceleration (shorter travel time) with less effort (less energy expenditure) contribute to the user benefits (Popovich et al., 2014).

Note that while expenditure as a benefit can be an important research issue from a public health standpoint, I considered energy expenditure as a cost from the Japanese perspective. Though the motivation for e-bike purchases in Japan have not previously been investigated to our knowledge, the *Bicycle Ownership Report* reveals that e-bike users are predominantly female, elderly, parents or grandparents, and housewives, and shopping is the most important usage (Japan Bicycle Promotion Institute, 2013). Considering the physical limitations of e-bike users and the need to carry children and luggage, I speculate that being able to ride with less effort as an important characteristic in e-biking.

The following components are not considered in the calculations presented here: (1) contributions from dedicated cycling paths and traffic volume, due to the lack of actual measured data from e-bike users; (2) charging station locations, because the maximum calculation range in this study (approximately 18 km) is set to be smaller than the mileage per charge of sample e-bikes in standard assist mode from (Japan Bicycle Promotion Institute, 2017), assuming e-bike users charge them at home and use them the next day; and (3) e-bike parking spaces, due to the difficulty in finding their location data, and the consideration that their users can park them almost anywhere.

The service area is calculated using a built-in network analysis tool in ArcGIS 10.4.1. The transportation mode is specified by applying the road network that contains the travel time and energy expenditure information of that mode.

4.3.2 Data processing

The three modes of transportation in this research are e-bike, conventional bicycle, and transit, which is defined as a combination of walking, bus, and railway. The main data used are shown in Figure 4-1. Choice and analysis of the four cities will be explained in Section 4.4.

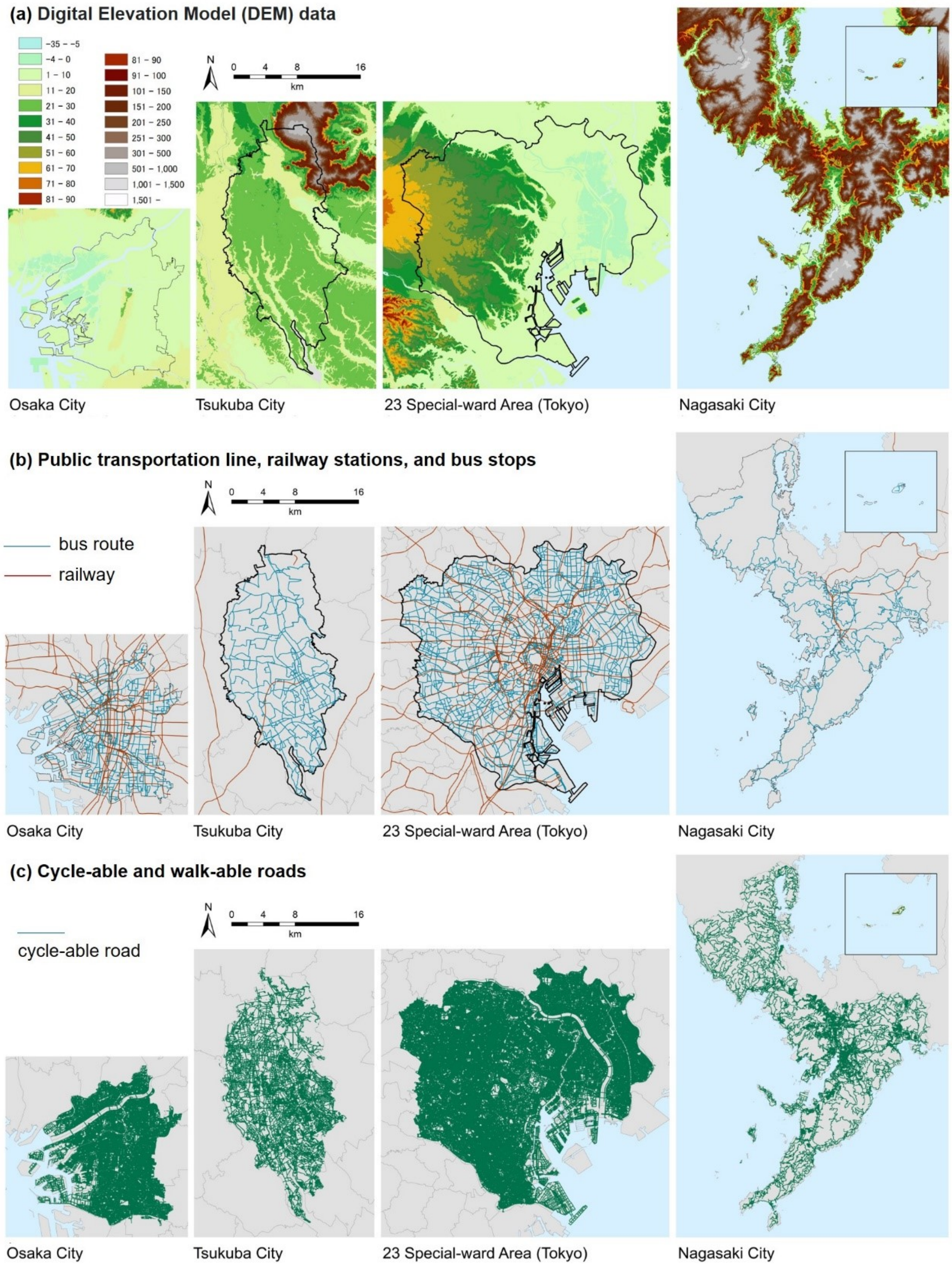


Figure 4-1 Main data used in analysis.

According to the studied modes, three sets of road network were built: bicycling network, e-biking network, and transit network. E-bikes refer to electric-power-assisted bicycles in Japan. Conventional bicycles and e-bikes are assumed to be privately owned, and they are the only means of transportation from the origin to the destination. The bicycling and e-biking networks share the same form, named the “cycling network,” but contain different travel time and physical energy information. The cycling network data, consisting of road network and traffic signal positions, is from OpenStreetMap (OSM). The lines labeled with “motorway,” “footway,” and “pedestrian” are extruded referring to the definition of OSM (OpenStreetMap, 2018), and ones labeled with “path,” “track,” “steps,” and “bridleway” are excluded because they are considered to be unsuitable for cycling after visually checking Google Street View.

The transit network consists of three parts: pedestrian network, bus network comprising bus routes and bus stops, and rail network comprising railways and stations (Figure 4-2). The bus routes are split at bus stops and railway lines at railway stations. The pedestrian network connects to bus routes via bus stops, and to railways via stations; thus, the three parts are connected to each other. In the pedestrian network, the “motorway” is excluded referring to the definition from OSM (OpenStreetMap, 2018). Bus route, bus stop, railway, and railway station data are from the National Land Numerical Information Download Service. To concentrate on intra-city transportation, the Shinkansen lines, i.e. intercity bullet train lines, are removed from the railway data. From bus route data, the segments longer than 5 km between bus stops are treated as high-speed bus routes and removed from the analysis. When connecting pedestrian network to bus stop or railway station, I drew start point, end point, and middle point on every pedestrian road link, and to find the nearest road point from the bus stop or railway station point, then created a line between the road and terminal points.

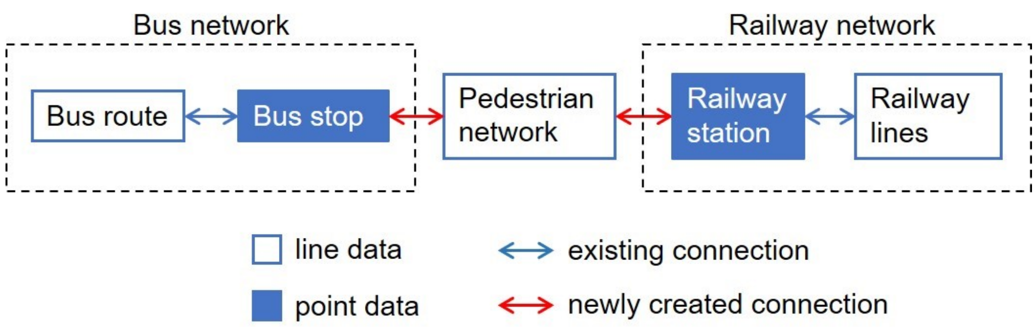


Figure 4-2 Composition of transit network

To consider the gradient of roads in cycling and pedestrian networks, roads are cut to shorter links at intersections. Then, each link is attributed with an average slope value based on the topography information from the grid-cell digital elevation model (DEM) raster files from the Geospatial Information Authority of Japan (GSI). The highest possible resolution of 5-m grid-cells is mainly adopted, and 10-m cells are used only when 5-m ones are not available (Figure 4-3).

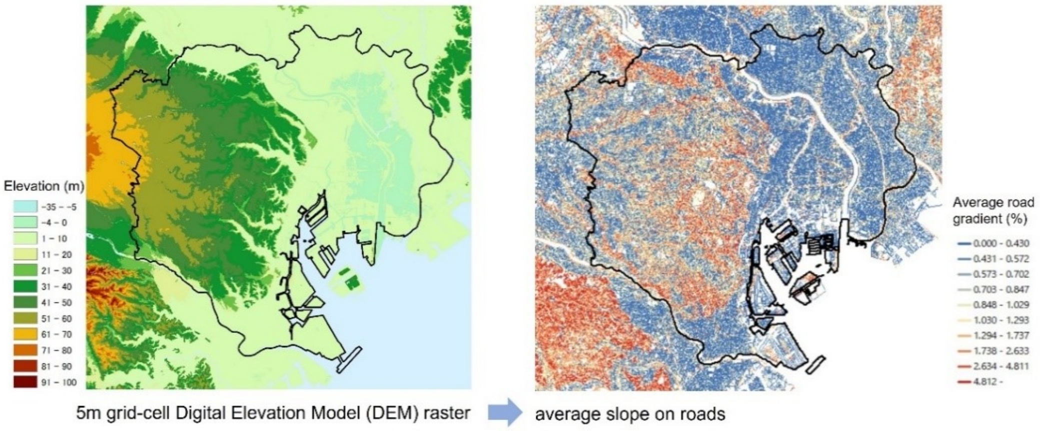


Figure 4-3 Elevation data is used to calculate the average slope on walk-able and cycle-able roads

Travel time and physical energy expenditure are assigned to each link segment in the three resulting sets of networks using the methods in Sections 3.3 and 3.4. In the following parts, the three modes of transportation are referred to as follows:

$$m = \begin{cases} 0 : \text{e-bike} \\ 1 : \text{bicycle} \\ 2 : \text{public transit} \end{cases}$$

4.3.3 Travel time settings

For every resulting cycling network link, speed is assigned related to gradient according to empirical data from (Inagaki et al., 2011). Note that the e-biking speeds are lower than cycling for uphill segments. While Inagaki et al. (2011) state that there is no significant difference between e-biking and conventional bicycling in all three scenarios, they speculate the difference may result from the feature of e-bikes that the assist ratio drops when the speed increases. This set of data was adopted since it was the only data that could be found regarding the measured value of the gradient-speed relationship for e-biking in Japan, and the number of samples is relatively large (294 bicycle riders and 5854 road links). The results in uphill trials are considered reasonable since the e-bike riders may slow down to get a higher assist ratio when e-biking uphill.

For each pedestrian link, speed is also set relative to the road gradient, corresponding to previous studies on physical activity. The physical energy value when the gradient is above 4% is based on (Hagiwara & Yamamoto, 2011), in which the energy is measured when the speed is fixed to 50 m/min. When the gradient is less than 4%, the energy in walking at a speed of 2.5 m/h on a level and firm surface (NIHN, 2012) is adopted. Therefore, the walking speed is set to 4.0 km/h and 3.0 km/h, respectively. For the bus and railway links, the scheduled speed is adopted and waiting time at bus stops or railway stations are not considered (Table 4-1).

Table 4-1 Velocity settings of transportation methods.

Cycling speed				Transit speed			
Gradient	Conventional bicycle [a] (km/h)	E-bike [a] (km/h)	Wait at signal (sec)	Gradient	Walking (km/h)	Bus [d] (km/h)	Railway [e] (km/h)
Uphill ≧2%	14.0	13.6	24	Uphill ≧4%	3.0 [b]	11.0	43.4
<2%	14.3	14.4		<4%	4.0 [c]		
Downhill ≧2%	16.5	16.8		Downhill ≧4%	3.0 [b]		

a: from (Inagaki et al., 2011)

b: corresponds to physical activity data in (Hagiwara & Yamamoto, 2011)

c: corresponds to physical activity data in (National Institute of Health and Nutrition, 2012)

d: schedule speed, from (Toei Transportation, 2017)

e: schedule speed, calculated based on (Ministry of Land, Infrastructure, Transport and Tourism, 2016) and (Toei Transportation, 2017)

4.3.4 Physical energy expenditure settings

As there is no complete set of data of physical energy consumption of e-biking corresponding to different slopes (Section 2.4), I developed my own methods of calculation.

Physical energy expenditure (EE) is quantified in this study. I use MET-h as the unit of expenditure for a transportation mode user. MET is a unit of physical activity (PA) measuring the rate at which the body expends energy while sitting at rest. It is widely used to compute the calories consumed as kilocalories = physical activity (MET) × weight (kg) × duration (h). In this study, each road link is assigned an energy expenditure (MET-h) = physical activity during transportation (MET) × travel time (h).

The PA when standing quietly or riding on a bus or train (1.3 MET) and walking (Figure 3-3) can refer to the existing research (Ainsworth et al., 2011; Hagiwara & Yamamoto, 2011;

Inagaki et al., 2011; National Institute of Health and Nutrition, 2012). While there are empirical studies on physical activity in cycling and e-biking (Table 2-1), there is no known complete data set of physical activity values varying with the velocity and gradient. Thus, the PA in bicycling and e-biking is estimated as follows.

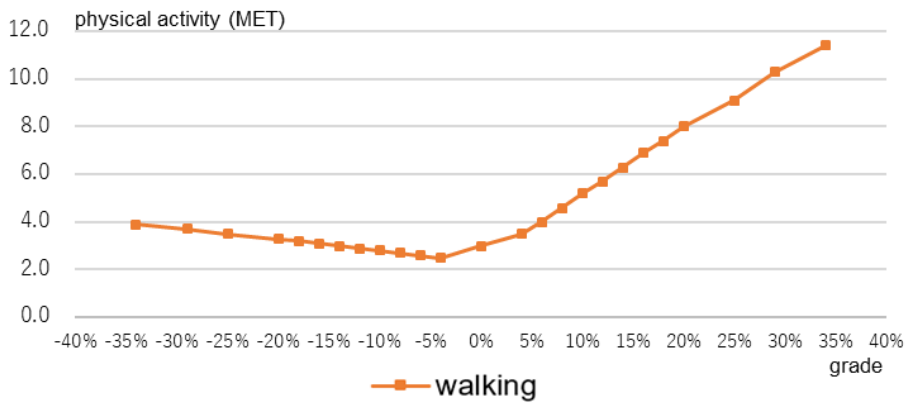


Figure 4-4 Calculated physical activity values (MET) for walking by gradient.

(gradient ≧4%: calculated based on (Hagiwara & Yamamoto, 2011); gradient <4%: based on (NIHN, 2012)).

There are three steps in the bicycling and e-biking PA calculation. First, the output power of bicycling (W_1) is calculated using the bicycling power requirement in Eq.(4.1) (Parkin & Rotheram, 2010; Wilson et al., 2004), considering air resistance, slope resistance, rolling resistance, and average bump resistance:

$$W_1 = \frac{C_{\mathrm{v}}}{\eta_{\mathrm{mech}}}\left[Mg\left(C_{\mathrm{r}} + \frac{s}{100}\right) + 0.5C_D A\rho(C_{\mathrm{v}} + C_{\mathrm{w}})^2\right] \tag{4.1}$$

where C_{v} is the speed of the bicycle (m/s), which is set based on measured bicycling speed data on roads with different gradients (Inagaki et al., 2011); s is the road gradient in percentage, set to -7~7 as an integer; and M is the gross mass (kg), including a 15-kg bicycle and a 60-kg cyclist. As for the other factors, I assumed the mechanical efficiency of the bicycle (η_{mech}) to be 95%, gravitational acceleration (g) to be 9.807 m/s^2, rolling resistance coefficient (C_{r}) to be 0.008, aerodynamic drag coefficient (C_{D}) to be 1.2, the frontal area of the cyclist and bicycle (A) to be 0.616 m^2, the density of air (ρ) to be 1.226 kg/m^3, and the headwind (C_{w}) to be 0 m/s. The acceleration is neglected in this study.

Second, to calculate e-biking physical activity, I considered the assistance ratio, which is the ratio of the engine output to the personal output. The measured assistance ratio can be summarized by Eq. (4.2)based on prior research (Japan Bicycle Promotion Institute, 2016) (Figure 4-5):

$$a = \begin{cases} 1.4, 0 \le C_v < 10 \\ 1.4 - 0.1(C_v - 10), 10 \le C_v \end{cases} \quad \textbf{(4.2)}$$

where C_v is the speed of the bicycle (m/s).

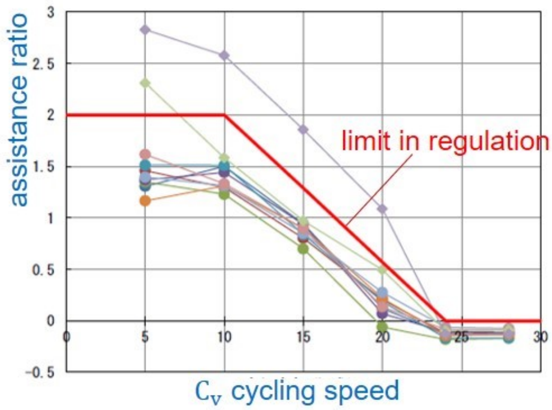


Figure 4-5 Measured data of assistance ratio in e-bike samples

(Japan Bicycle Promotion Institute, 2016)

Then, the human output in e-biking (W_0) is calculated based on W_1 using Eq. (4.3):

$$W_0 = \frac{W_1}{(1 + a)} \quad \textbf{(4.3)}$$

Third, the oxygen consumption rate (VO_2) is calculated using Eq. (4.4) according to (Zoladz et al., 1995):

$$VO_{2m} = 450.00 + 9.7067\, W_m \quad \textbf{(4.4)}$$

where W_m is the output power of e-biking (W_0) or that of bicycling (W_1). Then, the units of VO_2, ml/(kg-min), are converted into MET by dividing the VO_2 result by 3.5. The results smaller than 1.5 MET are manually changed to 1.5 MET since that is the value corresponding to inactivity.

Compared to the previous study of MET (Table 2-1), the results here are considered to be acceptable. The results of physical activity when bicycling and e-biking are plotted in Figure 4-6.

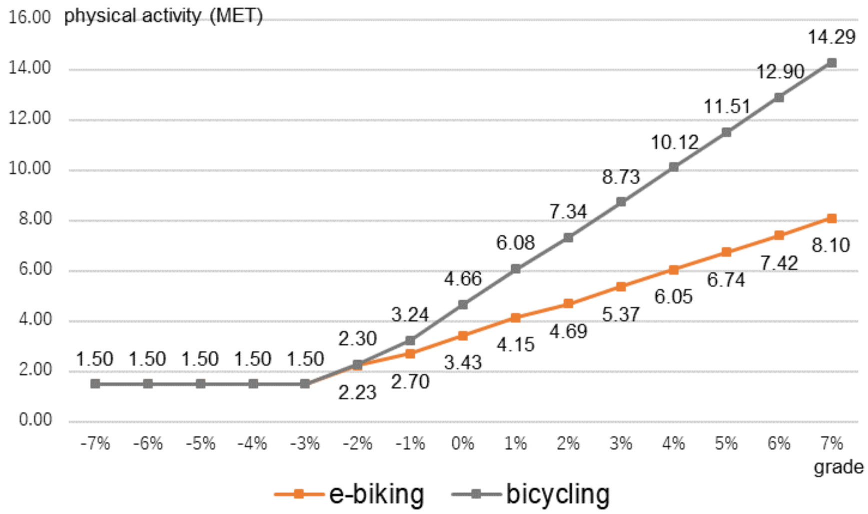


Figure 4-6 Calculation results of physical activity values (MET) in bicycling and e-biking by gradient.

4.3.5 E-bike applicability index (community)

As defined, the e-bike applicability refers to the change of convenience due to the introduction of e-bikes. Referring to the form of the modal accessibility gap (MAG) equation in (Kwok & Yeh, 2004), the index bike-service area gap (BAG) Eq.(4.5) is proposed to denote the e-bike applicability on a community-wide scale:

$$BAG_{mi}^{k} = \frac{S_{0i}^{k} - S_{mi}^{k}}{S_{0i}^{k} + S_{mi}^{k}}, m \neq 0 \qquad \textbf{(4.5)}$$

where S_{0i}^{k} is the service area of e-bikes from community *i* at a cost of *k,* i.e. travel time or physical energy expenditure; and S_{mi}^{k} is that of another transportation mode *m,* i.e. conventional bicycle (*m*=1) or public transportation (*m*=2). BAG standardizes the difference of service areas between e-bikes and another transportation mode, ranging from -1 to 1. If BAG is positive, e-bikes in the community *i* are more convenient than transportation mode *m;* consequently, e-bikes are applicable for users there.

To illustrate the BAG results, I consider a simplified version in which (1) the service area is a circular area with a departure point as its center and the furthest round trip distance as its radius; (2) the accessible distance is calculated as a straight-line distance and the road grade is constant throughout the trip; and (3) in a transit trip, the ratios of distance by walking, bus, and railway are simplified to 5%, 35%, and 60%. The service area (*S*) at costs of 65 min and 1.5 MET-h and the resulting BAGs are illustrated in Figure 4-7 (b) and (c).

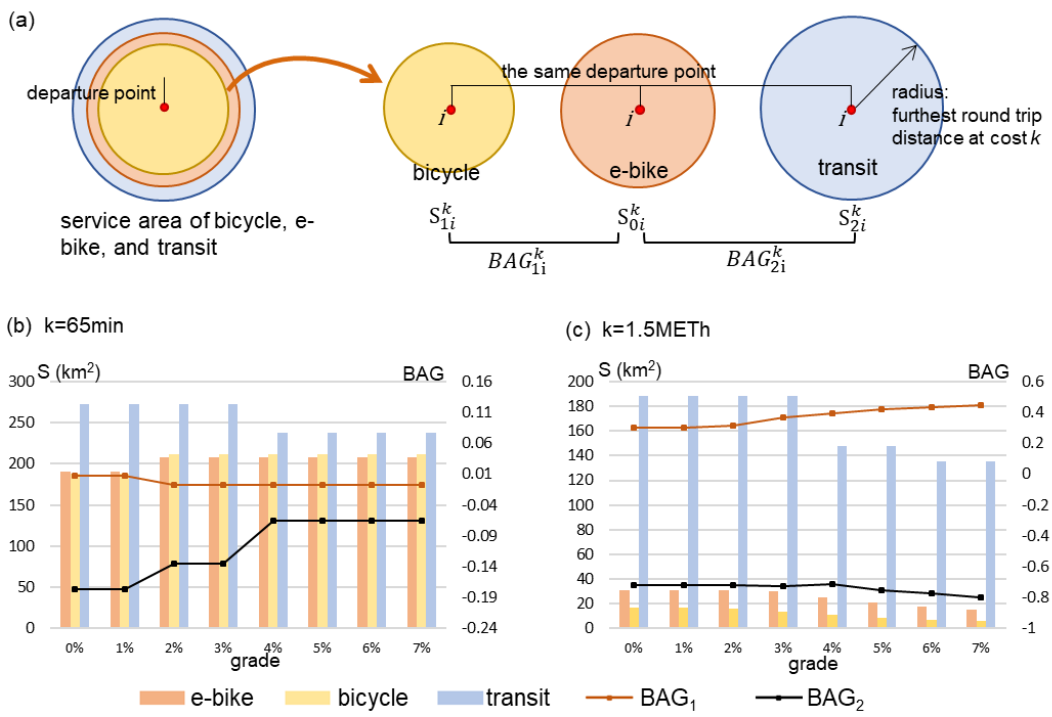


Figure 4-7 Simplified version of S and BAG calculation.

(a) related factors; (b) results when k=65 min; (c) results when k=1.5 MET-h.

4.3.6 E-bike applicability index (city)

The index average of BAG (ABAG) is proposed based on the BAG, denoting the e-bike applicability on a city-wide scale, and is calculated using Eq. (4.6):

$$ABAG_m^k = \frac{\sum_{i=1}^{N}(p_i BAG_{mi}^k)}{\sum_{i=1}^{N} p_i}, m \neq 0 \tag{4.6}$$

where N is the number of communities and p_i is the population in community i. The ABAG varying with ascending travel time or physical energy expenditure can be plotted as a curve with the x-intercept representing the applicable range of travel time or physical energy for e-bikes in the specific city.

4.4 Case study

4.4.1 Target cities

In this section, the methods described in Section 4.3 are applied to 4 Japanese cities to answer the question of where e-bikes has the potential to improve the mobility of residents, and to explore the e-bikes applicability in cities with different characteristics.

Four cities, the 23 Special-ward Area (Tokyo), Osaka City, Nagasaki City, and Tsukuba City, were chosen based on the e-bike applicability relevant factors, density of public transportation lines and grade of road segments (Table 4-2, Figure 4-8), as well as their urban form indicator results and bicycle modal shares (Figure 4-9). Regarding transportation related features, Tokyo has high density of public transportation lines. Nagasaki City has typical steep grade of roads. Osaka City and Tsukuba City, with a mild grade of roads and a lower density of lines, were chosen for comparison. Tokyo and Osaka have better cycle-able road coverage than the two others.

Regarding urban form, all the four cities have a higher population density than average (Figure 4-9(a)). Tokyo is in the centers of the nation's largest metropolitan, and has been keeping pulling population. Tsukuba with many research and education institutions is seeing a high population growth rates among Japanese cities. Compared to these two cities, population in Osaka slightly increased and that in Nagasaki decreased. Tokyo and Osaka have evenly distributed population as the urbanization in metropolitan areas tend to progress in a uniform way, followed which is Tsukuba, then Nagasaki have the most uneven pattern (Figure 4-9(b)). Moran's I varies in subregions in Tokyo and Osaka. Those in Osaka have low values, showing a dispersed pattern while those in Tokyo shows a clustering pattern (Figure 4-9(c)). Osaka has the highest percentage of bicycle and motorcycle commuters of about 30%. Ratios in Tokyo varies by area that in the city center and the western side the values are low, while the outer fringe areas bear higher values. Ratio in Tsukuba is about 20% and 13% in Nagasaki (Figure 4-9(d)).

Table 4-2 Descriptive statistics of the case study city.

City	Land area (km^2)	Population		Number of communities ("chouchomoku" in Japanese)	Average road gradient (%)	Transit line density [a] (km/km^2)	Cycling road density (km/km^2)
		Number	Density (num/km^2)				
Tokyo	618.97	9,272,730	14,980.90	3,192	1.44	19.54	26.21
Osaka	225.21	2,691,185	11,949.67	1,913	0.94	14.02	23.53
Nagasaki	405.86	429,508	1,058.27	629	5.91	6.10	6.24
Tsukuba	283.72	226,963	799.95	338	1.67	4.88	9.42

a: Different bus and railway systems on the same route are counted redundantly.

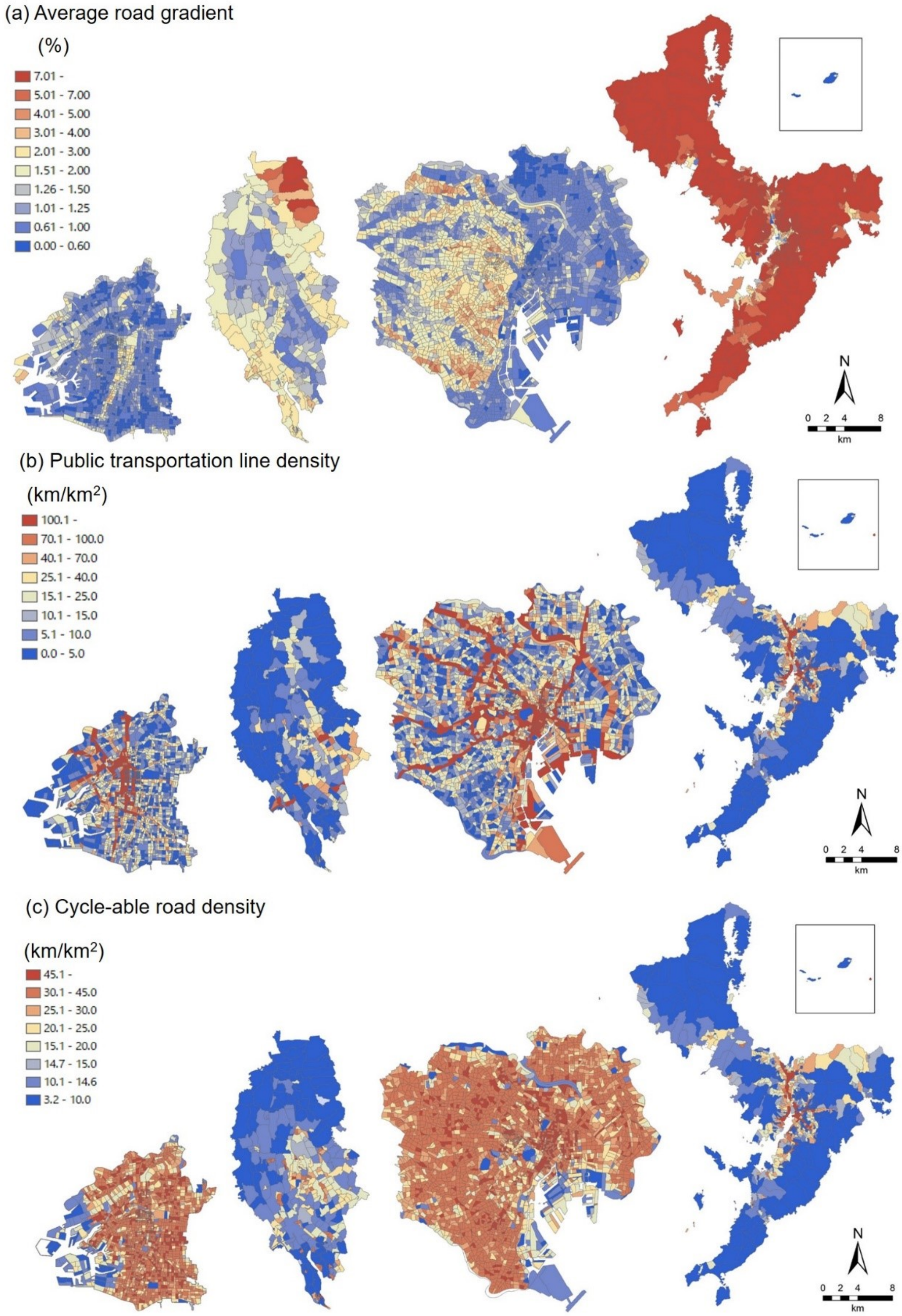


Figure 4-8 Visualization of statistics in communities.

Cities from left to right are Osaka, Tsukuba, Tokyo, and Nagasaki.

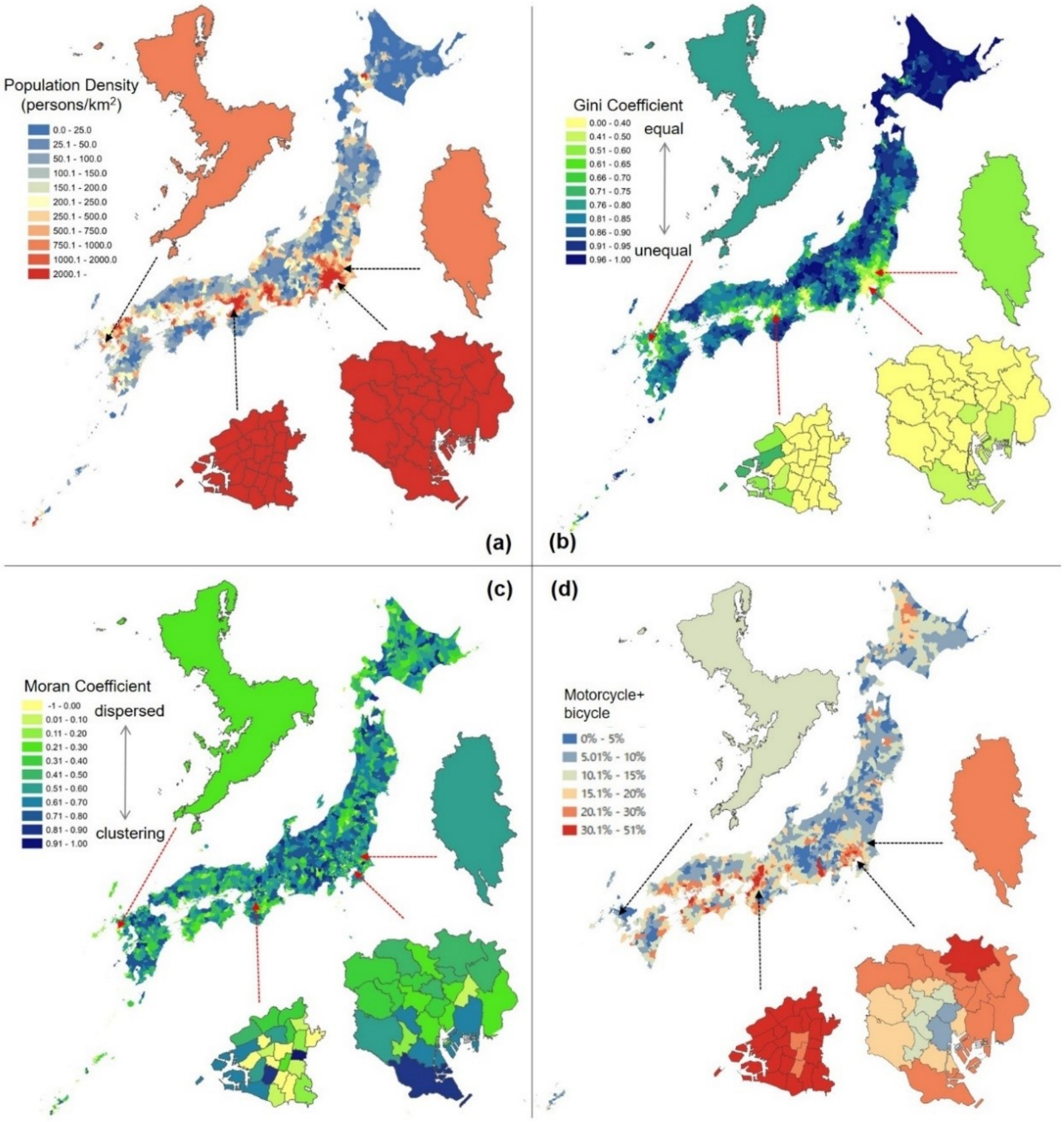


Figure 4-9 Urban form indices and usage ratio of motorcycle and bicycle.

Cities clockwise from upper left corner are Nagasaki, Tsukuba, Tokyo, and Osaka.

4.4.2 Improvement compared to transit and bicycle

The BAG was calculated to identify where e-bikes can improve the resident mobility compared to transit and bicycle. Different from the simplified version mentioned in Section 4.3.5, (1) network distance is used instead of straight-line distance to better describe the impact of e-bikes based on network structure characteristics; (2) road grade is calculated for every segment, leading to a variable gradient along a trip; (3) the ratios of three methods in a transit trip are not fixed; and (4) the service area is not circular.

When compared to public transportation, as expected, e-bikes tend to be more applicable in communities with lower transit line density (Figure 4-10). Such tendency can be seen in the 4 case study cities in Figure 4-11. The well-developed transit system in central part of Osaka and Tokyo, and the relative high transit line density in south-east Tsukuba and central Nagasaki, makes e-bikes tend to be not applicable there, but applicable in fringe areas.

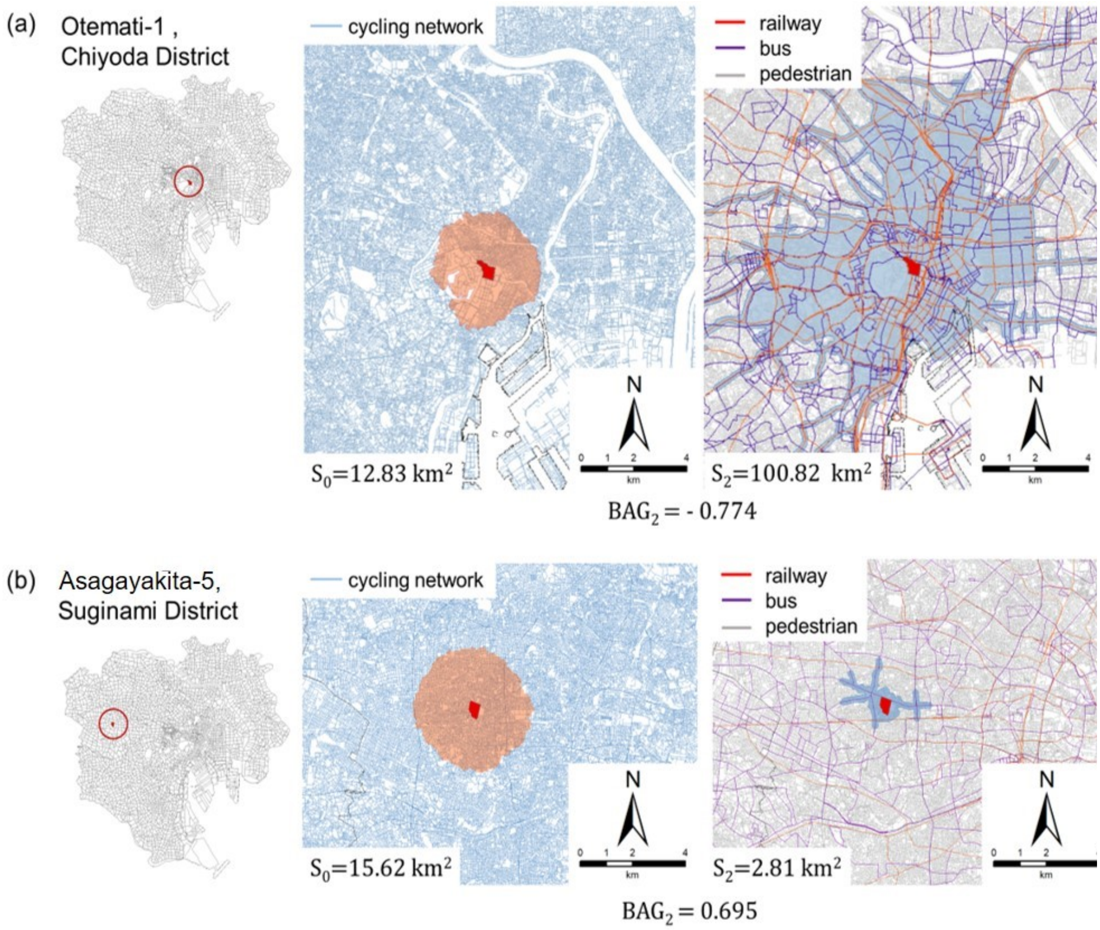


Figure 4-10 Example of resulting S and BAG in Tokyo when m=2 and k=1.25 MET-h.

This tendency can be seen in the case study city in Figure 4-11. The well-developed transit system in the central parts of Tokyo tends to make e-bikes not applicable there, but applicable in the fringe areas.

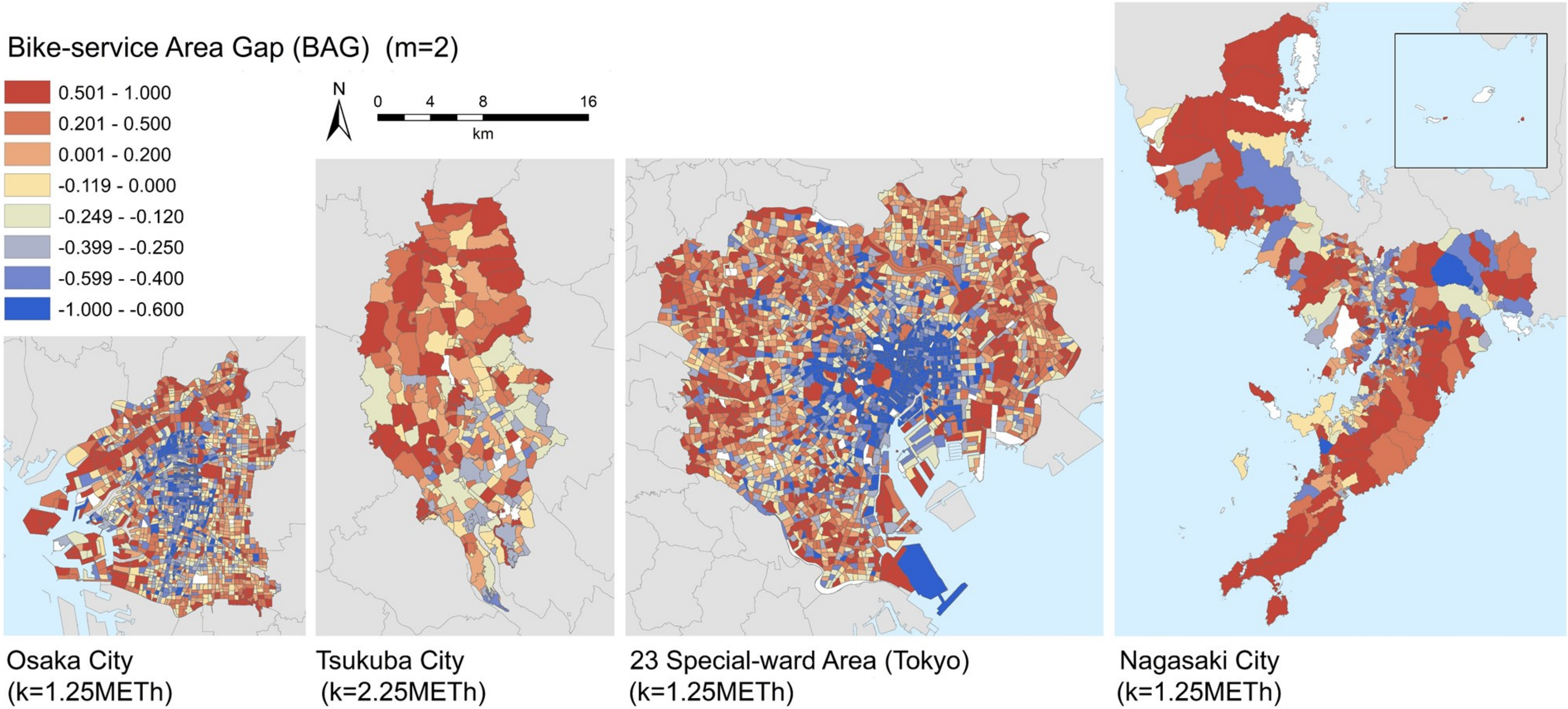


Figure 4-11 Results[a] of the BAG (m=2) in Osaka, Tsukuba, Tokyo, and Nagasaki.

a: To compare the results with the same legend, figures are shown when average of BAGs are near 0.

When compared to bicycles in terms of physical energy expenditure, the results show e-bikes can improve their mobility anywhere, but especially when roads are steeper (Figure 4-12(a) and (b)), or with geographical obstacles requiring a detour (Figure 4-12(a) and (c)). The elevation profile in Figure 4-12 show the change in elevation of a surface along a line drawn manually through the community centers. Note that the scales in x- and y-axes are different, that the slopes in Consider a riverside community as an example (Figure 4-12(c)), on the river the only accessible road is the bridge, whether a vehicle can reach and cross a bridge can considerably affect the size of the service area. In the e-bike case on the left side in Figure 4-12(c), e-bike crossed the northern bridge but in the conventional bicycle case it could not. The service area of an e-bike covers the river area but that of a bicycle does not, thus making the difference in service areas between them. Since e-bikes are more likely to cross bridges than conventional ones costing the same physical energy, e-bikes perform better on river side or other places with suddenly decrease of road density, like a big park.

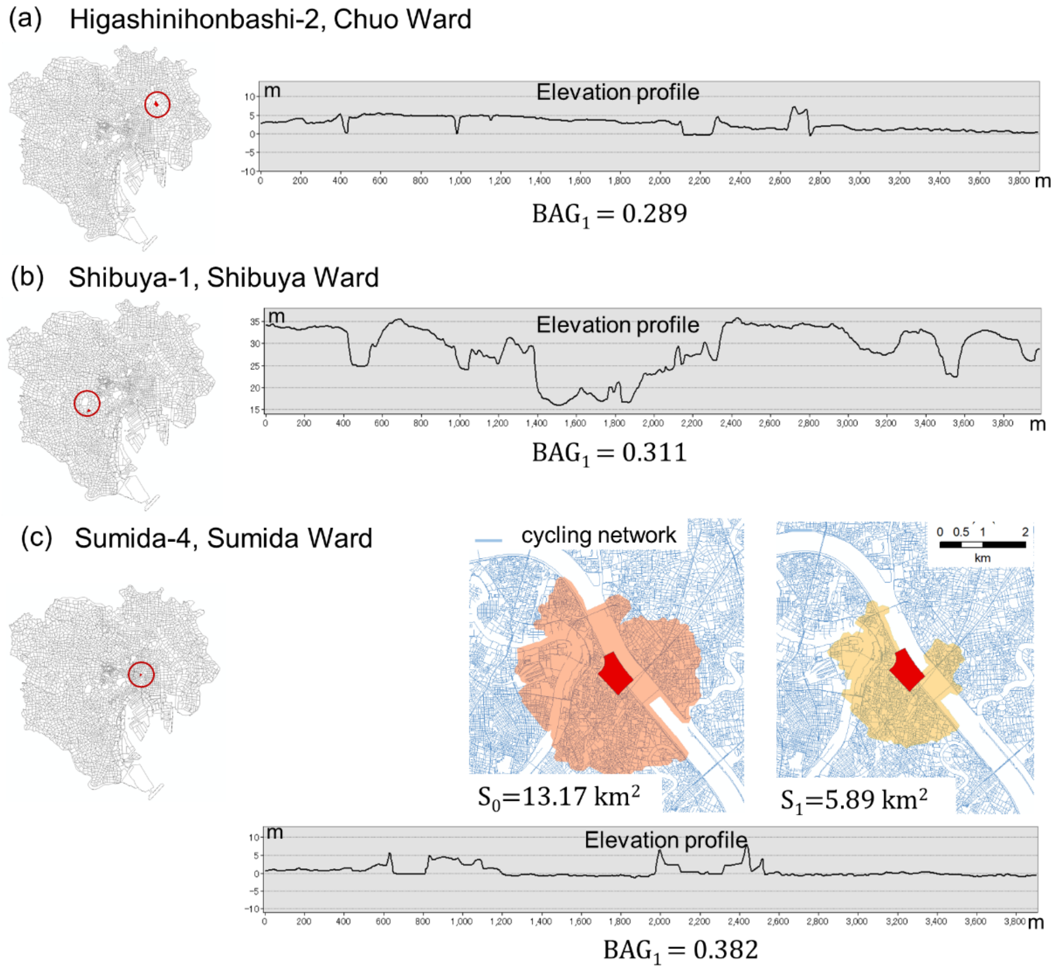


Figure 4-12 Example of resulting S and BAG in Tokyo (m=1, k=1.25 MET-h) and elevation profile of e-bike service area.

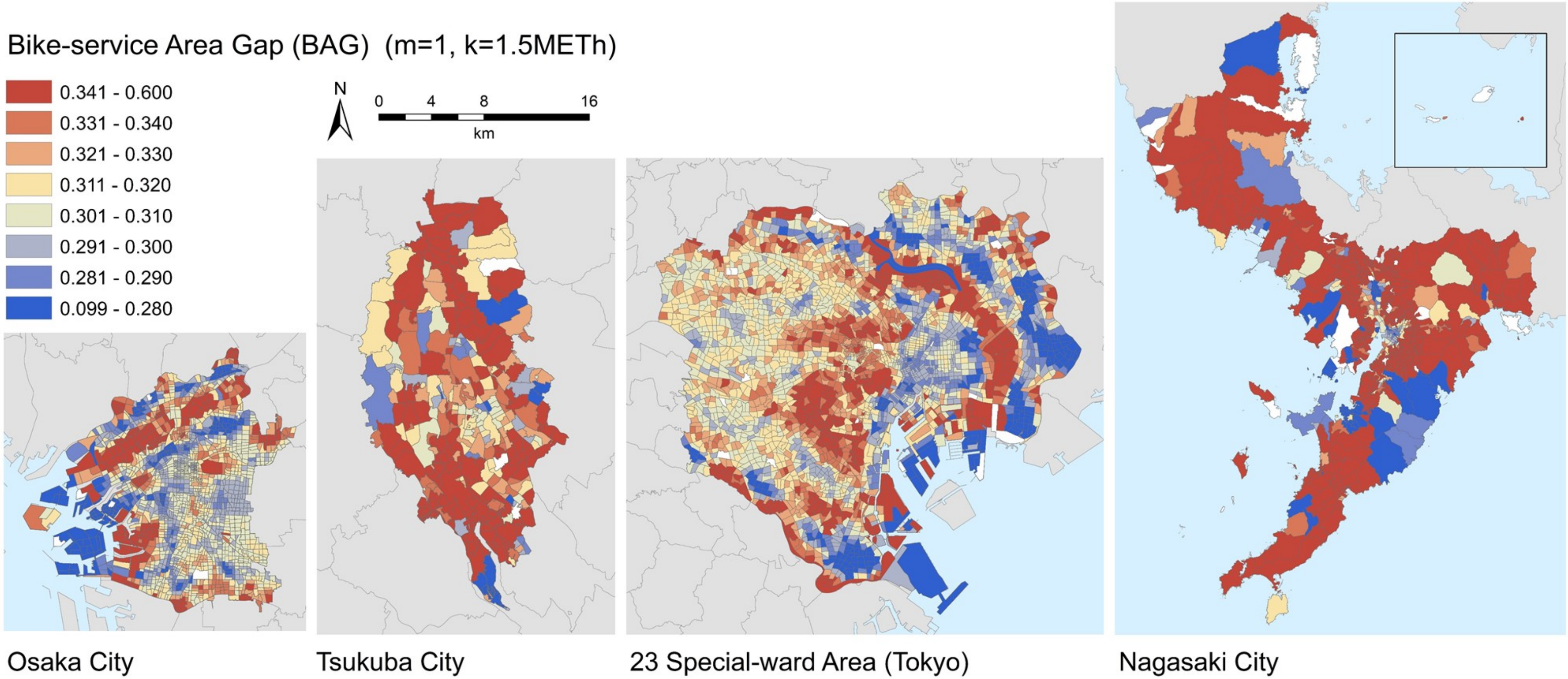


Figure 4-13 Results of the BAG (m=1, k=1.5 MET-h) in Osaka, Tsukuba, Tokyo, and Nagasaki.

The same tendency can be seen in the cities (Figure 4-13) as was seen in the communities. The steep roads show their effect in southwest and north part of Tsukuba, central and west part of Tokyo, and the outer side of Nagasaki. The red area in southwest seaside and stripe-like areas in north part going east-west in Osaka and the red strip in northeast and southwest in Tokyo suggest the impact exerts from wide rivers. Similar impacts from large parks can be seen in Osakajo Park (Osaka) and Yoyogi Park (Tokyo). Otherwise, the cycling road density can also affect the results. Low cycling roads can lead to margin difference between e-biking and bicycling, thus little applicability of e-bikes over bicycles.

4.4.3 E-bike applicable communities

The communities where e-bikes are applicable considering both bicycles and transit were selected. According to (MHLW, 2013), three MET physical activities exceeding 1 h/day are recommended since meta-analysis performed for studies targeting Japanese people shows that the risk of lifestyle-related illness and dysfunction is significantly lower in persons with more than 22.5 MET-h per week of physical activity. I assume that half of the daily activity, 1.5 MET-h, is attributed to transportation. Thus, the criterion for an e-bike applicable community is set to $\mathrm{BAG}_1^{1.5\ \mathrm{MET-h}} \geq 0$ and $\mathrm{BAG}_2^{1.5\ \mathrm{MET-h}} \geq 0$. The travel time range is not used since it is already used in the physical energy calculation.

To better inform policy decisions about where the introduction of e-bikes can improve the local resident mobility, the e-bike applicable communities with a high probability of e-bike demand were selected. The e-bike potential users are narrowed down based on the following information. (1) E-bike users are predominantly female, elderly, parents or grandparents, or housewives (Japan Bicycle Promotion Institute, 2013). (2) The elderly above 70 years old cannot renew their driving license unless they attend a lecture (TMPD, 2018), suggesting the elderly are considered to be high-risk car drivers and may transfer to e-bikes. (3) Considering that carrying children is an important function for e-bikes in Japan, riding double on a bicycle is prohibited, except for cycling with a child under 6 years old as the passenger. The proportion of potential users in each community is visualized in Figure 4-14.

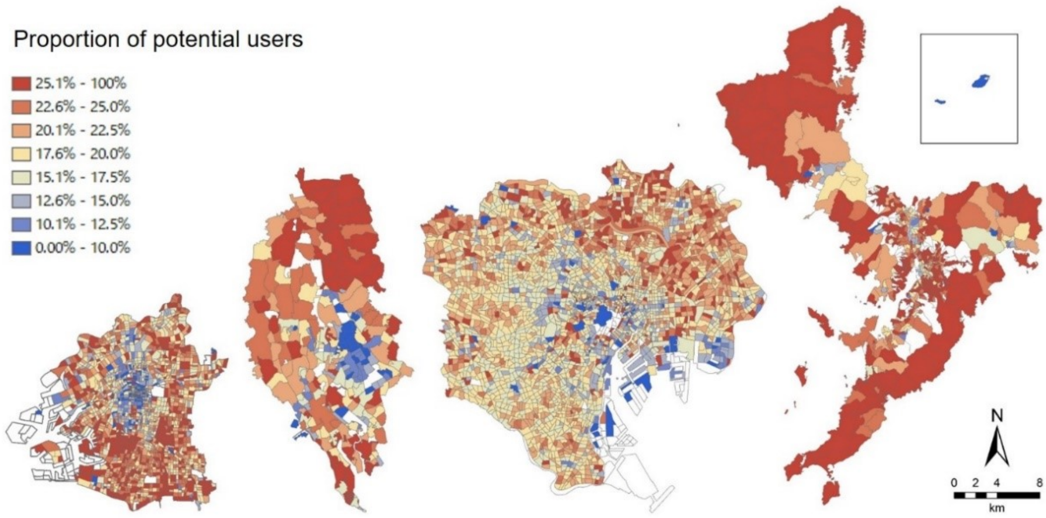


Figure 4-14 Proportion of potential users in communities.

Cities from left to right are Osaka, Tsukuba, Tokyo, and Nagasaki.

Considering the accessibility of data, I took the ratio of the elderly above 70 years old and children under 5 years old in the population to be an indicator of potential users, and a ratio higher than 20% is assumed to be high. The results are shown in Figure 4-15.

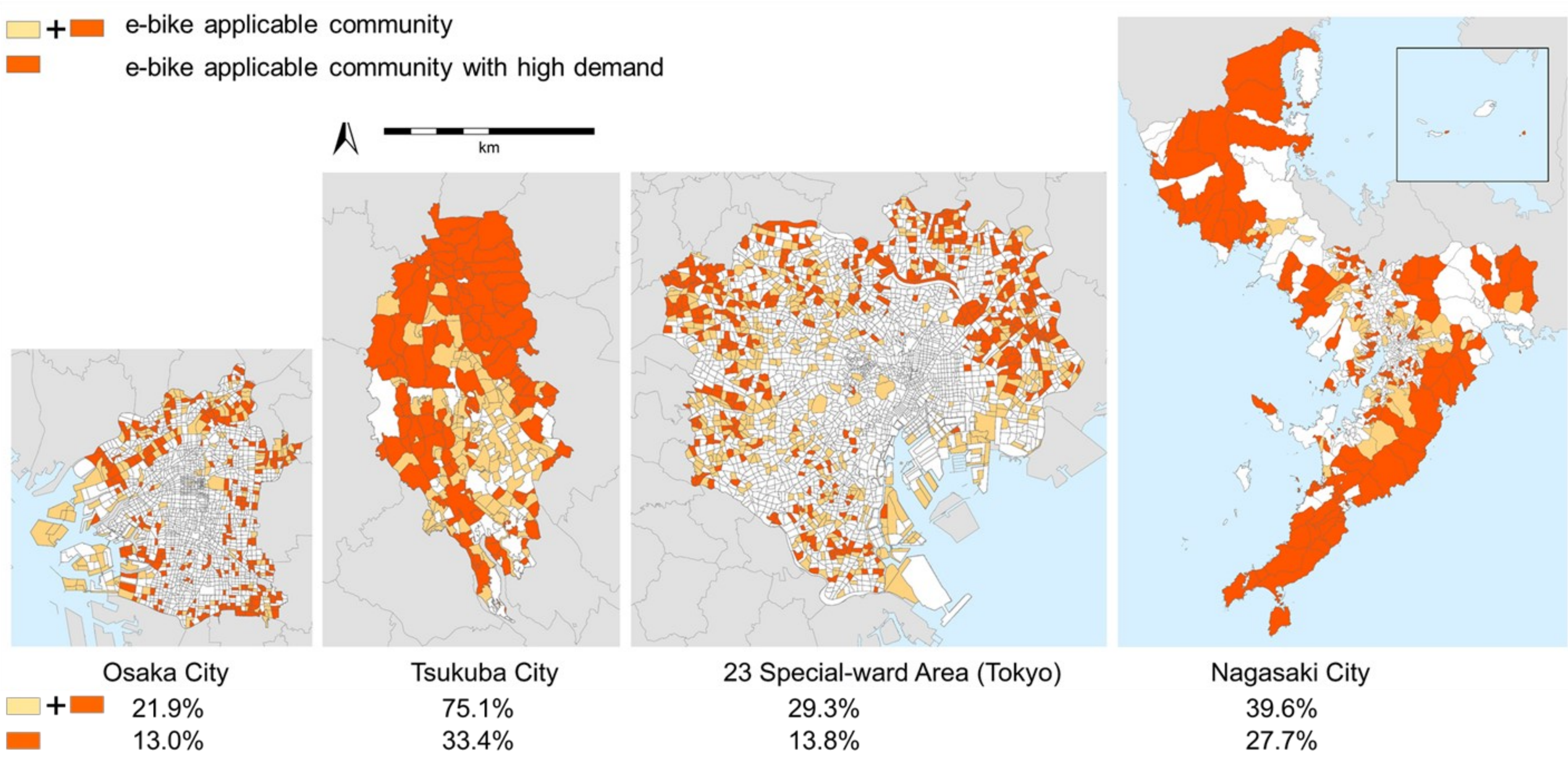


Figure 4-15 E-bike applicable communities in Osaka, Tsukuba, Tokyo, and Nagasaki.

4.4.4 E-bike applicability in different cities

To investigate the e-bike applicability in different cities, the ABAG values were calculated and plotted (Figure 4-16). When compared to public transportation (Figure 4-16 (a)(b)), in cities with well-developed transit systems, i.e. Tokyo and Osaka, e-bikes show to be applicable for short trips the applicable travel time range and physical energy range are approximately 65min and 1.25METh round trip respectively (Figure 4-16 (a)(b)). Tsukuba, the local city with flat roads, shows a longest applicable travel time and largest physical energy of 2.25 METh among the 4 cities. In Nagasaki, while the applicable time range is longer than 100min, the steep roads make e-bikes there have the smallest e-bike applicable physical energy range. Note that, the corresponding e-biking time at the applicable physical energy range in Fig.9(b), assuming the cycling roads are flat, are 22min(1.25METh) and 39min(2.25METh), which is shorter than the applicable range of 65min when only travel time is considered (Figure 4-16 (a)).

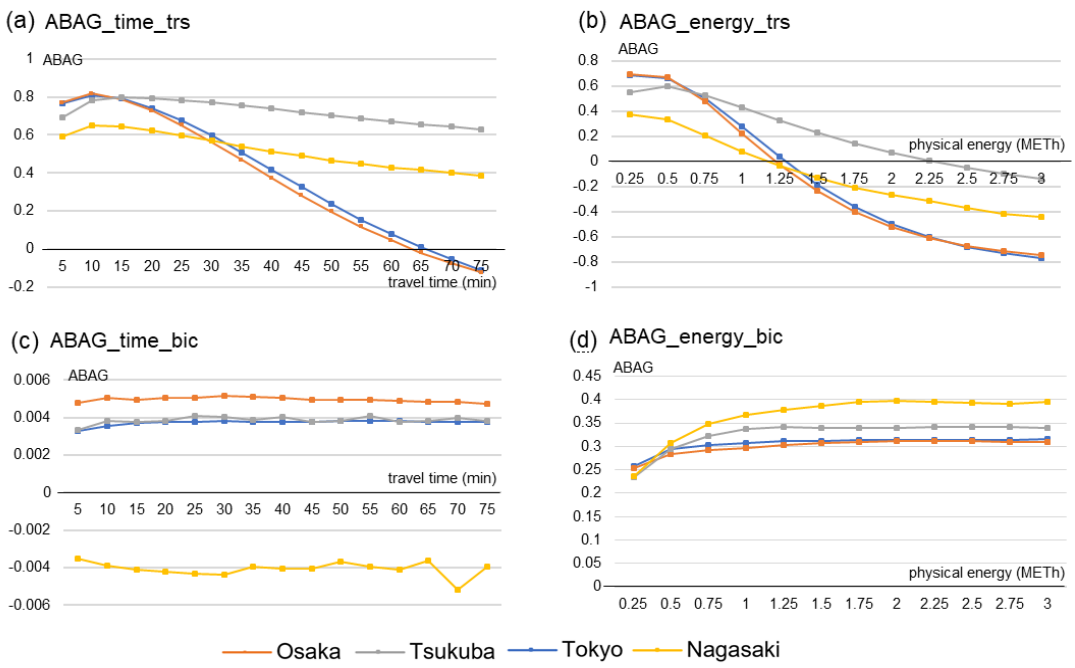


Figure 4-16 Results of the ABAG in Osaka, Tsukuba, Tokyo and Nagasaki.

4.5 Discussion

With the research goal to evaluate e-bike potential and limitations for local users, especially when compared with conventional bicycle and public transportation, I defined e-bike applicability as the change of convenience due to the introduction of e-bikes into the existing urban transportation system, and proposed an assessment methodology based on comparison. Then, the method is applied to four Japanese cities with different environments, including road gradient and transit density, and with their urban form and bicycle modal shares. as a case study.

The study in this chapter can extend the literature on bicycling convenience by (1) proposing an evaluation method for e-bikes, (2) adopting a comparative method to explore the potential and limitations of e-bikes, and (3) quantifying physical energy expenditure in different transportation methods, especially conventional bicycling and e-biking.

This methodology can be a valuable tool that provides urban planners with knowledge about e-bikes in two spatial scales: community-wide scale (with BAG) and city-wide scale (with ABAG). The indices can be valuable tools providing urban planners with knowledge about e-bikes in two spatial scales: community-wide scale and city-wide scale. Addressing the first research question about places and conditions in which e-bikes can improve the resident mobility, the results show that (1) when compared to conventional bicycles, e-bikes are applicable in areas with steeper road grades or with geographical obstacles requiring a detour and (2) when compared to transit, e-bikes are applicable in areas lacking public transportation, e.g. fringe areas in large cities or local cities. The e-bike applicable communities and those with likely high e-bike demand are selected to inform the policy decisions about where to establish the infrastructure to support e-biking. With regard to the second question about the e-bike applicability in different cities, the results show that (1) e-bikes are applicable for short-distance trips in cities with well-developed transit systems, as the applicable travel time and physical energy expenditure are 65 min and 1.25 MET-h round trip; (2) e-bikes are promising alternative means of transport in local cities; and (3) e-bikes show their limitation in terms of physical energy expenditure when compared to transit.

Here are some discussions on the implication and limitation of the results in this chapter.

The information used in the extraction of high e-bike demand districts can be specific to Japan, but a similar method can be applied with other demographic perspectives for a specific city and to inform policy decisions concerning mobility equalities. For instance, in some developing country cities, e-bikes are considered by the local government to be dangerous and should be forbidden, but they also play a role as important transportation methods in low-income fringe communities where the public transportation system is not well-built. A comparison of BAG data with socio-economic data can help explain the extent that policy may influence the inhabitants' lives.

While the present study focuses on the improvement of mobility and calculating the physical energy as a cost, e-bikes as an active transportation mode are expected to advance public health by promoting physical activity. In future e-bike applicability evaluations, the viewpoint of treating physical activity as a benefit is needed.

Although e-bikes are assumed to be privately owned and riders use them as the only transportation mode in their travels, multi-modal transport is an important issue that needs to be investigated, with the possibility of combining e-bikes with bus and railway.

The influence of dedicated bike lanes, charging stations, and e-bike parking areas on e-bike impact can also be studied in the future, as the scope of e-bike applicability evaluation in this study is limited to the rider's personal standpoint, and the components were limited to travel time and physical energy expenditure. A wider and more external range of perspectives, including economic, environmental, traffic safety, and social equity need to be evaluated.

Going back to the context of this thesis, where the status quo has a high proportion of bicycles is not precisely in line with what the research has yielded as appropriate for the development of e-bikes. This is partly because e-bikes are different from bicycles, and bicycles in the status quo do not reflect the advantages of e-bikes in terms of saving physical energy, and perhaps the introduction of e-bikes would help to increase the number of bicycles.

On the other hand, it is also because not every aspect of the users' choice is considered. For example, in Nagasaki's suburbs, the results show that e-bikes are suitable for development, but the bicycle share data for the whole of Nagasaki shows that the percentage of bicycles used is not high, while the rate of buses is high. I supposed it is because the study did not consider the frequency of buses and railways and the correspondence between positions of workplace and residence, etc. Shorter headways and well-designed bus routes similar to the origin-destination demands can increase the willingness to use buses. Although the northern and western parts of Tsukuba are shown to be suitable for e-bikes, the proportion of e-bike usage is far less than that in Osaka. This is because the analysis did not consider private cars, which account for 60% of the trips in the current situation. Relative to the other three cities, Osaka has a considerably high proportion of bicycle commuters, but the results do not show the relative advantage of e-bikes at the city or neighborhood scales. This may be due to the flat terrain and the correspondence between workplace and residence or the existing cycling share system, which was not considered in the study.

While some factors were not considered in this chapter of the study, they will not pose a challenge to the main conclusion that e-bikes have the advantage of being able to improve convenience in terms of both physical energy cost and travel time cost for residents, especially outside of urban centers where transit is not widely available.

Despite their potential, bicycles face conflicts with pedestrians and motorized vehicles, as shown in Section 1.3.3. While providing services that meet various demands, mitigating conflicts between transportation users is also necessary. In the next chapter, I focused mainly on road space for multiple types of transportation users.

5. Road space allocation for multi-modal users on road segment and at intersection

5.1 Introduction

After confirming e-bikes have the advantage of being able to improve convenience for residents in Chapter 4. I focused on mitigating conflicts between e-bikes and other transportation users in this chapter.

Road space must provide diverse users. As many cities consider car-based transportation system is no longer desirable from the environmental and financial perspectives, discussion raised about multimodal transportation planning and fair service that road space can provide (Creutzig et al., 2020; Haas, 2018; Nello-Deakin, 2019; Silvano et al., 2016; S. Tsigdinos et al., 2021).

Among the active transportation methods, cycling is promoted in many places as a sustainable and healthy means. Meanwhile, e-bikes have an increasing usage on public roads in Japan, and together with the expectation on them to help with sightseeing and local mobility, e-bike usage on public roads is increasing. Since bicycles are regulated to use car lanes, car-bicycle conflicts in mixed traffic can hinder car speed and can raise cycling safety concerns, especially on narrow roads in urban areas. Though categorized as bicycles and sharing the same traffic rules, e-bikes have higher average speed and quicker acceleration than conventional ones. When promoting cycling, planners have options of where and how to construct bikeway facilities. Therefore, cycling promotion requires a scope of multi-modal transportation design.

On bikeway design modeling when considering traffic on road, previous research has been conducted with different approaches. Cellular automata model is a kind of temporal and spatial discrete traffic flow model. The Nagel-Schreckenberg (NaSch) (Nagel & Schreckenberg, 1992) CA model and the multi-value CA (MCA) model are two categories of CA model widely used to simulate nonmotorized traffic. Though the cellular automata modeling reported being well-performed in mixed traffic simulation on road segments, it is difficult in nature to applied for simulation at crossings, which can be critical in bikeway design.

Microscopic simulation methods are applied recently. Different from cellular automata model that simulates traffic flow in a spatially and temporally discrete way, microscopic model that simulates space continuously, is reported to be a useful tool, providing another option to simulate traffic flow.

5.2 Objective

To assist decision making in bikeway planning, this study aims to provide information about transport efficiency in different bikeway links, intersection treatments, and local bikeway network when considering the compatibility of e-bikes with other transportation methods on road.

This chapter focused on three sub-topics specifically. (1) In the road link model, transport efficiency was explored in road space allocation scenarios, considering mixed traffic of cars, bicycles, e-bikes, and buses. (2) In the intersection model, the passing efficiency of three intersection treatments was estimated, (3) In the network model, a grid network is used to discuss the importance of intersection treatments using efficiency.

5.3 Multi-agent road space models

Analysis in Section 5.3 is conducted using multi-agent models.

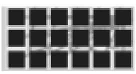
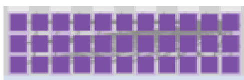
5.3.1 Agent settings

To obtain the basic knowledge of the relation of transport efficiency with road width, e-bike ratio, and traffic volume, a one-way bikeway model is built using a grid-based multi-agent approach analogous to the CA model. NetLogo is used as the platform, which is a multi-agent programmable modeling environment (Wilensky, 1999).

The model is temporal and spatial discrete. which means the coordination, time unit, and agent size and speed are integers. The time unit is a tick, 1 tick = 1 second. One agent occupies area of one square meter with side length of one meter. There are two kinds of agents: (1) Mobile agents ("turtles" in NetLogo) are used to simulate vehicles. Because I combined several mobile agents as a vehicle, I will avoid using the word "agent" but use "unit" to refer to vehicles in the model (Table 4-1).

(2) Stationary agents ("patches" in NetLogo), used as the background on which mobile agents move. They are used to control the permission of mobile agents' road area usage. For example, to simulate bicycle dedicated lane with physical separation, stationary agents "bike lane" can forbid mobile agents labeled as "car" to move on; to simulate the strip shared use by cars and bicycles, the stationary agents "car lane" are set to allow both kinds of agents of "bicycle" and "car" to move on. Road space in horizontal direction is infinite, which means when motive agents move past the horizonal edge, they disappear and reappear on the opposite edge. The mobile agents move in right-hand traffic.

Table 4.1 Size settings of mobile units.

Unit	Width [m]		Length [m]		Shape in model
	In reality	In model (lateral distance incl.)	In reality	In model (rear distance incl.)	
Bicycle	< 0.6	1 (0.2)	< 1.9	2 (0.1)	(2 agents)
E-bike	< 0.6	1 (0.2)	< 1.9	2 (0.1)	(2 agents)
Car	1.7	3 (0.65)	4.7 [a]	6 (1.3)	 (18 agents)
Bus	2.5	3 (0.3)	7~9 [b]	11 (1)	 (33 agents)

5.3.2 Forward movement

In cellular automata models used to simulate bicycles mixed traffic, there are two types of prototype models, Nagel-Schreckenberg (NaSch) model and Burgers CA (BCA) model (Section 2.6.1). NaSch model was employed due to it is seemingly easier to transformed into a multi-agent simulation model.

NaSch model is applied to determine the basic forward movement of mobile units, which can be divided into 4 steps in every tick. (1) Acceleration: the unit finds the highest speed it can reach. (2) Deceleration: it revises the speed based on the distance to the nearest previous unit. (3) Randomization: it slows down at a probability, because not all vehicle users move at the maximal possible speed, besides, something uncertain can also disturb traffic flow. The widely used slowdown equation of $v_{t+1} - 1$ is employed. Since 1 is the smallest positive number in NaSch model system, this equation means slowdown at the smallest extent. (4) Position update: the unit advance v_{t+1} cells forward. The steps can be summarized as Eq. (5.1)-(5.4). The relevant settings of each unit categories are listed in Table 5.1.

(1) Acceleration: $$v_{t+1} = \min(v_{t+1} + a, v_{\max}) \quad \textbf{(5.1)}$$

(2) Deceleration: $$v_{t+1} = \min(v_{t+1}, d_t) \quad \textbf{(5.2)}$$

(3) Randomization: $$v_{t+1} = \max(v_{t+1} - 1, 0) \text{ at probability of } p_{\text{radm}} \quad \textbf{(5.3)}$$

(4) Position update: $$x_{t+1} = x_t + v_{t+1} \quad \textbf{(5.4)}$$

where

v_t	speed at time *t*
$v_{\max}$	max speed the vehicle can reach
a	randomized deceleration probability
d_t	distance to the previous agent at time *t*
p_{radm}	randomized deceleration probability
x_t	position of unit at time *t*
$\min(x_1, x_2, \cdots)$	the smallest of the x_i
$\max(x_1, x_2, \cdots)$	the largest of the x_i

Table 5.1 Settings in forward movement of mobile units.

Units	Maximum speed [m/sec]	Acceleration [m/sec^2]	Randomization probability
Bicycle	6	1	0.2
E-bike	7	2	0.2
Car	20	2	0.2

Bus	15	2	0.2

5.3.3 Lateral movement

The NaSch model is for forward movement. It is necessary to add the lateral movement into the model, to simulate cyclists' preference to the sidewalk side when riding on an on-road path to keep a distance from the cars nearby, drivers' preference to maintain on the current lane.

I added a lateral movement into movement model. When a unit moves in lateral direction, it moves to the direction vertical to its heading direction, at the distance of its own width. For instance, a car moving forward can move 3 agents left or right. I proposed a lane changing coefficient $c_{m,t}$ as Eq.(5.5), which is decided by both the preference to change to a specific side and the distance to the previous agent on that side.

$$c_{m,t} = d_{m,t} f_{m,t} \qquad \textbf{(5.5)}$$

where

$c_{m,t}$	coefficient of lane changing to lane *m* at time *t*
$d_{m,t}$	distance to the previous agent in lane *m* at time *t*
$f_{m,t}$	preference factor to change to lane *m* at time *t*

$$m = \begin{cases} 0 & \text{current lane} \\ 1 & \text{car lane side lane} \\ 2 & \text{sidewalk side lane} \end{cases}$$

Table 5.2 Setting of preference factors.

Unit	Preference factor		
	Sidewalk side	Current	Car lane side
Bicycle and e-bike	2	1	0.5
Bus	2	1	0.5
Car	0.5	1	0.5

If the unit is not allowed to use lane *m*, $c_{m,t} = 0$. After calculating all $c_{m,t}$, the unit will choose the lane with maximal $c_{m,t}$. If the unit change lane, i.e. m=1 or m=2, its speed minuses 1. Then the unit decides its lane and take the forward movement using method in last section. The settings of preference factors for different unit categories are set in Table 5.2. Figure 5-1 shows an instance of lane changing coefficient calculation for cars. The cars A and B will choose staying in its current lane because c_0=max (c_0, c_1, c_2).

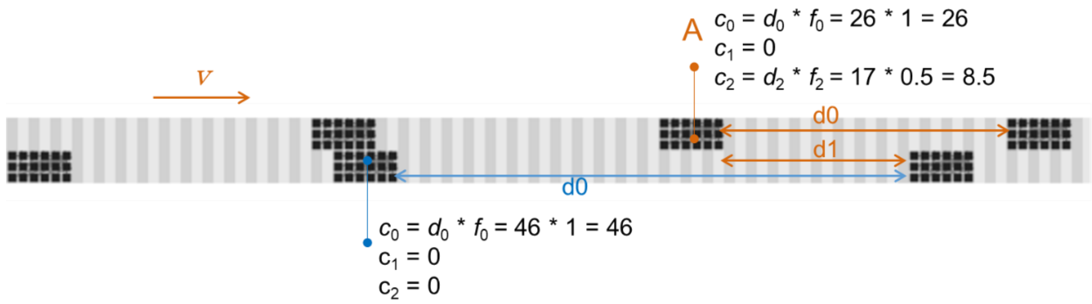


Figure 5-1 Example of lane changing decision

The main input variables are the number of lanes, the permission of mixed traffic on lanes, and traffic density, i.e. number of each category of vehicles per 100m. The output variable is traffic volume in a specific period, which is taken as a measure of transport efficiency.

When simulating, mobile units are initially put randomly on lanes following the lane permission before moving tick by tick. Then in one tick, the mobile units update their states one by one in the order of car, bus, e-bike, then bicycle. In a same unit category, the units update their position in a random order. A course from randomized initial to 1200th ticks is one loop. Outputs from first 200 ticks are discarded and those from 201~1200th ticks are summed up. Average of the sums from 50 loops is adopted as final results.

5.3.4 Compare e-bike efficiency with others

First, I considered e-bike efficiency when compared with solely one type of transportation modes. Inputting the density of vehicles as the variables, I simulated the number of vehicles passing through in 1000 ticks. In the case of all bicycles and all electric bicycles, when considered 1m, 2m and 3m, the e-bikes are 1.24 times efficient in using road space when compared with conventional bicycles (Figure 5-2).

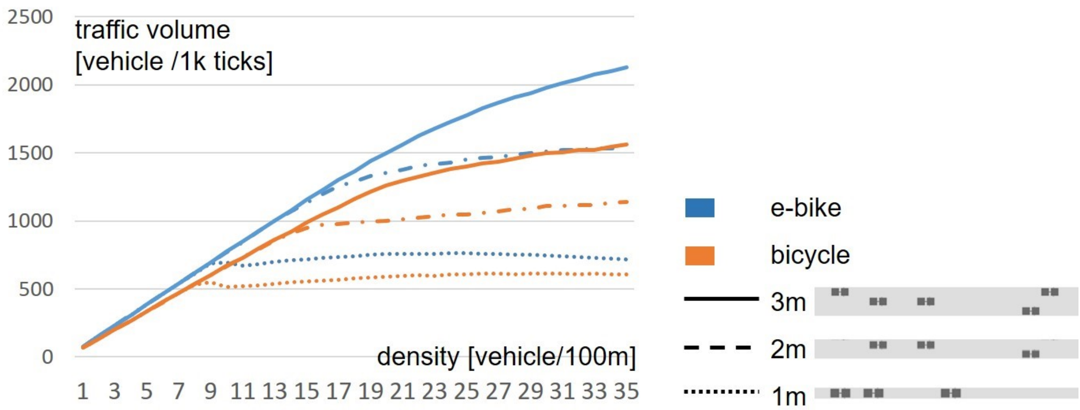


Figure 5-2 E-bike vs. bicycle (1m, 2m, 3m roads)

Next, I compare road space usage efficiency of e-bikes to cars or bus on a road with width of 3 meters (Figure 5-3). The x-axis is the number of cells with users on the road. This is the coverage of the road. For example, one bicycle has 2 cells and one car has 18 cells of different sizes. The y-axis is the number of people passing through, which is depends on the number of passengers onboard the vehicles. Result shows that when the roads are congested, bicycles have an advantage in terms of efficient use of road space, even when there are three people in a car. This is because bicycles are more agile and flexible than cars, thus more unlike get stuck in traffic jams. Even though bicycles have an advantage over cars, bicycles have their limitation when compared with buses. If there are 9 people on a bus, the bus can always beat bicycles in road space usage efficiency.

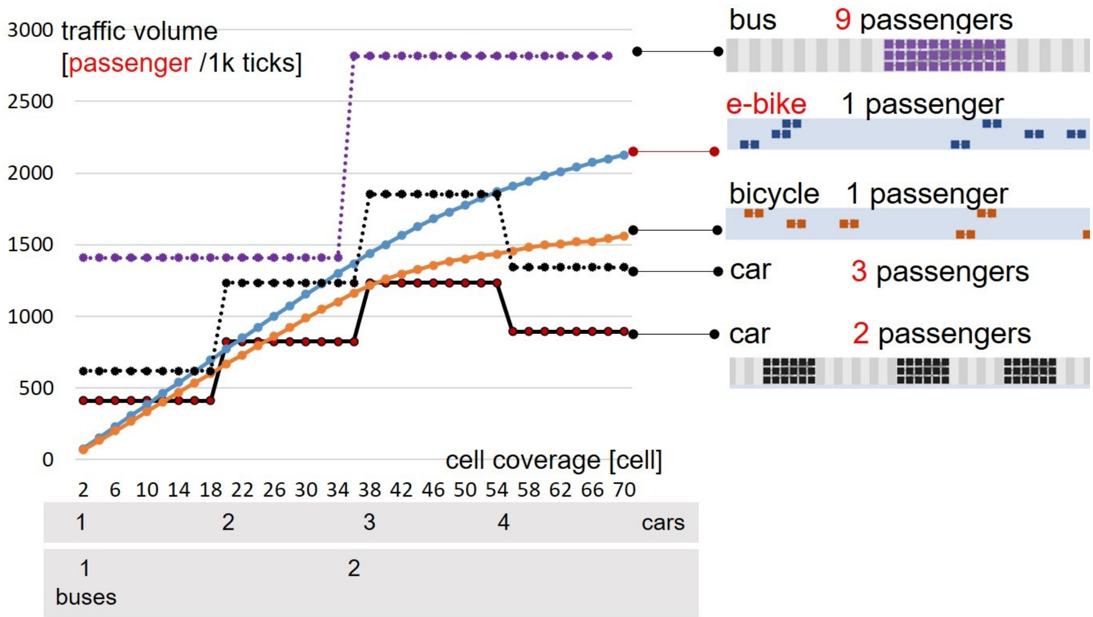


Figure 5-3 E-bike vs. bicycle/car/bus on 3m road

5.3.5 Road allocation between e-bikes and others

This section considers road allocation between e-bikes and other road users. Figure 5-4 considered mix with bicycles. Two scenarios are set: mixing bicycles with electric bicycles and separating them on the same 2-meter road width. Bicycle density is constant as 10 units/100m lane, and the variable is e-bike density.

Results show that mixing e-bikes and bicycles always provide better efficiency than separation. In the agent movement rule settings, the assumption is that vehicles attempt to move as fast as possible. E-bikes with faster speed can clear the way out for both e-bikes and conventional bicycles to move forward, while with high conventional bicycle ratio the previous bicycles limit others' cycling speed behind.

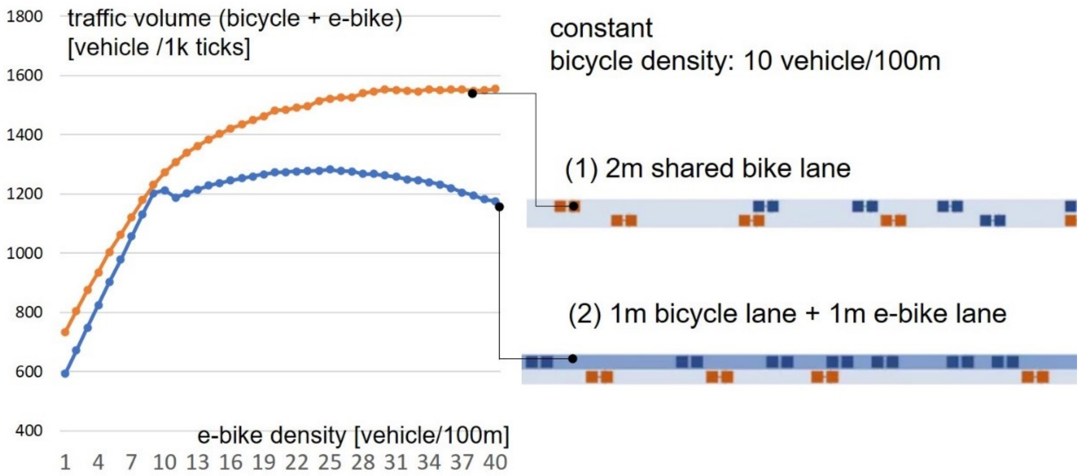


Figure 5-4 Road allocation between e-bikes and bicycles

To investigate impacts from cyclist-car interference on efficiency in different road space reallocation scenarios (Figure 5-5), three scenarios are set as (1) 1 car lane + 2m bike lane; (2) 1 car lane + 1m bike lane; (3) 1 car lane + 1m separate bike lane + 1m mix bike lane. Car density is a constant of 5 vehicles/100m, and or e-bike density is variable.

The result shows that up to 8 e-bikes/100m, scenario (1) and (2) have same traffic efficiency as both the e-bikes and cars enjoy free flow speeds, but scenario (2) has advantage of using road space economically that use less road space. When density is over 10 e-bikes/100m, sharing 1m of car lane to e-bikes can be a trade-off alternative to save place and improve efficiency. When bike lane become crowded, the cyclists may spill out to use the neighborhood car lane. The result indicates in this case, painted bike lane allowing the “spill out” can be better than physically separated bike lane with less elasticity.

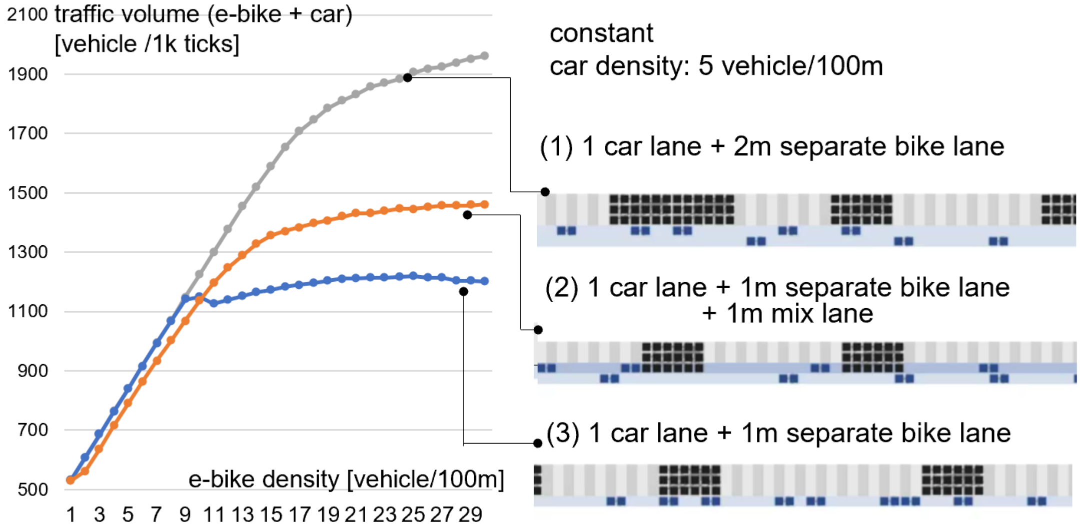


Figure 5-5 Road allocation between e-bikes and cars

To search an efficient way to reallocate road space for bicycles and buses (Figure 5-6. Figure 5-7), three scenarios are set: (1) 4m shared bus lane; (2) 3m bus lane + 1m bike lane; (3) 4m bus lane including 1m shared lane. Bus density is constrained to 1 vehicle/100m. Here passenger number is used as measure of transport efficiency instead of traffic volume. We assume 5 passengers on bus and 1 passenger on one bicycle or e-bike. Result shows scenario (2) and (3) have the same efficiency, suggesting that when building a combination of bus lane and bike lane within 4m road width, there is no need to physically separate them, a painted bike lane will do just fine. When bicycle density is higher than 16 vehicles/100m, sharing all bus space can be a more efficient alternative.

I have to admit that I cannot explain some phenomenon in the results in Figure 5-2, Figure 5-4, Figure 5-5, Figure 5-6. In cases when bicycles cannot change their lanes in all the figures (Figure 5-2 (1m lane), Figure 5-4(2), Figure 5-5(3), Figure 5-6(2)(3)), after the peak in traffic volume at some e-bike density (about 9 e-bike/100m), the volume decreases to about 10 e-bike/100m and then the volume increases with a gentle slope and maintain or decreases slowly again. The volume increases steeply when the density is lower than 9 e-bike/100m as the vehicles are running at their maximum speeds, performing a free flow. It is considerable that after the peak of the volume the congestion occurs and no matter how densely the vehicles are, they can only move slowly thus the volume does not increase as quickly as when there is free flow. But I cannot explain why the down-and-up happens in cases when bike lane is 1m. This phenomenon happens when there is only one type of vehicle in Figure 5-2, so it is not due to the way to count the total number of bicycles and another kind of vehicle. Because the phenomenon recurs in a similar form in different scenarios, it could be a systematic error, or it could have some sort of mechanism that I failed to understand.

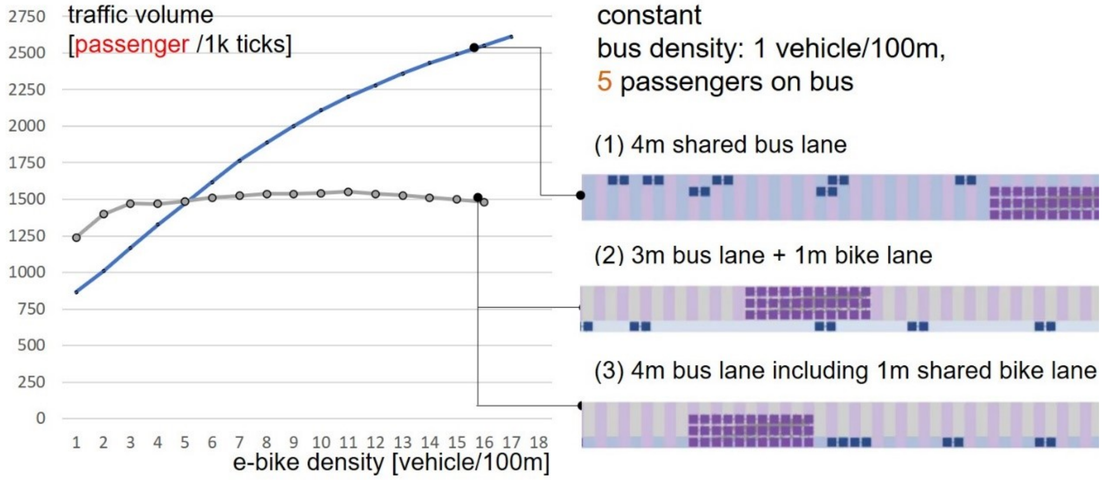


Figure 5-6 Road allocation between e-bikes and buses

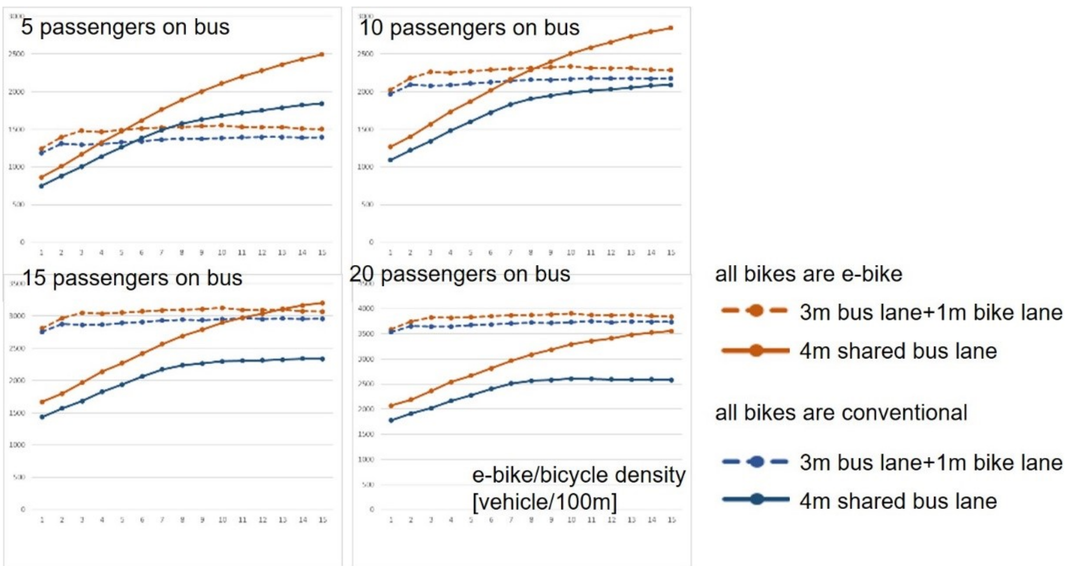


Figure 5-7 Road allocation between e-bike/bicycles and buses

5.3.6 Modal shift to e-bikes

Figure 5-8 consider a modal shift from car to e-bikes or bicycles, assuming that there initially are 10 cars on a 200m road and two passengers in each car. The x-axis of the graph is the modal shift rate. For example, a modal shift rate of 10% means that two people in one car to begin with would ride two electric bicycles instead of a car.

The result is that Scenarios 1 and 3, i.e., separating the car and bike lanes, are most efficient at a 40% shift rate, while Scenario 2, the mixed case, would not be advantageous unless all cars were changed to bicycles. The results for a modal shift to conventional bicycles are similar with that to e-bikes.

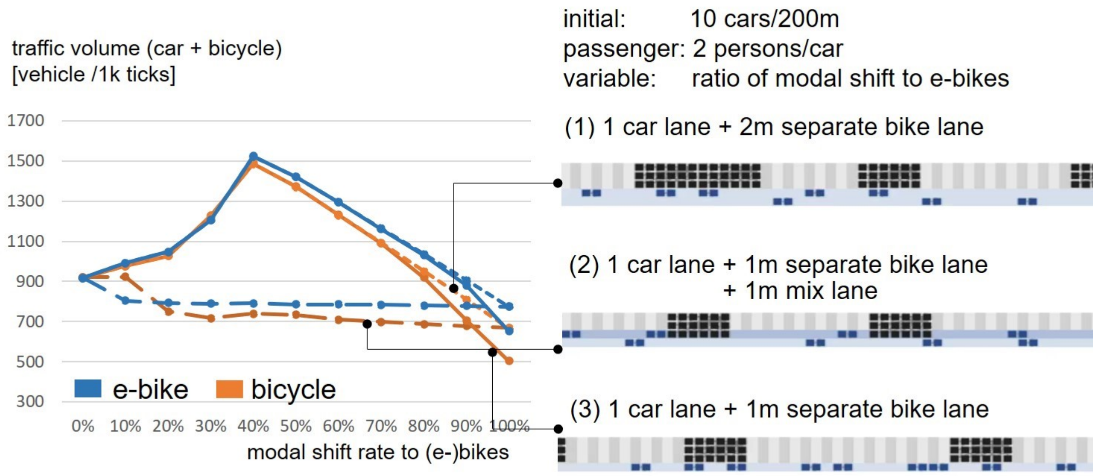


Figure 5-8 Shift from car to e-bike/bicycle

Figure 5-9 considers a modal shift from conventional bicycles to e-bikes when the density is 20 bicycles per 100 meters. Mixing is more efficient than separation at any shift rate, and efficiency is best at 100% shift rate. Different densities would give different results, but the conclusion that mixing is better and that efficiency is best at 100% shift rate tend to maintain the same.

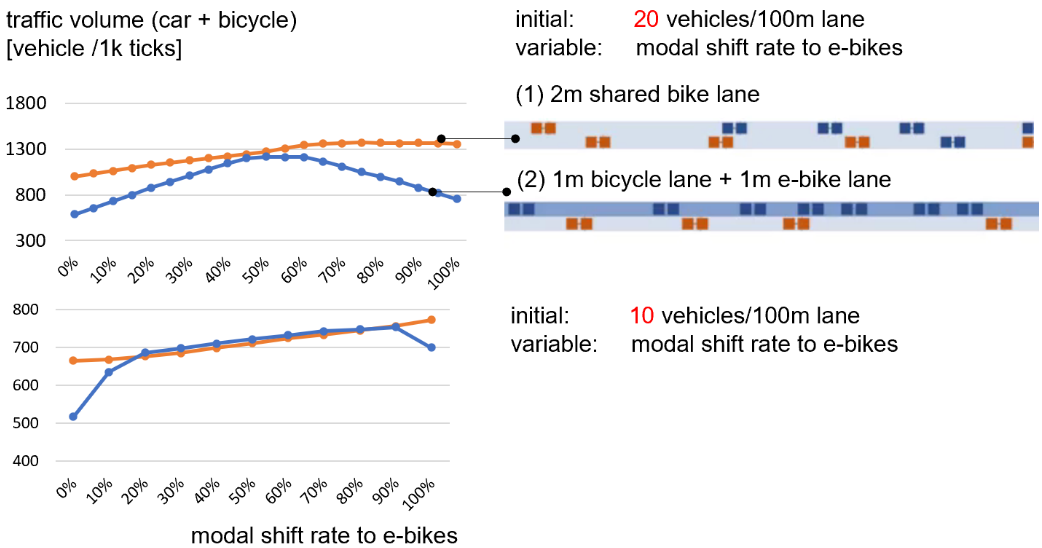


Figure 5-9 Shift from bicycles to e-bikes

5.4 Microscopic models

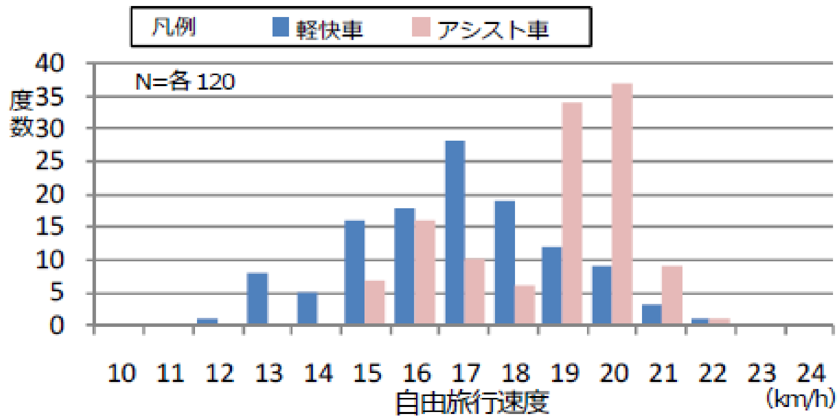
Analysis in Section 5.4 is conducted using microscopic models.

5.4.1 Vehicle features and road space models

After trying the multi-agent models on NetLogo, I tried out the microscopic traffic simulator software PTV Vissim.

To simulate e-bikes and bicycles, variables are needed to input. For desired speed distribution settings, a set of empirical free flow speeds from a previous Japanese study (Yamamoto, A., Owaki, T., and Uesaka, K. 2011) is used for both e-biking and bicycling. Regarding other settings of acceleration functions, deceleration functions, and driving behaviours settings including following, and overtaking movement, detailed settings are absent in Japanese studies. Thus, a research report (COWI. 2013) on microsimulation of cyclist behaviours in Copenhagen is adopted, assuming the Japanese cycling behaviours are consistent with those in Copenhagen. The left-hand traffic in Japan is different from the COWI model, so I modified the desired position at free flow, overtaking side and minimum longitudinal speed to correspond.

While cars follow the lane-based rules in the model, the bikeway model is a non-lane-based traffic model, in which only the width of the bikeway link is assigned but no lanes are allocated. Thus, bicycles can move more freely than lane-based cases and overtake actively without sticking to certain lanes as automobiles. be The car model employed default settings, and the desired speed is set to be 30-35km/h.



	平均値	中央値	85%タイル値	最大値	標準偏差	歪度
軽快車	16.8	16.8	18.2	21.7	2.1	0.001
ｱｼｽﾄ車	18.6	19.1	19.8	21.7	1.8	-0.677

Figure 5-10 Free-flow speed

(Yamamoto, A., Owaki, T., and Uesaka, K. 2011)

To obtain the basic knowledge of the relation of transport efficiency with road width, e-bike ratio, and traffic volume, one-way bikeway models are built (Figure 5-11). The driving behavior of cyclists are non-lane-based, which means each bikeway link is not separated into lanes. Thus, (e-)bikes are allowed to be at any position on the link as far as they satisfy some conditions, and they are able to overtake actively without sticking to certain lanes as automobiles.

The widths of 150m bikeways are set to 1.0m, 1.5m, 2.0m, 2.5m, and 3.0m. The volumes of bicycle (including e-bikes) are 250 vehicle per hour (vph), 500 vph, 1000 vph, 1500 vph, and 2000 vph. The e-bike ratio among bicycles is set from 0% to 100% at an interval of 10%. The average speed of (e-)bikes running through the finish line is used as the measurement for transport efficiency. The speeds obtained from 10 runs are averaged.

In one-direction road models, it shows that the e-bike ratio among bicycles can bring up the average speed and also the conventional bicycle speeds. I speculate that this is because previous e-bikes moves fast and can clear the way out fast for both e-bikes and conventional bikes, increasing the following bicycle speed when it is slower than its desired speed. Note that the increasing speed can increase the risk in traffic accident.

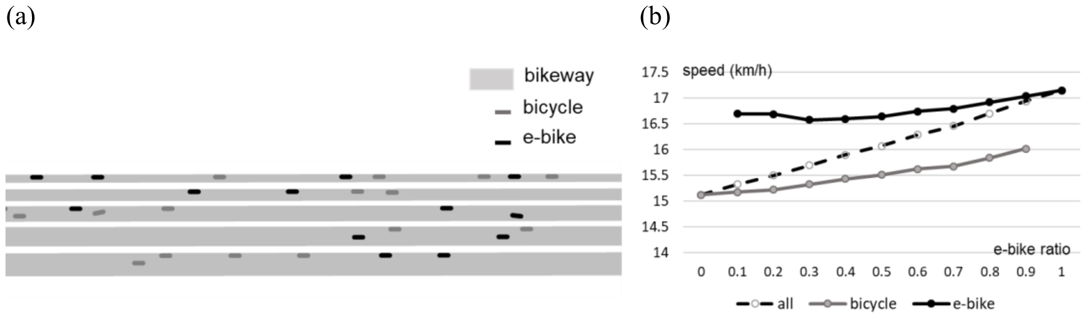


Figure 5-11 Models and result

(a) One-way road models (volume = 1000 vph)

(b) E-bike ratio and average speed (road width = 1.5m; volume = 1000 vph)

5.4.2 Bicycle-considered intersection models

In intersection model, the passing efficiency of three intersection treatments was estimated. Three kinds of intersection treatments models are (1) intersection with two direction bike way, (2) intersection with one direction bikeway, and (3) intersection with bike box.

The two-direction bikeway is not an advised type in the *Guideline for building safe and comfortable cycling environment*, because the bicycles that runs in different direction with motorized vehicles are faced with accident risk, and at intersections bicycles moving in different directions with each other can increase danger, the bicycles lanes are basically in one-direction. However, bi-direction bicycle traffic exists where bikeways are designed to be bi-direction (Figure 5-12) or bicycles on sidewalks move against the direction of motorized vehicles.

Figure 5-12 A bi-direction bikeway near Shinmatsudo Station, Japan
(retrieved from Google Street View)

Figure 5-13 shows the intersection layouts, including the waiting zone, width of car and bicycle lanes, and bicycle and car routing decisions, and the whole size of an intersection model. The one-direction bikeway is advised type. When setting the layouts of intersection with one- and two-direction bikeways, I referred to some features in protected intersection. I could not reflect all protected intersection designs in the layouts, because pedestrians are not included and the simulated vehicles do not react to painted markings. I considered the elements of refuge island and the forward stop line for bicycles. Taking the vehicles from the western leg as examples, bicycles and cars move following routing decisions in Figure 5-13(b) and (c) respectively. When it is red signal, bicycles and cars stop in waiting zones shown in Figure 5-13(a). When choosing a direction among possible routing decisions, the probabilities are equal. When there are 3 routing options, the probabilities are 0.333, when 6, then 0.167.

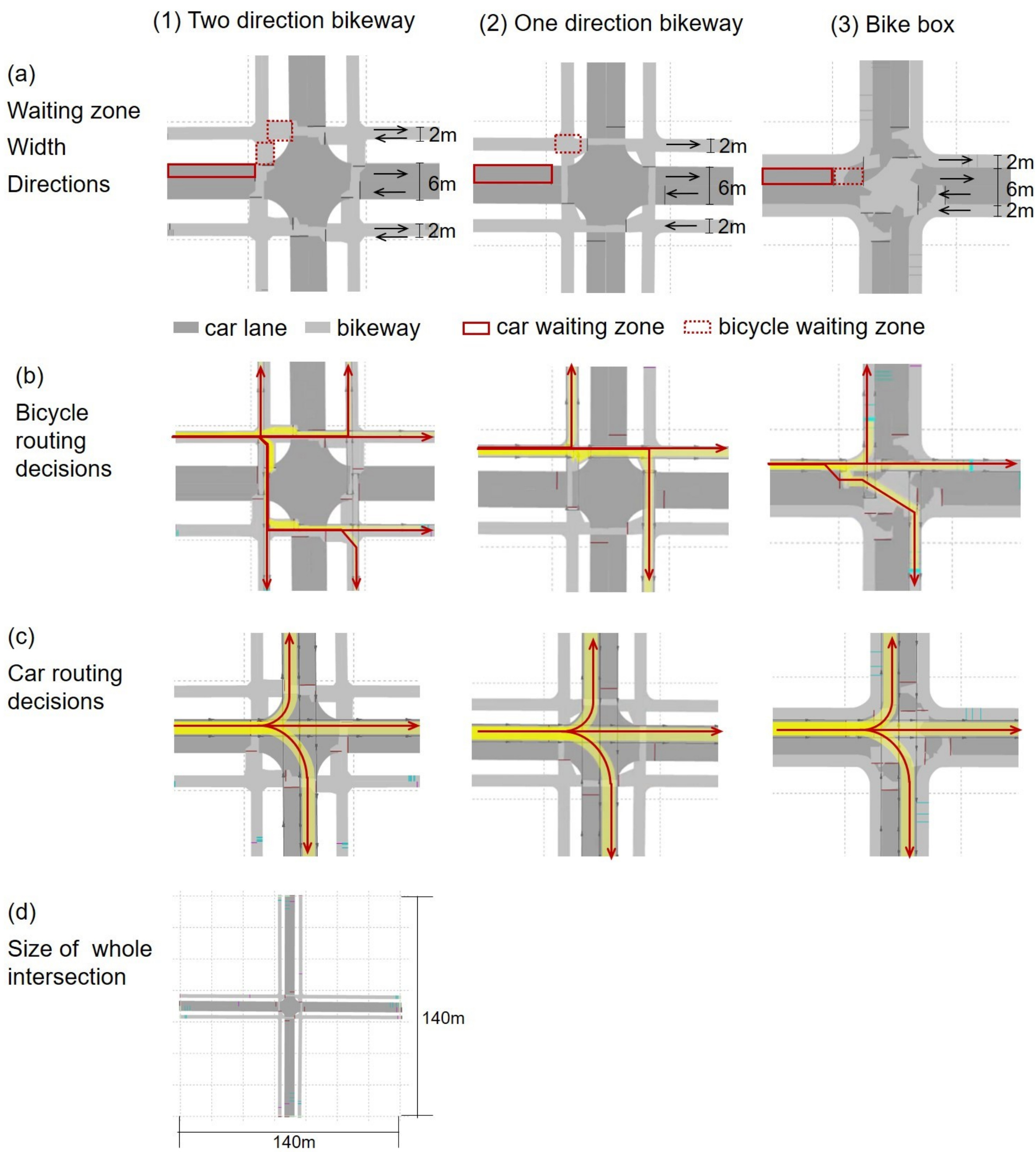


Figure 5-13 Scenarios in intersection model

(a) Waiting zones for signal (picture shows the zones for vehicles approaching from western leg), width, direction of car and bicycle;(b) Bicycle routing decisions (arrows shows directions for vehicles approaching from western leg); (c) Car routing decisions.

In conflict areas, which means the locations where vehicle routes overlap and interfere with each other, (e-)bikes take priority over cars. All three scenarios adopted one same signal cycle of 60 sec, within which the signal sequence is red-amber-green-amber, and periods for each phase is 30sec, 1sec, 23sec, and 5sec respectively (Figure 5-14). The input traffic volume of cars and bicycles are 200 vehicles per hour (vph). The average passing time of all directions going through the intersections in for 3600 simulation seconds in 10 runs is calculated as the measurement for transport efficiency. The point at which begin counting the passing time is 70m away from the center of an intersection.

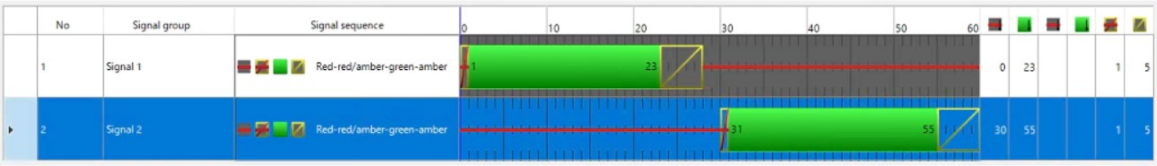


Figure 5-14 Signal sequence

Figure 5-15 shows the average passing time from the simulations. Comparing the general trends between the three scenarios, the scenario 3, intersection with bike box can produce the shortest passing time for bicycles compared to the other two treatments. While the waiting zone for cyclists in front of waiting cars can help cyclists start up earlier, the car acceleration seems hindered about 5 seconds by these cyclists, leading to a suppression of car speeding compared to scenario 1 and 2. The passing speed of all vehicles turned out to be the shortest among the three scenarios as well in this case.

Comparing the results with different e-bike ratios, higher e-bike ratio can shorten the passing time for all bikes. I supposed the reasons can be that (1) e-bikes runs faster then conventional bicycles, thus a higher ratio of e-bikes shortens the passing time as a whole; (2) fast e-bikes clear up the space quickly thus also speed up conventional bicycles. Meanwhile, high ratio of e-bikes seems to hinder car movement especially in scenario 2. I guess this possible because that e-bikes tend to cross the streets when there is no much time left for crossing, the scenario 2 stands out in these three scenarios because the number of routing decision for bicycles is less than scenario 1 while bicycles do not have the chance to pass the intersection in bunch like scenario 3, thus bicycles are more like to pile up at the intersection. Although the difference between two and one direction bike way in scenario 1 and 2, when e-bike ratio is below 25%, the difference is marginal.

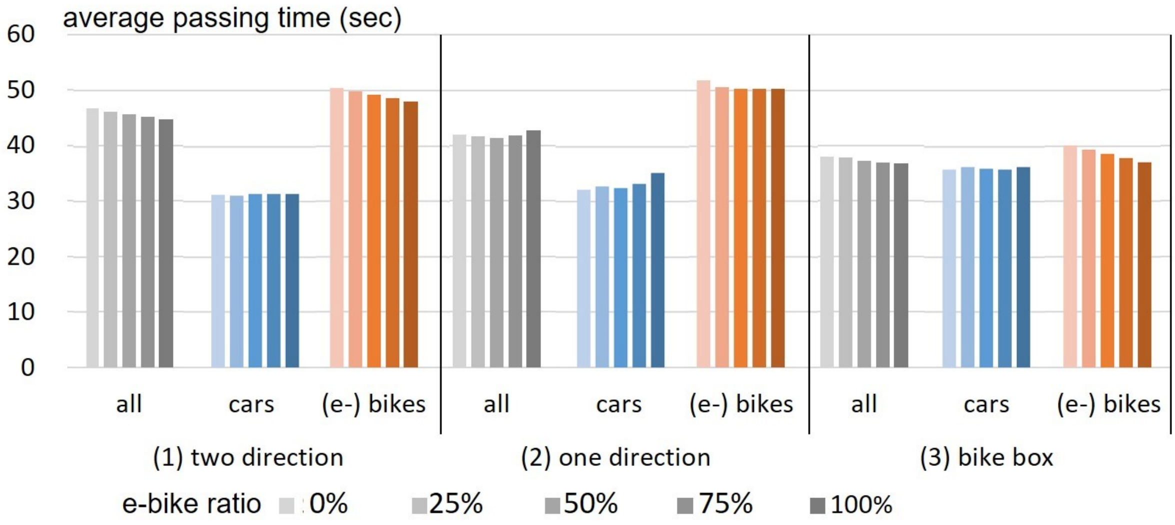


Figure 5-15 Results from intersection model

To summarize the implication on practically using these treatments, the two-direction bikeway shows its marginal advantage in passing speed for both bicycles and cars. Considering the concerns of increasing safety risk mentioned in Guideline (MLIT and NPA, 2016), it is reasonable to maintain the basic rule to keep bikeway going one-way. As the bi-direction traffic occurs in reality on sidewalks and at the intersections these sidewalks connected to, it can be reasonable to emphasize the one-direction rule. As mentioned at the beginning of this section, the bike box is virtually forbidden by *the Road Traffic Law* virtually. The results show that bicycles' passing time can be shortened by 10 seconds by bike box while the cars are hindered by 5 seconds. As cars move faster than bicycles, the difference in between bicycles and them, 5 seconds, can be compensated when they run on road segments. Bike box can be a treatment to improve cycling environment and it can be beneficial for cyclists to change the law. Note that the analysis only considered the efficiency in the research scope, the possible outcome that increasing speed can increase the accident risk.

5.4.3 Road links and intersections in network

Although I separately simulated road and intersection models, in Sections 5.4.1and 5.4.2, I was wondering that whether intersections or on-road measures have a greater impact on the efficiency of bicycle traffic if being evaluated on the road network.

In this network model, a grid network is used to discuss the importance of intersection treatments and on-road treatment in efficiency. A local network covering about 3 ha is selected as a case study target area from a community near Takasago Station. All intersections in this network are non-signaled. Passenger cars and bicycles (including e-bikes) are considered. Passenger cars enter and leave this network with a traffic volume of 300 vph. At each crossing, the probability to choose a direction among possible ones is assumed to be equal. Bicycles enter from one origin with traffic volume of 500 vph and leave from one destination. The bicycle travel time between this pair of points is recorded and averaged to assess the transport efficiency of the designated bikeway network.

Scenarios are set about (1) positions of bikeways, which is shown in Figure 5-11, and (2) priority in intersections, the (e-)bikes or cars have priority to cross the intersection, which is set using the conflict area setting in software. Conflict areas are locations where vehicle routes overlap. When any conflict areas between car lane and bikeway occur in non-signalized intersections, in scenarios with car priority, the car lanes are set to be the main route, letting bicycles on bikeways give way for cars, while in scenarios with bicycle priority, cars yield for bicycles at conflict areas.

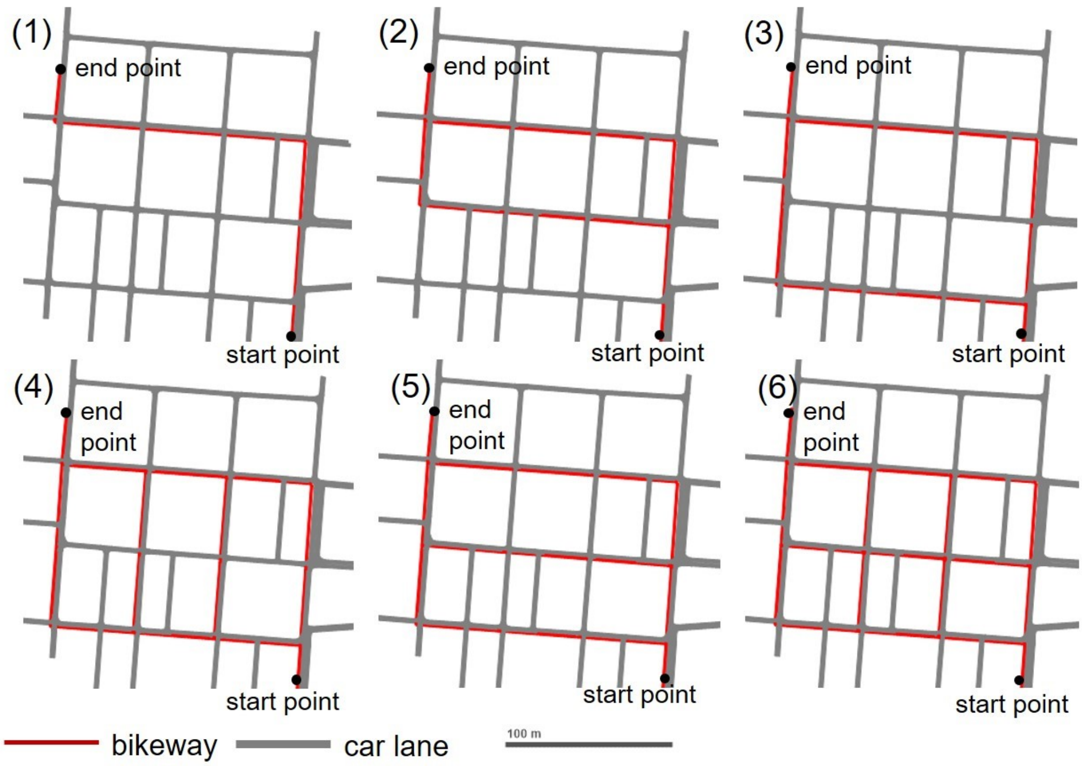


Figure 5-16 Six scenarios of bikeway design in network model.

The simulation results are shown in Figure 5-17. Note that only bicycles' passing time is recorded. Based on scenario 1, scenarios 2-6 increase the bikeway density in different ways. Comparing the brownish bars in scenario 1 with other scenarios, the results indicate that higher bikeway density (from scenario 1 to other scenarios) can increase cycle efficiency.

Focusing on the difference between brownish bars with blueish bars that shows the difference in giving priority to cars or bicycles respectively in each scenario, it is clear that the effect in increasing bikeway is less significant than giving cyclists priority at intersections. The result suggests the treatment at crossings can be critical in bikeway design. Meanwhile, the increase in efficiency due to the introduction of e-bikes is limited.

I have to admit I didn't scrutinize many of the details in the results. For example, the effect of changes in the proportion of bicycles on travel time is not consistent; the change in travel time is also disproportionate to the increase in bike lanes when comparing the same bike-first scenarios, etc. I think these may be for the following reasons. Roads on the network are mostly one-way because of their narrowness, and adding bike lanes might complicate traffic flow at intersections and thus affect the results. This is a simulation analysis and was conducted a limited number of times, and the random phenomena in the simulation itself can create uncertainty in the results. However, I do not think these pose challenge to the main results that bicycle-considered measures at intersections are of the same level if not a higher level of importance in terms of efficiency.

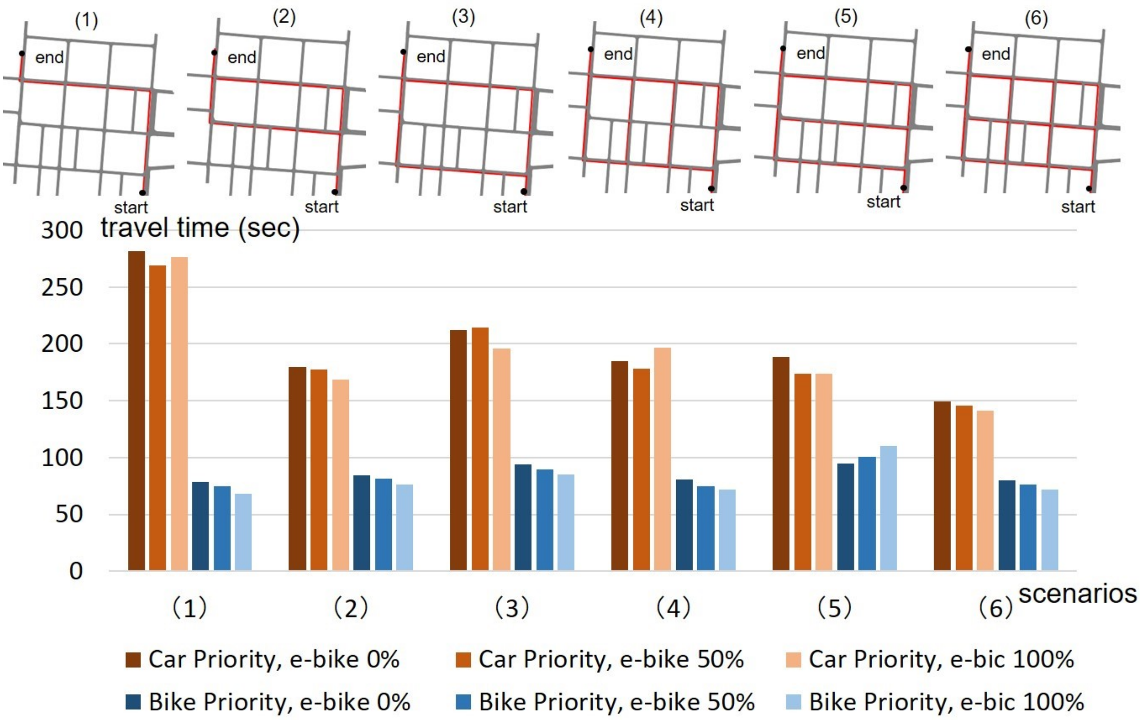


Figure 5-17 Bicycle travel time in from network model

Realizing the importance in considering both the intersection and road links in network, I intended to assess transport efficiency in larger network while consider the both. I spent time trying to combine the road models in NetLogo with intersection model in Vissim. Because with NetLogo it is possible to make various combinations of different mixture scenarios for roads, while the continuous models on Vissim is indispensable for intersection simulation.

It was necessary to confirm the consistency of the mixed traffic flow in both road link model and intersection model. The NetLogo model will be adjusted to fit the results of Vissim model. The coefficients to calibrate are preference factors and randomized deceleration probability (p_{radm}), which is mainly used to restrict the speed distribution. Taking values from Vissim model as baseline, goodness-of-fit test was conducted to NetLogo model. The difference was calculated using the following equation (Gundaliya, Mathew, & Dhingra, 2007; Li et al., 2014):

$$e = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(v_s^i - v_0^i)^2}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}{v_s^i}^2} + \sqrt{\frac{1}{N}\sum_{i=1}^{N}{v_0^i}^2}} \tag{5.6}$$

where

N number of road sections

v_s^i simulated average speed of (e)-bikes for section i in NetLogo model

v_0^i simulated average speed of (e)-bikes for section i in VISSIM model.

For calibration for p_{radm}, 6 road links of 1m width and 250m length were built in NetLogo and VISSIM respectively. Input volumes of these 6 sections are set from 500vph to 3000vph at an interval of 500vph. The average speeds used for calibration were taken from the road sections between 50m and 200m. The values of p_{radm} varied from 0.05 to 0.95 at an interval of 0.05. Other settings, including vehicle size, max speeds, acceleration, were set to be similar. The best goodness-of-fit p_{radm} for bicycles and e-bikes are 0.45 and 0.35, with difference of 0.071 and 0.053 respectively.

The resulting p_{radm} and speed settings are different from those in the model mentioned, leading to lower speeds of bicycles and e-bikes. The preference factors were also considered to be checked. If the combination of two kinds of model will be conducted in the following studies, the results from NetLogo model should be re-calculated based on the calibrated coefficients.

The idea to combine two kinds of models were then given up after I realized that it is possible to simulate a mixture traffic of bicycles and cars on the same road in Vissim, which I thought it is not capable of. As it will be introduced in Section 6.3.3, on mixed-use roads the non-lane-based rule was applied to cars and bicycles. While bicycles keep to the left, but in cases where the road is vacant, they also use the middle part to overtake. Cars prefer the middle of the road and can overtake bicycles on their right.

5.5 Summary

I focused on space allocation strategies at road links on road links and intersection separately. The main results are as follows.

(1) In road link models

The road space usage efficiency of 1 e-bike ≈ 1.24 bicycles. E-bikes use road space less efficiently than bus when it accommodates 9 persons. When e-bikes increase, mixed traffic provide better with bicycles on 2m bike lane; no physical separation between car and bicycle can be better on 4m road when e-bike density > 10veh /100m. Sharing all 4m bus lane can be efficient when few passengers on board or/and dense bicycle volume. When passenger total amount remains unchanged, modal shift from car to e-bikes/bicycles, physically separating bike lane and car lane is efficient; odal shift from bicycles to e-bikes, mixed allocation leads to better efficiency.

(2) In intersection models

Bike box can produce shorter average passing time among the three bicycle-considered intersection designs, intersection with one-direction bikeway, with two-direction bikeway, and with bike box. Apply of bike box requires law amendment as it is against *the Road Traffic Law* at present. Although the two-direction bikeway shows its marginal advantage than one-direction bikeway, considering the concerns of increasing safety risk, it is reasonable to maintain the basic rule to keep bikeway going one-way. Higher e-bike ratio can bring up the efficiency of all bicycles.

(3) In a case study for a network model at community scale

Increasing bikeway density may improve cycling efficiency. Intersection treatment can result in relatively more significant improvement than adding bike lanes. Assessing at road network scale can provide a comprehensive knowledge on bicycle-considered space allocation strategies.

The simulation on community network points out the direction of following investigation to consider both roads and intersections at a network scale.

Parts of results in this chapter are used in Chapter 6, for example the movement settings of cars, bicycles, and e-bikes in microscopic model; the result that is no need to separate conventional and e-bikes from a point of road space usage efficiency; the result that when e-bike modal share is low, separating bicycles and car give out a better performance; the one- and two-direction movements at intersection give similar results in passing time for cars and bicycles.

6. Exploring Network Scale Separation Strategies for Car-Bicycle Integration

6.1 Introduction

In Chapter 5, I focused on space allocation strategies at road links on road links and intersections separately. The case study near Takasago Station indicated two things: 1) Intersection treatments can result in relatively more significant improvement than adding bike lanes; 2) Assessment of the road network can provide comprehensive knowledge of space allocation strategies.

As shown in Section 1.3.2, there is a wide variety of approaches to allocate road space between bicycles and cars: shared space, sharrow, bike lane, bike path or bicycle highway. In the trend of developing cycling infrastructure among global cities, Copenhagen is also building completely car-free cycle paths. These include cycle superhighways for long-distance commuters that span municipal borders and green cycle routes through parks and residential areas. Although these space allocation methods, cycling dedicated facilities show their importance to reduce the impact of intervening with motorized vehicles to provide a comfortable and safe ride (Section 2.5). Despite the advantages of separating bicycles and cars, there is no discussion on a systematical strategy to split them into different roads at a network scale.

Inspired by car-free zone deployments (Section 1.3.1), the discussion on car-bicycle interference especially on narrow streets(*The Tokyo Shimbun*, 2021), Copenhagen's car-free cycle paths, the approvement of advantages in bicycle-dedicated facilities, the research gaps mentioned, as well as the suggestions from Chapter 5, I considered to propose and evaluate a system with bicycles and cars running on different roads at network scale: In places where no enough area to separate bicycles and cars on a same road, separating them to different roads can be an alternative.

This chapter will also use the microscopic models rather than the CA models that simulate traffic flow in a spatially and temporally discrete way. Microscopic models can simulate space continuously, thus suitable for simulating intersection turning movements with curves. To better connect with the intersection models, the road link models are also microscopic ones, that the CA road link models in Chapter 5 are no longer used. In previous studies, microscopic models are proved to be useful tool for assessing both bicycle-specific intersection designs (Kothuri et al., 2018) and bike lane designs (Boyle et al., 2023; del Carmen Almanza Mendoza et al., 2018; Grigoropoulos et al., 2021; B. Liu et al., 2021; Noland et al., 2015).

When building microscopic models, the following knowledge or setting are from Chapter 5. (1) The bicycle, e-bike and car movement settings are same. To keep the fluent in model introduction, some parts in Chapter 5 and 6 can be duplicated. (2) Because Chapter 5 resulted that no need to separate conventional and e-bikes from a point of road space usage efficiency, the two kinds of bicycles are mixed in this chapter. (3) Chapter 5 resulted that when low density of bicycles, physically separate them from cars can be efficient, so there is no physical separation between bicycles and cars on middle-class and local roads. (4) Chapter 5 resulted that intersection with one or two direction bikeway(s) give out similar average passing times. Considering that building two direction bikeways can complicate the intersection scenarios and time consuming, I chose to consider only the one direction bikeway.

6.2 Objective

To summarize the literature review: (1) Cycling promotion requires a multi-modal consideration; (2) Despite the importance of cycling dedicated facilities, there is no discussion on a systematical strategy to separate bicycles and cars into different roads at network scale; (3) Microscopic simulation is proved to be a helpful tool for bicycle and mixed traffic simulation, and applying their results from road space allocation scenarios can be applied to the road network for further analysis.

Here is the objective of this study. In the scope of multi-modal transportation design, this study attempts to investigate an approach where bicycles and cars are separated into different roads at a network scale. In places where no enough area to separate bicycles and cars on a same road, separating them to different roads can be an alternative. The separation of road space between automobiles and bicycles can serve a dual purpose: it can not only fit the cyclists' preference for comfort and right-of-way but also benefit motorists with a smooth drive without roads being narrowed down by bicycle facilities or hindered by cyclists. However, such separation may diminish travel efficiency by limiting the routes available to minimize travel distance. This suggests a trade-off between comfort and efficiency when considering the separation of road space.

Insights are required on the benefits of shared road lanes and the potential advantages of separating bicycles and cars onto different roads. More specifically, I wanted to answer in what kind of cases separating bicycles and cars can be preferred: on which kind of road hierarchy, with low or high traffic volume, with high or low bicycle modal share, in short or long trips? I designed various scenarios to address these research questions using varying parameters, including traffic volume, modal share, and road hierarchy. I assessed their performance through two key metrics: (1) travel efficiency and (2) the traffic stress imposed on cyclists.

6.3 Methodology

6.3.1 Network outline and road allocation

As I planned to evaluate the separate approach when applied to a network, it requires constructing a road network of a wide area. However, building such an extensive network using microsimulation software is time-consuming and infeasible for the author. Therefore, I used a split-assemble method is applied (Figure 6-1). The whole virtual network is split into community units with a side length of 1km, which is further split into intersections and roads to be simulated in microscopic models in PTV Vissim. In the assembly process, the output results derived from the simulation are into network data in ArcGIS, and then an efficiency and cycling stress evaluation is conducted. Sections 6.3.1 and 0 introduce the virtual network, the community units that compose the network, and the community network scenarios set. Sections 6.3.3 and 6.3.4 introduce how the road and intersection composing network are simulated in microscopic models. In Section 0, simulation results are combined into road network models in ArcGIS, on which the efficiency for bikes and cars in each network scenario is quantified.

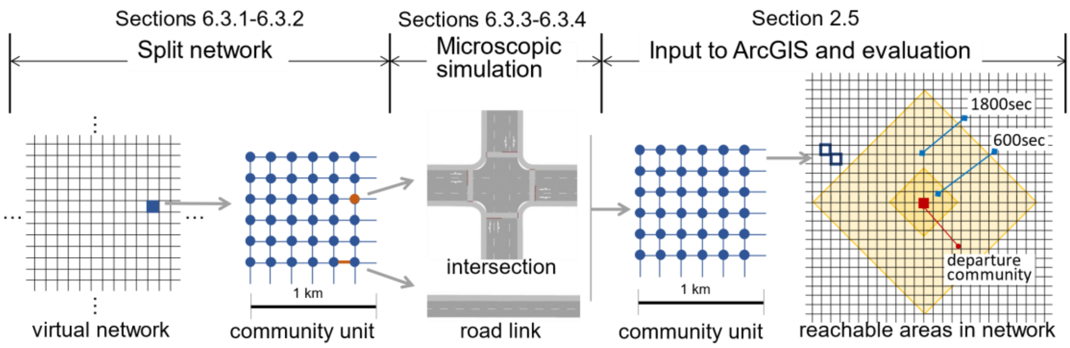


Figure 6-1 Workflow in methods.

Evaluation is conducted on grid-like virtual road networks that infinitely extend. To compose such networks, I designed square community network units with a side length of 1km. It is assumed that the same community units are endlessly connected. Within each community, 2×12 roads are arranged in a grid pattern with an even centerline-to-centerline distance of 83.3m. The road network features three levels of hierarchical organization (A-, B-, and C-class). The road area ratio is summed as 16.8%. The community unit's general layout (upper left corner in Figure 6-2) is constant in all network scenarios.

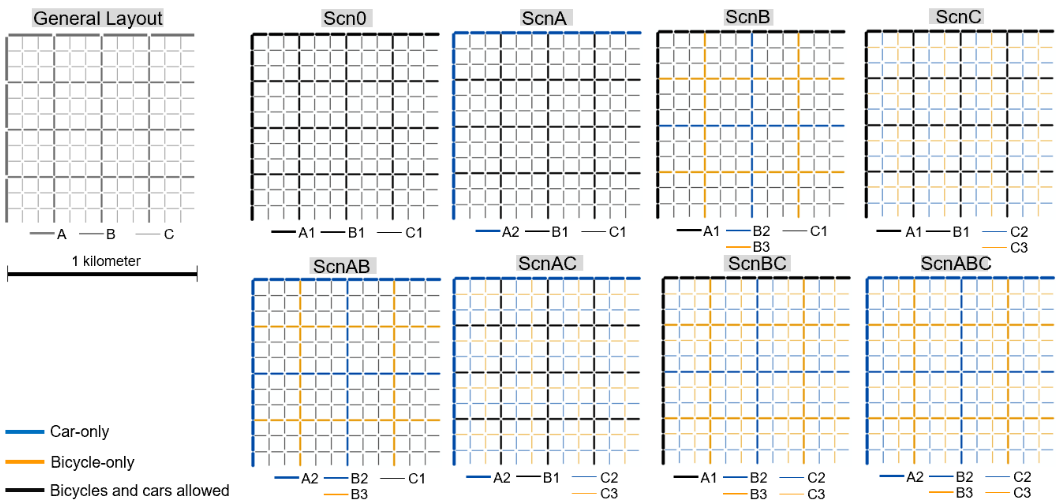


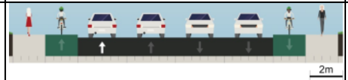
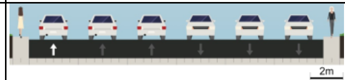
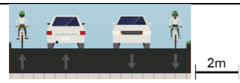
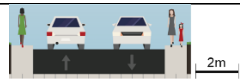
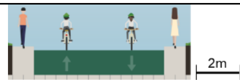
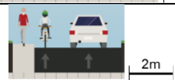
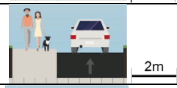
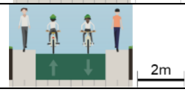
Figure 6-2 General community unit layout and network scenario layouts.

The width of each hierarchy of roads is determined, and then based on each class of road, different road segment separating strategies are designed: bicycle-car mix use, car-only, and bicycle-only (Table 6-1). For example, based on a B-class road width of 8m, three sub-classes, B1, B2, and B3, are designed. Table 6-1 summarizes the settings of three hierarchies, their sub-classes, the lengths of each class per community, and road space allocation for a single road.

The road cross sections are set considering the following rules. (1) Road width and minimum width of each part: The whole road width is decided by road class, A, B, or C. Car lanes are 3m, and the number of lanes is an integer. If a sidewalk is included, it is wider than 1m. If a bicycle lane is included, it is wider than 1m. (2) Mix or separate bicycles and cars on each road: A1, B1, and C1 class roads include bicycle and car lanes. A2, B2, and C2 roads do not include bicycle lanes. B3 and C3 roads do not include car lanes. For a bicycle lane no more than 1m, if it is adjacent to car lanes, there is no physical separation between the car lane and bicycle lane. It is labeled as “mix 4m” in Table 6-1. (3) Direction of traffic: Two-way roads are preferred for better accessibility than one-way roads. Two-way roads are symmetrical in two directions for simplicity. (4) Other aspects to fit in reality: A-class has no bicycle-dedicated road. Sidewalks in A1 road are 2m to accommodate many pedestrians on main streets.

The network scenario layouts with traffic direction information are shown in Figure 6-3. The roads without arrows are two-way, and those with arrows are one-way roads. When aligning roads, I tried to avoid clustering roads with the same kinds of vehicle usage or with the same directions.

Table 6-1 Settings for road segments.

Traffic survey[1]		Road segments in the virtual network										Level-of-Traffic-Stress (mentioned in Section 0)	
							Cross sections						
Road width	Length density [km/km²]	Class	Width [m]	Length [km]	Speed limit [km/h]	Sub-class	Side-walk [m]	Bike-way [m]	Car lane [m]	Traffic direction	Diagram[2]	LTS Level	Main criteria (Mekuria, Furth, & Nixon, 2012)
[25.0m, +)	0.813	A	20	2	50[3]	A1	2	2	6 (2 lanes)	Two-way		3	Car lanes per direction >=2; Bike lanes not alongside parking lane; Speed limit more than 30 mph
[19.5m, 25.0m]	0.524												
[13.0m, 19.5m]	1.372					A2	1	0	9 (3 lanes)	Two-way		-	No bike lane contained.
[5.5m, 13.0m]	5.332	B	8	6	40[4]	B1	0	Mix 4m		Two-way		2	Mixed traffic; Speed limit up to 25 mph; Street width of 2–3 lanes; Not residential; Bike lane width 5.5 ft or less.
						B2	1	0	3 (1 lane)	Two-way		-	No bike lane contained.
						B3	1	3	0	Two-way		1	Bike path.
[3.0m, 5.5m]	17.150	C	5	16	30[5]	C1	1	Mix 4m		One-way		1	Mixed traffic; Speed limit up to 25 mph; 2–3 lanes; Classified as residential
						C2	2	0	3 (1 lane)	One-way		-	No bike lane contained.
						C3	1	1.5	0	Two-way		1	Bike path.

[1] Summarized within Tokyo boundary, processed based on grid-cell data of road density and length in 2010 from National Land Information Division, MLIT of Japan
[2] Road cross section diagrams in this column are created using Streetmix (https://streetmix.net/).
[3] Standard speed of road type 5 and 6, four-car-lane road without median strip in urban area, on page 11 in (Traffic Bureau, n.d.).
[4] Standard speed of road type 1, two-car-lane road with many pedestrians, on page 11 in (Traffic Bureau, n.d.).
[5] Standard speed of local residential roads on page 12 in (Traffic Bureau, n.d.).

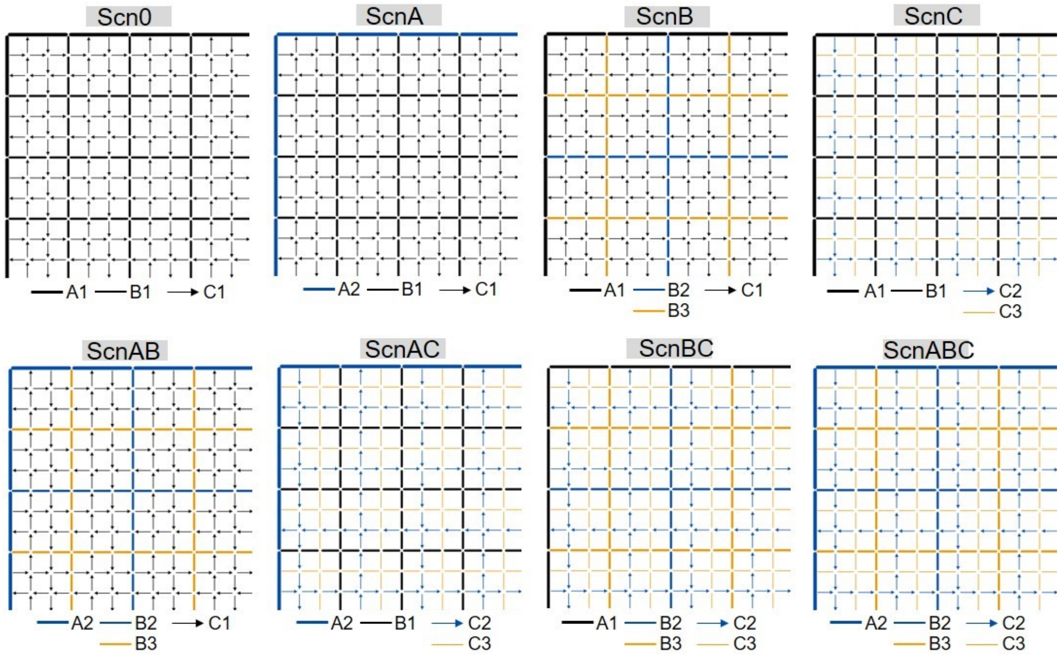


Figure 6-3 Network scenario layouts with traffic direction information.

6.3.2 Network scenario settings

Combining the road allocation scenarios in Table 6-1, eight network scenarios are set following the general layout (Figure 6-2). The Scn0 is the baseline scenario where all roads have bicycle lanes adjacent to car lanes. They are named ScnX, where the X includes A, B, and C, indicating the hierarchies of roads on which bicycles and cars are separated into different roads. For example, in ScnA, only A-class roads are changed from Scn0 to be car-dedicated; in ScnB, only B-class roads are modified to be a combination of car-only and bicycle-only ones; in ScnBC, B- and C-class roads are changed from Scn0. When allocating roads to community units, I attempt to set both cars and bicycles to obtain a similar chance to traverse the whole network. When car-only roads exist, they are set to be through the center of the community network, considering car-only roads perform a higher hierarchy than bicycle-only roads.

Traffic volume on each road is calculated based on space allocation in each network scenario. The traffic flow f_a^m of mode *m* on the road *a* in scenario *k* is proportional to its area in the gross area for mode *m* in scenario *k*:

$$f_{ak}^m = F^m \frac{l_{ak}^m w_{ak}^m}{\sum_{i=1}^{N_k^m} l_{ik}^m w_{ik}^m} \quad \textbf{(6.1)}$$

where l_{ik}^m and w_{ik}^m are road length and road width of mode m on road *i* in scenario *k* in one community unit, N_k^m is the number of roads for vehicle m in one community unit in scenario

k. Mode m indicates *bicycle* or *car*. F^{m}, the total input volume of mode m in one community unit, is constant across the network scenarios. F^{car} is calculated using Eq. (6.1) when keeping car traffic f on road A1 in baseline scenario Scn0 to be 200 vehicle-per-hour (vph), 300vph, or 400vph. 200vph and 300vph is the hourly nationwide average of 24-hour and 12-hour traffic volume on a road class similar to A1 in the setting. 400vph is the highest possible volume to input into the microscopic models the authors built that the queue length those models can hold. This method is used as data on road hierarchies similar to B- and C-class are unavailable from traffic surveys. Then $F^{bicycle}$is calculated as

$$F^{bicycle} = \frac{b\ F^{car}}{1 - b} \tag{6.2}$$

where b is the bicycle mode share, set to three levels: 10%, 20%, or 30%. The traffic volume on each road resulting from this is input into microscopic models.

6.3.3 Vehicle features in microscopic model

The travel time through road segments and intersections is estimated using a microscopic traffic simulator software PTV Vissim, version 10. Three kinds of vehicles are simulated: conventional bicycle, electrical assistant bicycle ("Bicycle" is the general term for these two kinds in this chapter, and all analysis are conducted on them without distinction), and car. Although sidewalks are designed in the road cross sections, pedestrians are not simulated in microscopic models.

Figure 6-4 gives the examples of 3D views of simulation on roads and at intersection. The three roads in Figure 6-4(a) are bicycles and cars on same road with physical separation, bicycle-only road, and mixed bicycles and cars on same. The green and red blocks in Figure 6-4(b) are signal heads for bicycles and cars.

(a) (b)

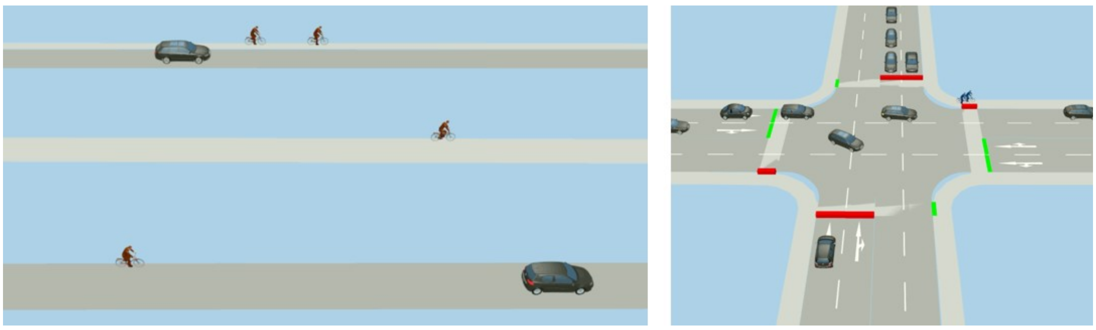


Figure 6-4 The image of simulating bicycles and cars (a) on road and (b) at intersection.

Desired speed distributions are required to define vehicles. For cars, three design speeds are set: 50km/h, 40km/h, and 30km/h. Based on each kind of design speed, the desired speed distribution is set to be linear, ranging from design speed ± 5 km/h, and the 85th percentile of the desired speed is set to be design speed. For two kinds of bicycles, their desired speed distributions are specialized differently in Japanese cases (Figure 6-5) based on a set of empirical free flow speeds from a previous study (Yamamoto et al., 2012).

Other vehicle features include acceleration and deceleration function, following and lateral movement. Cars employ default settings on these features. For bicycles, detailed settings are absent in Japanese studies; thus, a research report (COWI, 2013) on cyclist microsimulation in Copenhagen has been adopted. The desired position, overtaking side, and minimum longitudinal speed are modified to correspond to left-hand traffic in Japan. The ratio of e-bikes in all bicycles is set to 20%.

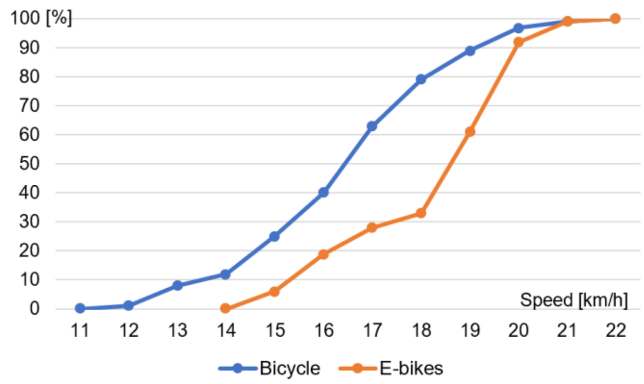


Figure 6-5 Desired speed distribution for conventional bicycles and electrical assistant bicycles.

Depicted based on (Yamamoto et al., 2012).

Both cars and bicycles used the car-following model to decide their movement to accelerate or cruise, considering the conditions of their heading vehicles. Lane-based or non-lane-based vehicle moving rules are applied depending on the road type and vehicle type. In car-only roads, longitudinal and lateral movements are based on fixed lanes. On bicycle-only roads, bicycles use a non-lane-based rule, in which no lanes are specified, but only the width of the bikeway area is assigned. Thus, bicycles can move more freely than lane-based cases and overtake actively without sticking to certain lanes as automobiles. The non-lane-based rule is applied to cars and bicycles on mixed-use roads, B1 and C1. Bicycles keep to the left, but in cases where the road is vacant, they also use the middle part to overtake. Cars prefer the middle of the road and can overtake bicycles on their right.

6.3.4 Road and intersection settings in microscopic models

Road segment models use the road cross sections introduced in Table 6-1. Traveling time passing 100m distance is averaged from 50 runs of 4,800 simulation seconds, during which the first 1,200sec are considered as warm-up time for the system; thus, the results are discarded.

The total size of an intersection, including four connected legs, is 70m×70m. Two crossing roads decide the layouts of intersections. Their center parts are shown in Figure 6-6. Note that A-C intersections forbid straight-forward crossing and right turns and only allow left turns.

Bicycles and cars use physically separated space before entering junctions in all layouts. When choosing a direction among possible routing decisions, the probability of turning left, of going straight through, and of turning right is 2:6:2. When cars waiting on a two-car-lane road, the ratio of Left-turning: Straight-heading: Right-turning (L: S: R) on the left lane is 2:5:0, on the right lane is 0:1:2. In three-car-lane cases, the L:S: R ratios on the left to right lanes are 2:2:0, 0:4:0, and 0:0:2. Ratios are set assuming that the queues have similar lengths and the time to turn right costs about 2 to 3 times to turn left or to go straight forward.

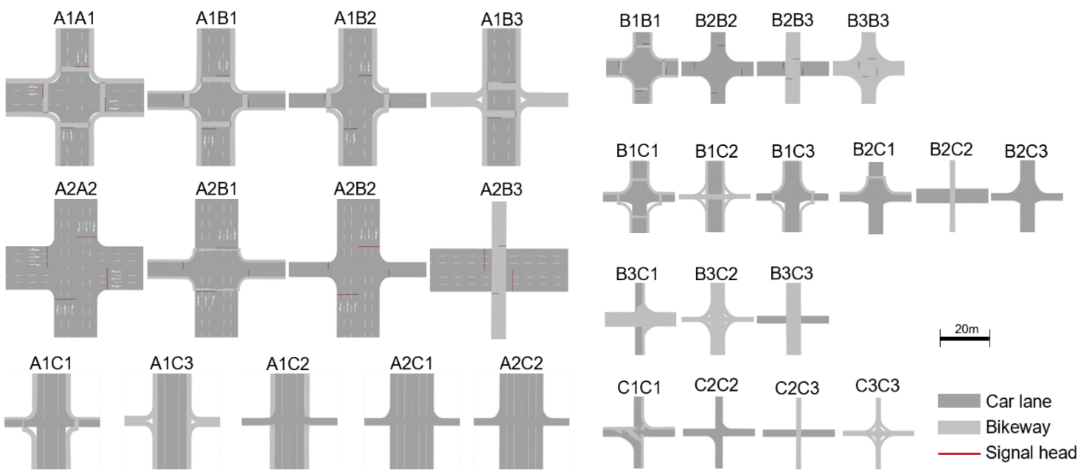


Figure 6-6 Intersection layouts in microscopic model.

Bicycles perform hook turns (two-stage turns) to turn right at intersections, except for bicycle-only ones or when crossing one car lane. To simplify interaction, bicycles travel in one direction when crossing. Cycling behaviors at intersections consist of 4 kinds of behaviors, according to (COWI, 2013): (1) cycling in the general lane when keeping left; (2) cyclists in a waiting zone in front of a red traffic light; (3) cycling through an intersection; (4)

transition from (3) to (1). Cars do not change lanes when approaching intersections. They reduce speed to a maximum of 30km/h at the center of intersections or in a left turn, regardless of the speed limits of the road links connected to the junction.

Conflict areas are locations where vehicle routes overlap and interfere with each other. In general, bicycles take priority over cars. For vehicles heading in different directions, the priority order from high to low is straight-heading, left-turn, and right-turn. In other cases, conflict areas are set to be undetermined, showing no right-of-way specified, and vehicles on both sequences watch out for each other and react. Four signalization types are applied depending on intersection types (Figure 6-7(a)). Cycle lengths for A-A, A-B, and B-B intersections are 90, 75, and 60 seconds. Intersections connect with C-class roads are non-signalized. The details of lengths of green-amber-red lights are shown in Figure 6-7(c). Signalized intersections of two-phase pre-timed signals are applied (Figure 6-7(b)). The compliance rate with signal control is 100%. Intersection passing time is averaged from 50 runs of 4,800 simulation seconds, during which the results from the first 1,200 seconds are discarded.

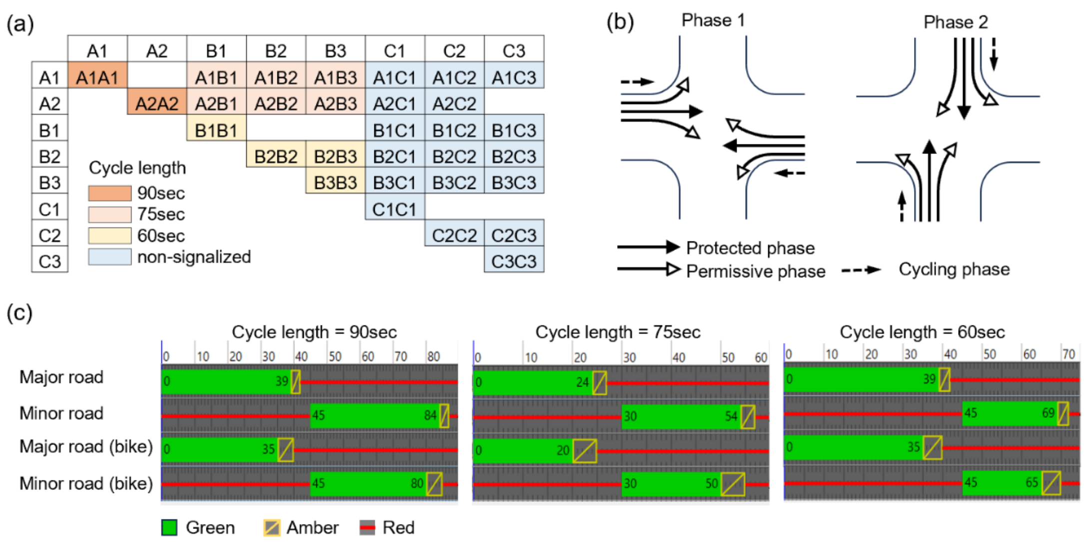


Figure 6-7 Signal control.

(a) Cycle lengths by intersection types

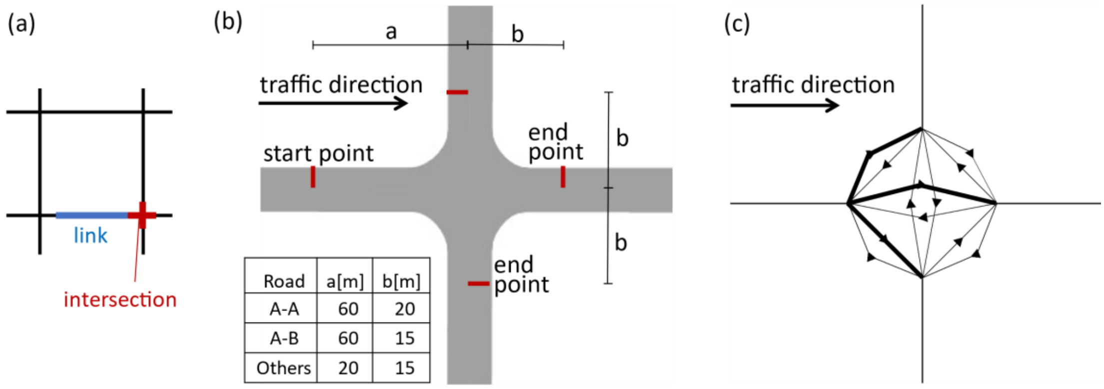
(b) Two-phase control scheme

(c) Signal programs by cycle lengths.

6.3.5 Efficiency and cycling stress assessment

The "assemble" process combines results from links and intersections on ArcGIS Desktop

10.6.1 and ArcGIS Pro 3.0. In PTV Vissim, passing time through an intersection is collected between the start point on the approaching legs and the end points on the departure legs. These outputs are input into ArcGIS (Figure 6-8). Figure 6-8(b) explains the positions of start points and end points when obtaining passing time at an intersection. The distance from a starting point to the intersection center point should be (1) long enough to accommodate waiting queues while (2) short enough to be out of the range of other passing time collecting points. The distance from the intersection's end point and center point should be (3) long enough to allow the vehicles to change from a limited-speed mode to a regular driving mode while (4) short enough to assemble with a road link. Requirement (4) is essential in the B1 and C1 road-type cases, where bicycles and cars share road space without physical separation but approach and pass the intersections separately. The table in Figure 6-8(b) shows the different positions of start and end points by the types of intersecting roads.



Road	a[m]	b[m]
A-A	60	20
A-B	60	15
Others	20	15

Figure 6-8 Intersections settings.

(a) Intersection parts split from road links in a network.

(b) Positions of start and end points to collect passing time data in the microscopic model. Three end points are for left-turn, straight-forward, and right-turn vehicles when traffic approaches the intersection from the west leg, as the arrow shows.

(c) Intersection lines in ArcGIS to input the passing time data. The thick lines are the ones to input data into when the traffic direction is as the arrow indicates.

I used the reachable areas in 300sec and 1,800sec to evaluate transport efficiency in each network scenario. Network models are built in ArcGIS 10.6.1. Each network model contains more than 900 community units to comprise the largest possible reachable area generated by car in 30 minutes from the central area.

Start points are drawn in every block in a community in the central part of the whole network. Block here is defined as a square surrounded by four roads. To simulate departures from all four neighboring streets, four start points are respectively drawn near one of the four roads surrounding the block. The efficiency metric of traffic mode m in scenario k is S_k^m, the average of A_{ki}^m, the largest reachable area from block i in scenario k by mode m, calculated as

$$S_k^m = \overline{A_{ki}^m} \tag{3}$$

where $A_{ki}^m = \max a_{kij}^m$, and a_{kij}^m is the reachable area from start point j in block i in scenario k by mode m.

In blocks where bicycles or cars cannot start because there is no available road for the specified mode (Figure 6-9), the result A_{ki}^m is the largest reachable area in 525sec or 1725sec from the four Neumann neighborhood blocks, assuming users walk the distance of a block to their neighborhood in order to use vehicles.

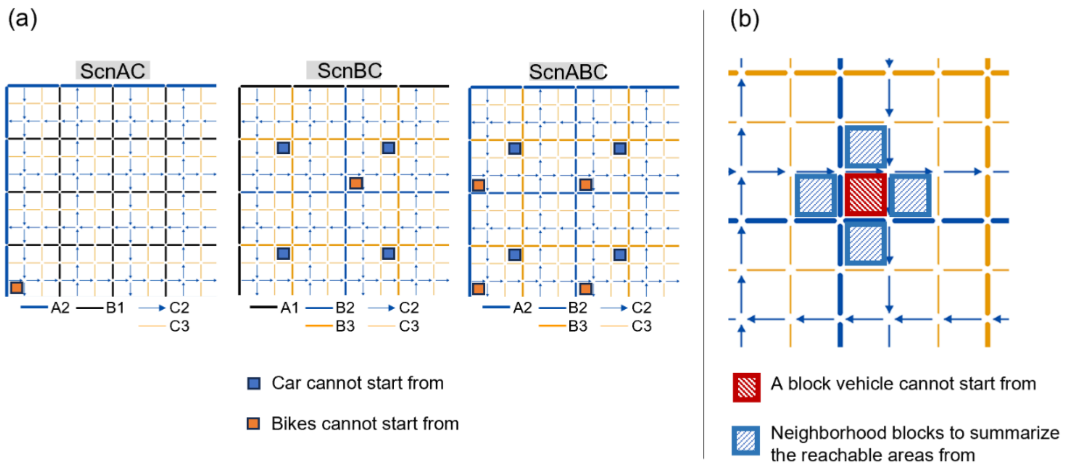


Figure 6-9 Blocks vehicles cannot start from.

(a) Blocks cars or bicycles cannot start from; (b) Example of neighborhood blocks to summarize reachable areas from when vehicles cannot start from a block.

The 75sec subtracted from 600sec and 1800sec is calculated by dividing the length of one side (83.3m) by the walking speed (1.1m/s). The number of scenarios is summed up to be 144 (8 network scenarios * 3 traffic volume levels * 3 bicycle modal share * 2 trip lengths).

To access the cycling environment, I used the Level of Traffic Stress (LTS) scoring system proposed by (Mekuria et al., 2012) to compare the scenarios. This scheme classifies cycling traffic stress into four levels, 1 to 4, denoting low to high stress on cyclists. Roads are assessed based on road segment features, traffic volume, motor vehicle speed, street width, and traffic mixture. Road link evaluation and criteria are listed in Table 6-1. The intersection LTS level is decided by the scores already assigned to the road links to which the intersection connects. The evaluation results are shown in Figure 6-10.

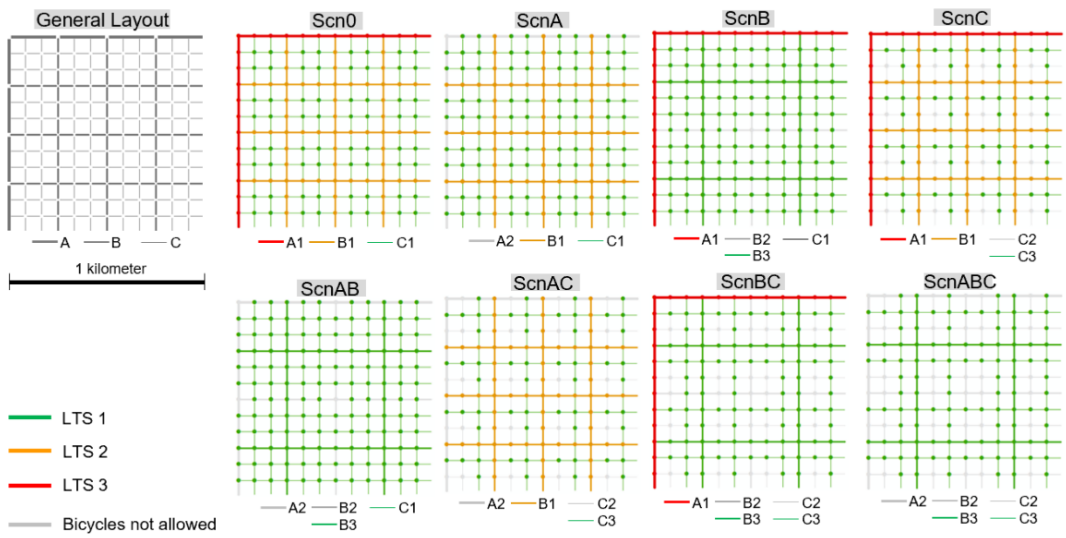


Figure 6-10 LTS score for intersections and road links.

To summarize the LTS score in each network scenario, points are assigned to links and intersections that 1 point to Level 1, 2 points to Level 2, and 3 points to Level 3. Scores are weighted and averaged from links and intersections covered by the largest reachable areas from every block. Road link LTS results are weighted by road length and bicycle traffic volume. Intersection LTS results are weighted by the sum of bicycle traffic from the roads that connect to the intersection. The roads where bicycles are not allowed are considered null in terms of score, thus not included in the average.

To summarize sidewalk characters in each scenario, the width of sidewalks covered by bicycles' reachable areas is averaged. Bicycle reachable areas are used rather than those of cars because bicycles sometimes use sidewalks, thus leading to conflicts between cyclists and pedestrians. A wide sidewalk can provide a place to spare and mitigate possible conflicts.

Bicycle share	10%						20%						30%					
Travel time [sec]	300			1800			300			1800			300			1800		
Traffic level [vph]	200	300	400	200	300	400	200	300	400	200	300	400	200	300	400	200	300	400
Bicycle efficiency [km^2] (Network scenario)																		
Scn0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ScnA	-2.515	-2.422	-2.371	-21.153	-20.236	-19.857	-2.442	-2.444	-2.392	-20.581	-20.660	-19.995	-2.408	-2.532	-2.523	-20.274	-20.857	-20.711
ScnB	-0.257	-0.022	-0.093	-0.938	1.267	0.517	-0.149	-0.080	-0.120	-0.026	0.636	0.140	-0.139	-0.132	0.015	-0.132	0.044	1.270
ScnC	1.669	1.671	1.714	13.521	13.555	13.791	1.644	1.652	1.641	13.023	13.034	13.070	1.708	1.573	1.555	13.471	12.543	12.555
ScnAB	-3.104	-3.070	-3.143	-25.033	-24.683	-25.327	-3.212	-3.242	-3.255	-26.068	-26.222	-26.208	-3.239	-3.384	-3.125	-26.169	-27.462	-25.025
ScnAC	-1.272	-1.242	-1.142	-10.670	-10.578	-9.845	-1.245	-1.247	-1.233	-10.731	-10.494	-10.235	-1.254	-1.235	-1.159	-10.553	-10.050	-9.340
ScnBC	1.327	1.303	1.214	10.866	10.818	9.898	1.253	1.218	1.153	10.159	9.852	9.444	1.271	1.178	1.094	10.270	9.798	9.135
ScnABC	-2.797	-2.805	-2.947	-23.010	-23.245	-24.651	-2.826	-2.902	-3.106	-23.639	-24.581	-25.446	-2.835	-3.046	-3.421	-24.113	-24.887	-27.740
Car efficiency [km^2] (Network scenario)																		
Scn0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ScnA	2.879	2.912	3.820	26.854	30.712	37.054	3.141	3.525	4.497	30.909	36.191	45.556	3.453	4.366	5.771	35.755	43.405	58.247
ScnB	-0.276	-0.466	-0.370	2.031	0.706	-0.513	-0.087	0.086	0.101	5.169	5.170	5.823	0.210	0.891	1.208	9.035	11.956	15.878
ScnC	-1.057	-2.041	-2.538	-7.828	-13.657	-21.106	-1.056	-1.789	-2.750	-7.136	-12.674	-21.517	-1.103	-1.368	-2.298	-6.750	-11.991	-20.332
ScnAB	2.404	2.591	3.586	27.297	31.534	38.780	2.757	3.412	4.451	32.344	38.709	49.434	3.159	4.378	6.195	37.868	47.078	66.410
ScnAC	1.729	1.454	1.988	20.577	20.561	23.206	2.047	2.271	2.760	24.907	26.977	32.481	2.445	3.271	4.254	29.866	34.807	46.662
ScnBC	-2.845	-4.077	-5.594	-13.586	-23.415	-45.514	-2.577	-3.473	-5.156	-9.973	-18.972	-40.663	-2.296	-2.607	-4.115	-6.504	-12.469	-32.620
ScnABC	-1.609	-2.149	-2.229	4.280	1.491	0.485	-1.180	-1.237	-1.210	9.577	9.150	11.894	-0.668	-0.011	0.440	15.426	19.401	26.637
Level of Traffic Stress at intersection (Network scenario)																		
Scn0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ScnA	-0.415	-0.415	-0.415	-0.418	-0.418	-0.418	-0.415	-0.415	-0.416	-0.418	-0.418	-0.418	-0.416	-0.416	-0.416	-0.418	-0.418	-0.418
ScnB	-0.518	-0.520	-0.518	-0.518	-0.518	-0.518	-0.519	-0.518	-0.518	-0.518	-0.519	-0.519	-0.518	-0.519	-0.518	-0.519	-0.519	-0.519
ScnC	-0.103	-0.102	-0.102	-0.104	-0.104	-0.104	-0.103	-0.103	-0.104	-0.104	-0.104	-0.104	-0.103	-0.104	-0.103	-0.104	-0.104	-0.104
ScnAB	-0.990	-0.991	-0.990	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.992	-0.992	-0.991	-0.991	-0.991
ScnAC	-0.488	-0.488	-0.488	-0.490	-0.490	-0.490	-0.488	-0.489	-0.489	-0.490	-0.490	-0.490	-0.489	-0.490	-0.489	-0.490	-0.490	-0.491
ScnBC	-0.561	-0.562	-0.562	-0.562	-0.562	-0.562	-0.562	-0.562	-0.563	-0.562	-0.562	-0.562	-0.563	-0.563	-0.562	-0.562	-0.562	-0.562
ScnABC	-0.990	-0.991	-0.990	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.992	-0.992	-0.991	-0.991	-0.991
Level of Traffic Stress on road (Network scenario)																		
Scn0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ScnA	-0.262	-0.262	-0.262	-0.265	-0.265	-0.265	-0.263	-0.262	-0.263	-0.265	-0.265	-0.265	-0.262	-0.263	-0.263	-0.265	-0.265	-0.265
ScnB	-0.286	-0.286	-0.286	-0.288	-0.288	-0.288	-0.287	-0.286	-0.287	-0.288	-0.288	-0.288	-0.286	-0.287	-0.287	-0.288	-0.288	-0.288
ScnC	0.100	0.100	0.100	0.099	0.099	0.099	0.100	0.099	0.099	0.099	0.099	0.099	0.100	0.100	0.100	0.099	0.099	0.098
ScnAB	-0.536	-0.536	-0.536	-0.537	-0.538	-0.538	-0.536	-0.536	-0.536	-0.538	-0.538	-0.538	-0.536	-0.536	-0.537	-0.538	-0.538	-0.538
ScnAC	-0.201	-0.201	-0.201	-0.204	-0.204	-0.204	-0.201	-0.201	-0.201	-0.204	-0.204	-0.204	-0.201	-0.201	-0.201	-0.204	-0.204	-0.204
ScnBC	-0.250	-0.250	-0.250	-0.252	-0.252	-0.252	-0.250	-0.250	-0.250	-0.252	-0.252	-0.252	-0.250	-0.250	-0.250	-0.252	-0.252	-0.252
ScnABC	-0.536	-0.536	-0.536	-0.537	-0.538	-0.538	-0.536	-0.536	-0.536	-0.538	-0.538	-0.538	-0.536	-0.536	-0.537	-0.538	-0.538	-0.538
Sidewalk width [m] (Network scenario)																		
Scn0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ScnA	-0.085	-0.084	-0.084	-0.084	-0.084	-0.084	-0.084	-0.085	-0.084	-0.084	-0.084	-0.084	-0.085	-0.084	-0.084	-0.084	-0.083	-0.083
ScnB	0.249	0.249	0.249	0.250	0.250	0.250	0.249	0.249	0.249	0.250	0.250	0.250	0.249	0.249	0.249	0.250	0.250	0.250
ScnC	0.334	0.334	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.334	0.333	0.333	0.333
ScnAB	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.167	0.167	0.166	0.166	0.166	0.166	0.167	0.166	0.167
ScnAC	0.247	0.247	0.247	0.249	0.249	0.249	0.247	0.247	0.247	0.249	0.249	0.249	0.247	0.247	0.247	0.249	0.249	0.249
ScnBC	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583
ScnABC	0.497	0.498	0.498	0.499	0.499	0.499	0.497	0.498	0.497	0.499	0.499	0.499	0.497	0.497	0.497	0.499	0.499	0.499

Legend: Improved from Scn0 / Worsened from Scn0

Figure 6-11 Result list of differences between each network scenario and baseline Scn0.

6.4 Results

6.4.1 Results from individual indicators

Figure 6-11 lists the differences between scenarios and the baseline scenario Scn0. Each bar length shows the relative scale of the value in a group comprising three columns in an item. Bars on the left side of the dotted axis show negative values, and those on the right side are positive. The blue indicates improved cases from the baseline Scn0, and the orange indicates worsened ones.

I focus on the results in three individual indicators: efficiency of cars, efficiency of bicycles, and LTS score. When looking at the transportation efficiency of cars, since bicycle modal share does not change the tendency in results significantly, Figure 6-12 gives an example where bicycle modal share is 20%. Compared with scenarios with A1 roads, those with A2 roads perform better as A2 has enlarged car lanes for car-dedicated usage. For example, ScnA is better than Scn0, and ScnAB is better than ScnB. While adding a car lane does not directly speed up cars on A-class roads, it helps shorten passing time at intersections and speed travel on low hierarchies of roads and intersections, functioning by attracting drivers to A-class roads.

Scenarios that separate bicycles and cars on C-class roads worsen car efficiency. For example, ScnBC is worse than ScnB, and ScnC is worse than Scn0. C-class roads are like capillaries that, although thin, have non-negligible length and routing alternatives. For example, in scenarios forbidding cars on B-class roads, 4km are affected in one community, but if forbidding on C-class roads, 8km are affected.

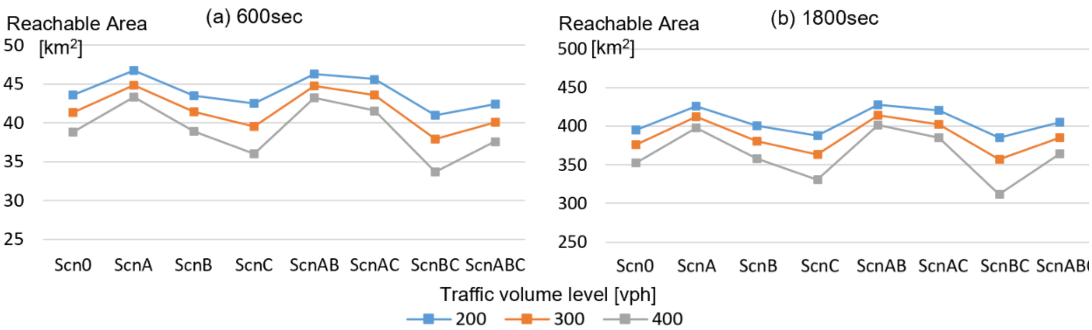


Figure 6-12 Car efficiency (Bicycle modal share is 20%).

(a) 600sec trips; (b) 1,800sec trips.

When looking at the transportation efficiency of bicycles. Figure 6-13 gives an example of when bicycle modal share is 20%. The reachable areas are not influenced much by modal share and volume changes. It may suggest that there is sufficient road space and that no congestion occurs to hinder cycling. Another reason can be that the speed of bicycles is not as fast as that of cars, and the slow-down caused by high traffic is not as significant as the latter. While scenarios applying A2, such as ScnA and ScnAB, can increase car efficiency, forbidding bicycles on A-class roads limits their traversable area.

I assumed that separating bicycles from cars can speed up cycling on single roads. However, such an effect is of no show in the network scenarios. The reason can be that though changing a mixed-use bikeway to a bicycle-only path can expand the cycling area, it also attracts more cyclists. Meanwhile, some road space allocations attract cyclists but cannot provide sufficient width for cycling, which happens on C3 road, where a bikeway of 1.5m attracts more cyclists than 1.0m. However, since one bicycle needs a 1.0m width to ride, it cannot provide better efficiency than a 1.0m bikeway.

Intersection is the place where separation makes a difference. When turning through multiple car lanes, bicycles take hook turns for safety when merging with motor traffic rather than turning through the center of the intersection. On bicycle-only streets or one-car-lane roads, hook turns are not required and thus can turn at a higher speed. In the meantime, an intersection generated by a bicycle-only road and a car-only road is a crossing consisting of straight-ahead routing without a left or right turn, thus simplifying the intersection and speeding vehicles up. Excluding cars also makes cyclists cross intersections smoothly without dodging cars.

Such effects are more apparent when separating C-class roads than B-class roads. Since there are more C-class roads, there are more intersections. Therefore, ScnBC and ScnC tend to give out the best performance in terms of bicycle efficiency.

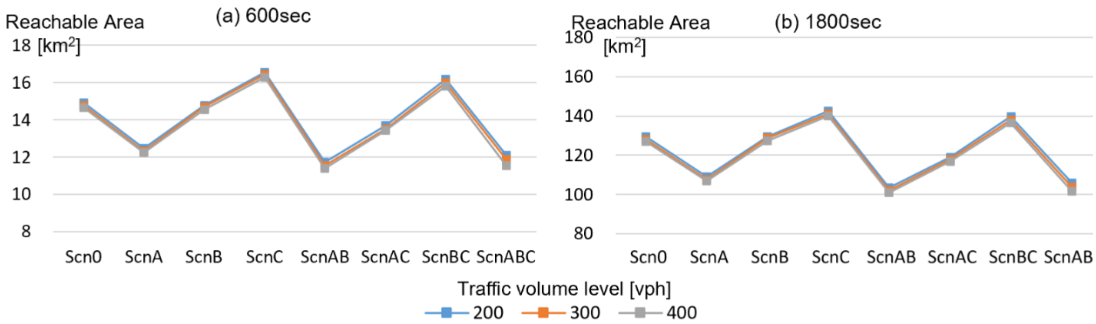


Figure 6-13 Bicycle efficiency (Bicycle modal share is 20%) in (a) 600sec trips; (b) 1,800sec trips.

Regarding cycling stress evaluation (Figure 6-14), all separating scenarios can improve LTS. For road links, ScnAB and ScnABC rank best, as all traversable roads are scored as level 1. Scenario A, B, AC, and BC have similar LTS scores of 1.2–1.3. Following this, Scn0 and C score worst among scenarios, above 1.5. For intersections, while ranking groups can be split as intersections as (AB, ABC), (A, B, AC, BC), and (0, C), the difference between scenarios tends to be more apparent than that for road links. The middle group ranges from 1.4 to 1.5, and the worst ranges from 1.8 to 2.0.

Except from the metrics on bicycles and cars, I also summarized length weighted average sidewalks in Figure 6-11. Except ScnA, all network scenarios enlarged average sidewalks compared with baseline Scn0, that they are expected to provide a place to spare and mitigate possible conflicts between bicycles and pedestrians.

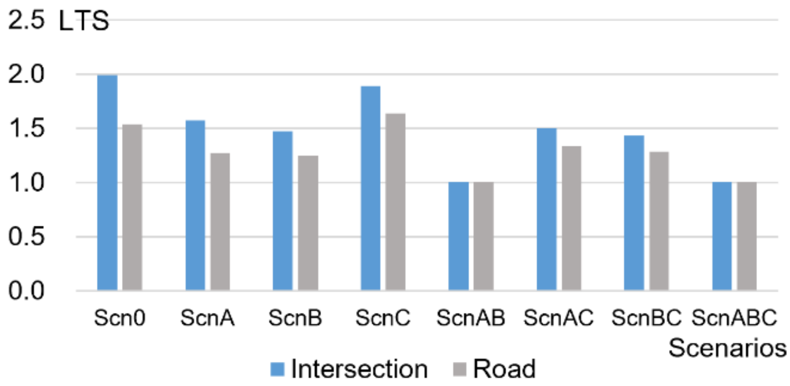


Figure 6-14 LTS scores in network scenarios

(Volume at 300vph level, bicycle modal share is 20%, 600sec trips).

6.4.2 Comprehensive results

When focusing on transportation efficiency (Figure 6-15, Figure 6-16), cars and bicycles tend to have a trade-off relationship across network scenarios on separated roads, i.e., when compared to the baseline, a scenario attractive for drivers usually is unpleasant for cyclists in terms of speed, regardless of its modal share and traffic volume settings. The only scenario that improves both efficiency is the ScnB. Other constraints include bicycle modal share being 20–30%, traffic volume at the level of 300–400vph, and bicycles being cars taking 30-minute trips. The improvement can be more distinct than others when the bicycle modal share is as large as 30%.

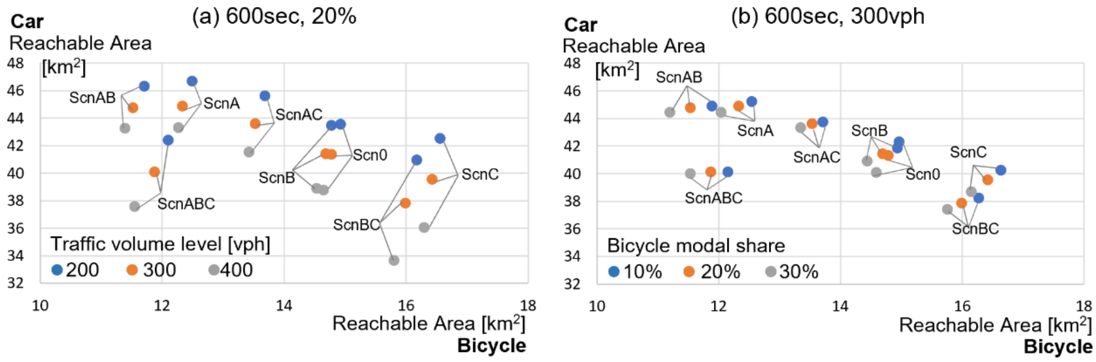


Figure 6-15 Bicycle vs. car efficiency (600sec trip).

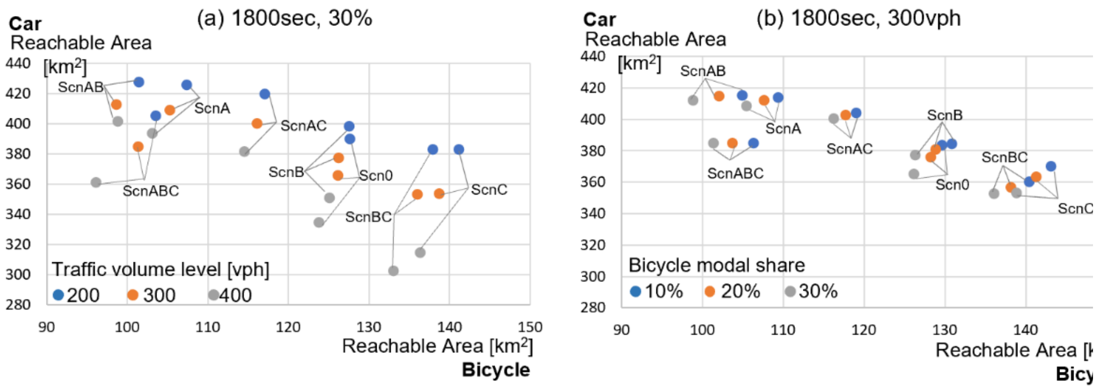


Figure 6-16. Bicycle vs. car efficiency (1800sec trip).

Regarding the cycling environment of cycling efficiency and stress (Figure 6-17(a)), ScnBC that separates bicycles from cars on B-class and C-class can upgrade efficiency while mitigating stress at intersections and on roads compared to baseline Scn0. The scenario that is not as good but fair is ScnC, which provides better speed and comfort on roads but not intersections.

To mitigate conflicts between motorists' calls for speeding and cyclists' requirement for no-stress cycling (Figure 6-17(b)), the separating strategy provides many alternatives, including ScnA, ScnB, ScnAC, ScnAB, and ScnABC. Four of these five choices have an approach in common to enlarge A-class roads for car-dedicated use.

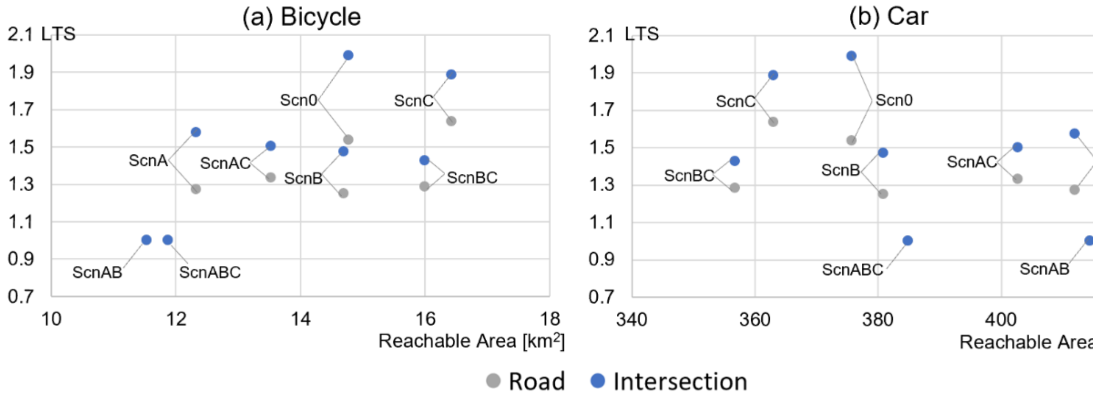


Figure 6-17. Efficiency vs. LTS score (300vph level, bicycle model share is 20%).

(a) Bicycle efficiency (600sec trip) vs. LTS score;

(b) Car efficiency (1800sec trip) vs. LTS score.

6.5 Discussion

Following the analysis on road space and intersection in Chapter 4, this chapter extends the literature on road allocation methods by exploring an approach where bicycles and cars are separated into different roads at a network scale. In places where no enough area to separate bicycles and cars on a same road, separating them to different roads can be an alternative.

Comparing scenarios with traffic volume, modal share, trip length, and hierarchy of separated roads, the study can provide insights for designing multi-modal transportation systems when considering the advantages of both sharing and separating.

The main findings are as follows. (1) Cars and bicycles have a trade-off relationship in efficiency across network scenarios on separated roads. The only scenario that improves both is to separate bicycles and cars to different roads at middle-class roads when bicycle modal share is 20–30%, traffic volume at the level of 300–400vph, and bicycles are cars are taking 30-minute trips. (2) Regarding the cycling environment, separating bicycles from cars on middle-class and local roads can upgrade the overall cycling environment, including efficiency and comfort on the road and at intersections. The not-as-good but fair scenario is to separate solely on local streets. (3) To reconcile conflicts between motorized speed and cyclists' comfort, the separating strategy provides many alternatives. The main idea is to enlarge high-hierarchy roads for car-dedicated use.

Based on the three main findings, I would like to discuss the practical implementations of this separation approach. By efficiency, although finding (1) shows some potential improvement from the status quo baseline, there is no improvement, or it is marginal when the bicycle mode share is 10–20%, similar to the real-world share in Japanese cities. While the result suggests an advantage in a 30-minute trip, the network radii (approximately 6km) of derived reachable areas in 30 minutes is longer than 80% of bicycle trips of 5km. Considering the modal share and trip length at present, separating bicycles from cars systematically out of efficiency reason is radical.

However, efficiency is not all mobility is about. Cycling can be valuable because it provides residents with a cheap, active, and environmentally friendly alternative. Some pilot projects can test the methods suggested in finding (2): separating middle-class roads in part of the area and gradually transiting to middle and minor streets to provide a cozy cycling environment, especially in some residential areas. Not only cycling's value but also other elements should be considered in its promotion. For cities with sparsely populated and weak transit systems, cars can be indispensable, and caution is required to promote bicycles as a primary task in a city planning vision. In this case, the suggestion in (3) can be helpful. The main suggestion is to balance car speed and cycling comfort is excluding bicycles from arterial roads while adding lanes for motorized traffic. It can mitigate bicycle-car conflicts, but mobility is limited because traversable roads are restricted.

Note that I proposed such system mainly considered it an alternative for places where no enough area to separate bicycles and cars on a same road. It needs other analysis to confirm the necessity to separate them to different roads when roads are wide enough to accommodate separated bicycle lanes and car lanes, like Figure 1-9(e) left and Figure 1-9(f) middle.

I did not create the car-free bikeway form. As shown in Figure 1-9(g), there exist bike paths that choose routes different from car lanes for leisure use (Figure 1-9(g) left). Under the concept of “bicycle highway” in London and Copenhagen, parts of the highway are not parallel with car lanes, although the concept itself does not indicate independent bikeways. As the introduction in Section 6.1 mentioned, this proposal is inspired by existing ideas, and the results can also contribute to routing of independent bikeways from cars.

The Guideline (MLIT and NPA, 2016) introduced in Section 1.3.3 advises physical separation on roads when car speed is higher than 50km/h, mixed traffic when car speed equals or lower than 40km/h and the average daily traffic equals or lower than 4,000, visually separation in other cases. In this analysis, speed limit setting is that A-, B-, and C-class road to be 50km/h, 40km/h and 30km/h respectively. That is to say that bike lanes on A-class are preferred to be physically separated, which is consistent with the Guideline. The traffic volume was set to keep car traffic on road A1 in baseline scenario Scn0 to be 200vph, 300vph, or 400vph, where that 200vph and 300vph is the hourly nationwide average of 24-hour and 12-hour traffic volume on a road class similar to A1 in the setting. The daily traffic on A1 road is 4748, which is already similar to the threshold of 4000 vehicles to build mix use road for bicycles and cars. Thus, on the 40km/h B-class roads and 30km/h C-class roads, their daily traffic are lower than the threshold. The settings in the mix traffic scenario that bicycles and cars on B- and C-class roads are not physically separated is consistent with the Guideline. Meanwhile, the analysis in this section provides an alternative to build bicycle dedicated roads, which is not mentioned in the Guideline, as well as a system to separate bicycles and cars to different roads when streets too narrow to add proper bicycle lanes into the existing driving area.

I am discussing limitations in this analysis and possible future research topics. The grid-like network applied in this study differs from that in the real world. The fluctuation of the length of road links and the variety of intersections can affect the assessment of a separating system. It can be possible in the future world to assign different lengths to road links, to use a larger variety of intersections than now, to apply data from the real world, and to input the passing time from models into actual road networks.

I neglected the spillover effects between adjacent intersections in intersection models by constraining the traffic volume input. Thus, the models are not capable of showing situations during busy hours. This disability is rooted in the split-assemble method, in which a network is split into intersections and road segments because building a wholesome network using microsimulation software is time-consuming and infeasible for the author. As the network cannot be considered as a whole, coordination and optimization for multiple signals, like a green wave, are not applied.

Although the settings of sidewalks in road cross sections, pedestrians are not simulated in the microscopic model. In the real world, cyclists use sidewalks sometimes. Thus, their conflict with pedestrians is another critical topic for welfare and safety. PTV Vissim uses different basic models to simulate the movements of pedestrians and vehicles: the social force model for pedestrians and the car-following model for vehicles. Although the simulator can describe the crossing movement of pedestrians and vehicles, it cannot describe their interactions, like dodging or overtaking, when moving in parallel or opposite directions. Although pedestrians can be simulated as vehicles, it is not straightforward to consider cyclists' usage on both sidewalks and bike lanes. Aiming to start from a simple condition and focusing on car lane usage, I left such consideration to future studies.

Sharing or segregation is one of the dilemmas when describing urban roads of the future from different aspects (S. Tsigdinos et al., 2021). While I focused on the method to separate, another option is mixing multiple kinds of road users while prioritizing active transportation means, including shared space and cycling boulevards. To optimize the method for multiple kinds of road users, it is necessary to consider the mixing methods and other features in the real world, like ridership and destinations.

Up till this chapter, the calculation and analysis came to the end. Next chapter will be conclusion.

7. Conclusion

7.1 Summary of each chapter

In Chapter 1, I tried to describe the different proportions of commuting by different modes of transportation, including walking, bicycle, railway, bus, motorcycle, and private car, in Japanese municipalities. Based on these, I summarized the geographic, demographic, and climatic characteristics of the cities where the popular modes of transportation are located. Although these are choices for transportation modes, there are more emerging types of vehicles as industrial development answers to people's demands. Among the newly emerging vehicle types, I picked up e-bikes and e-scooters and introduced their increase in sales, usage, and the regulations regarding them. Introducing the concept of "microbility" which includes e-bikes and e-scooters, I mentioned the variety in means of transportation can bring a variety in vehicle size and fleet characteristics, requiring reconsidering from various perspectives, including space allocation, safety issues, fairness in mobility, users' demands, and regulations. Then, I mentioned road space allocation for multi-modal users and bicycle-considered road allocation methods in the real world. Introducing the status quo on Japanese streets that cyclists face stressful environments from cars and are involved in conflicts with pedestrians, I chose special attention to bicycles and e-bikes as sustainable and healthy means of transportation. Then, I proposed the objectives of this thesis to contribute to finding ways to provide better mobility services for residents while considering the dynamics of population distribution. I will focus on road space because the growing ridership, vehicle size, and fleet characteristics can be problematic.

Corresponding to the objectives, I reviewed studies on urban form metrics, bicycle convenience evaluation, cycling considered facilities, and bicycle-car mix traffic simulation. I found the research gaps to fill in the following studies and the supportive and inspiring reports.

Regarding the classification of urban form, while previous studies have revealed insights into the regional diversity of urban form, research on urban form at the global scale is rare. Among urban form metrics, I chose one for its focus on socio-economic, thus suitable for analyzing transportation usage, and its simplicity, thus making it more likely to access required data for calculation. Regarding bicycle convenience, while previous studies on bicycle convenience focused on the cycling environment itself, they need to be specified to consider a new transport mode like e-bikes that requires insights into their potential and limitations. Regarding e-biking, although studies confirmed the advantages of e-biking for saving physical energy consumption, there is no complete set of data on e-biking corresponding to different slopes, especially the Japanese-style electric assistant bicycle.

Regarding bicycle-considered road space and intersection design, cellular automata and microscopic models are valuable tools for simulating bicycles. Although the studies simulate mixed traffic and road space re-allocation, research gaps also exist in comparing how different road space allocations affect efficiency involving e-bikes, and there needs to be a discussion of a systematical strategy to separate them into different roads at a network scale. I tried to fill these research gaps mentioned above in the studies in the following chapters.

In the first step in analysis in Chapter 3, I aimed to grasp the correlation between transportation mode usage and urban form to provide background information on mobility service provision. I classified the urban form using metrics proposed initially in (Tsai, 2005) by applying four indices: population size, population density (pop/km2), the degree of equal distribution (Gini coefficient), and the degree of clustering (Moran coefficient). There are three analysis parts in this chapter: Part (1): a comparison among cities worldwide in 2015 at the global scale, to fill the research gap in global urban form comparison. Part (2): I summarized the trends in population distribution dynamics over the long term in the global agglomerations and Japanese municipalities. Part (3): I analyzed the correlation between modal share and population distribution in Japanese municipalities.

The long-term dynamics analysis in Parts (1) and (2) reveals that the most populated cities have been growing fastest with the highest levels of density and agglomeration. Asian cities have an intense trend of clustering and even while growing larger, but they have slowed down to be denser recently. In Japanese municipalities, population distribution in large cities became dense, even, and dispersed in the past but otherwise in suburban areas. In the future, municipalities will see a major trend to be sparse, unequal, and concentrated. Part (3) connected the urban form indices to the usage of transportation modes in Japanese municipalities. Railway, bus, bicycle, and motorcycle users have similarities in correlation with equal and dense distribution and large population size.

If viewing the results of part (2) and part (3) against each other, as the Japanese municipalities will see a major trend to be sparse, unequal, and concentrated, private cars are the natural choice for most future urban commuters. In contrast, there seems to be a dim future for active modes and public transportation in Japanese cities. The hope to increase public transit and bicycle usage may lie in the following findings: There are large growing cities that fit with the usage of transit and bicycle usage; motorcycles, which are similar to bicycles, show relatively weak correlations, probably suggesting they are adaptable to a broader range of urban forms; While the relationship shown here between usage rates and urban form is a static status quo, the factors affecting mobility provision are variable, especially detailed condition changed in specific subdivided areas can make difference in transportation method choices.

Answering the discussion in Chapter 3 that motorcycles may fit more various urban forms than bicycles, I focused on a vehicle in-between bicycles and motorcycles, electric bikes (e-bikes) in this chapter. I analyzed subdivided urban areas after choosing target cities considering urban form features. I aimed to explore the applicability of e-bikes in the transportation system within the urban environment, specifically by answering two questions. (1) Whether and where e-bikes can improve resident mobility compared to bicycles and transit (community-wide scale). (2) What are the ranges of applicable time and physical energy costs for e-bikes (city-wide scale)? The two alternative transport modes selected for comparison are conventional bicycles and public transit, which, as shown in Chapter 2, share similarities in mode choices regarding urban forms.

I evaluated e-bikes, used a comparative assessment against other modes of transportation, and quantitatively considered the physical energy expenditure. All of these are the originalities in this research. The method is applied to four Japanese cities with different environments, including road gradient and transit density, and with their urban form and bicycle modal shares as a case study.

Results showed that e-bikes are applicable in areas with steeper road grades or with geographical obstacles requiring a detour and in areas lacking public transportation, e.g., fringe areas in large cities or local cities. At the city scale, e-bikes are applicable for short-distance trips in cities with well-developed transit systems, as the applicable travel time and physical energy expenditure are 65 min and 1.25 MET-h round trip. They are also promising alternative means of transport in local cities.

After realizing e-bikes have advantages in improving mobility services for residents by means of both physical energy cost and travel time cost for residents, especially outside of urban centers where transit is not widely available in Chapter 4, I considered maximizing their strengths while reconciling the conflicts between road users in the scope of multi-modal transportation design mainly on road space in the following Chapters 5 and 6.

Chapter 5 focused on space allocation strategies on road links, intersection models, and a local network between multiple transportation methods. I used multi-agent models and microscopic models to concentrate on exploring the knowledge of how traffic efficiency is affected by allocation.

The results are as follows. (1) In road link models, the road space usage efficiency of 1 e-bike ≈ 1.24 bicycles. E-bikes use road space less efficiently than buses when they accommodate 9 persons. When e-bikes increase, mixed traffic provides better with bicycles on a 2m bike lane; no physical separation between car and bicycle can be better on a 4m road when e-bike density > 10veh /100m. Sharing all 4m bus lanes can be efficient when few passengers are on board and/or dense bicycle volume. When the passenger total amount remains unchanged, the modal shift from cars to e-bikes/bicycles, physically separating the bike lane and car lane, is efficient; a modal shift from bicycles to e-bikes, mixed allocation leads to better efficiency. (2) In intersection models, the bike boxes can produce shorter average passing times among the three bicycle-considered intersection designs: an intersection with a one-direction bikeway, a two-direction bikeway, or a bike box. Applying a bike box requires an amendment to the law as it is currently against the Road Traffic Law. Although the two-direction bikeway shows a marginal advantage over the one-direction bikeway, considering the concerns of increasing safety risk, it is reasonable to maintain the basic rule to keep the bikeway going one way. A higher e-bike ratio can bring up the efficiency of all bicycles. (3) In a case study for a network model at the community scale, increasing bikeway density may improve cycling efficiency. Intersection treatment can result in relatively more significant improvement than adding bike lanes. Assessing the road network scale can provide a comprehensive knowledge of bicycle-considered space allocation strategies.

The simulation of the community network points out the direction of following Chapter 6 to consider both roads and intersections at a network scale. Meanwhile, parts of the results in this chapter are used in Chapter 6, for example, the movement settings of vehicles in microscopic models; the result is that there is no need to separate conventional and e-bikes. Separating bicycles and cars can give a better performance than mixing, etc.

Inspired by car-free zones and car-free cycle paths, the discussion on car-bicycle interference, especially on narrow streets, the approvement of advantages in bicycle-dedicated facilities, as well as the suggestions from Chapter 5, I considered proposing and evaluating a system with bicycles and cars running on different roads at network scale: In places where no enough area to separate bicycles and cars on a same road, separating them to different roads can be an alternative. More specifically, I wanted to answer in what cases separating bicycles, and cars can be preferred: on which kind of road hierarchy, with low or high traffic volume, with high or low bicycle modal share, in short, or long trips? I designed various scenarios to address these research questions using varying parameters, including traffic volume, modal share, and road hierarchy. I assessed their performance through two key metrics: (1) travel efficiency and (2) the traffic stress imposed on cyclists.

The main findings are as follows. (1) Cars and bicycles have a trade-off relationship in efficiency across network scenarios on separated roads. The only scenario that improves both is to separate bicycles and cars on different middle-class roads when bicycle modal share is 20–30%, traffic volume is at the level of 300–400 vph, and bicycles and cars take 30-minute trips. (2) Regarding the cycling environment, separating bicycles from cars on middle-class and local roads can upgrade the overall cycling environment, including efficiency and comfort on the road and at intersections. The not-as-good but fair scenario is to separate solely on local streets. (3) To reconcile conflicts between motorized speed and cyclists' comfort, the separating strategy provides many alternatives. The main idea is to enlarge high-hierarchy roads for car-dedicated use.

Based on the findings, I discussed the practical implementations of this separation approach. Considering the modal share and trip length at present, separating bicycles from cars systematically out of efficiency reason is radical considering general trip lengths and modal share. Separating middle-class roads in part of the area and gradually transiting to middle and minor streets to provide a cozy cycling environment, especially in some residential areas. For cities with sparsely populated and weak transit systems, cars can be indispensable, and caution is required to promote bicycles as a primary task in a city planning vision.

7.2 Main values and applications to cities

While writing this thesis, I was asked what values you maintain and what you would like to say after writing this thesis. I would like to depart slightly from the specific research data and discuss some of my values related to this.

China has long been known as a nation of bicycles, and bicycles have long been associated with high population density and the needs of the working class. E-bikes, similar to electric motorcycles, are an extension of this fit. Benefiting from its flexibility and convenience and noticing that its emissions are less than those of a typical motorcycle, I have always considered e-bikes an environmentally friendly way of traveling while meeting people's mobility needs. This is the starting point of my research. Or rather, my value is striking a balance between personal needs and externalities.

Recently, China's car ownership has been increasing. Many of them are new energy vehicles, including hybrid, pure electric, and fuel cell vehicles. The maturity of the technology, the user's quest for convenience, and the subsidies for new energy vehicles have all contributed to this outcome. Perhaps new energy vehicles, rather than bicycles, will also achieve the balance of personal needs and environmentally friendly externalities that I expect.

But the choice between a bicycle and a car also has the fundamental issue of how much space it takes up. Along with increased car ownership come widening roads, disappearing stores along the street, and fewer pedestrians on the road with street life. Add to that the block system of gated communities already in place, and sometimes I feel that this is no longer a city for people. The choice of the automobile over the bicycle also seems to me to be a separation from the lifestyle and cultural context of the past. Streets filled with individually owned stores become parking lots, and the curbs where we once played chess and chatted are just glimpses of what we can't see from cars. Witnessing this process of change is very frightening for me.

Even though there have been many calls for street life since Jacobs, I still sometimes wonder if this is a torrent of changing times that is hard to resist in people's choices or if it's just a deterioration. But I think people still need the physical experience of being there: the inelastic travel and consumer demand after COVID-19, the growth in consumption of live concerts today when digital streaming is so advanced, the store experience and dining that remains undiminished today with the convenience of online shopping. From this point of view, cities that are close to human physical sensations, close to human scale, still need to exist. In this sense, I believe that small-size mobilities are never obsolete.

My research is based on such values. That is, bicycles and e-bikes are a mode of transportation that achieves personal needs and environmentally friendly externalities, maintains a small local economy, and preserves the indispensable urban experience for urban dwellers. Based on such values, I hope to contribute to the topic of providing mobility services for residents, especially to identify the advantages of the bicycle and its similar peers while mitigating conflicts with other modes of transportation to suggest possible directions for their promotion.

I have discussed the application of the results of each chapter to cities at the end of each chapter. Here, I provide a brief summary. Chapter 3 combines the correlation between transportation and urban structure with the trend of long-term changes in urban structure to sound the alarm for automobile-centered urban development while pointing out that e-bikes, similar to bicycles and motorcycles, can adapt to diverse urban structures. Using four case studies of Japanese cities as examples, Chapter 4 identifies locations where introducing e-bikes can improve residents' convenience and provides a methodology for similar analyses in other cities. Chapter 5 points out the benefits of separating the two on car-bicycle shared-use paths when the number of existing bicycles is relatively small, the importance of bike boxes for bicycle convenience, and the importance of taking measures at road intersections. Chapter 6 proposes separating bicycles and automobiles to different roads in areas with narrow roads, suggesting that bicycle lanes be closed while automobile lanes be widened on high-grade highways to balance automobile efficiency with bicycling comfort and that bicycling comfort and efficiency be achieved by separating bicyclists on local streets in residential neighborhoods, and on medium grade roads in areas with long-distance bicycling commuting needs.

7.3 Possible future research topics

(1) Expand the topics to other micro-mobility means of transportation.

The main transportation modes in this thesis are bicycles and e-bikes. But as mentioned in Chapter 1, there is an increasing number of various vehicles being used; there remains the possibility of expanding the topic to other micro-mobility species.

(2) Consider pedestrians.

While pedestrians are excluded from most of this study for simplicity, they cannot be ignored. They can take part in analysis, as cyclists use sidewalks; thus, their conflict with pedestrians is another critical topic for welfare and safety.

(3) Consider mixed use in the road space area.

Share or segregation is one of the dilemmas when describing the urban road of the future from different aspects (Stefanos Tsigdinos, Tzouras, Bakogiannis, Kepaptsoglou, & Nikitas, 2022). While I focused on the method to separate, another option is mixing multiple kinds of road users while prioritizing active transportation means, including shared space and cycling boulevards. To optimize the process of various types of road users, it is necessary to take into consideration the mixing methods as well as other actual features, like ridership and destinations.

(4) Link the road space allocation topic to the contexts in the real world.

In Chapter 6. the grid-like network, the evenly distributed departures, and the method using reachable areas without considering specific destinations are all settings out of simplicity. To apply the proposal to the real world, the destination facilities, the road with irregular lengths and angles, and the population distribution patterns can primarily affect the performance.

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