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Quantifying e-bike applicability by comparing travel time and physical energy expenditure: A case study of Japanese cities

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Declaration of interest

None

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Abstract

Background

E-bikes are a growing market around the world and public policies regarding their usage are varied among cities. There is a need to inform policy decisions about integrating e-bikes into urban transportation systems. 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 when introduced into the existing urban transportation system.

Methods

E-bike applicability is defined as the change of convenience due to their introduction and the service area is adopted as a measure of convenience for a transportation mode. Indices for e-bike applicability are proposed by comparing the service area of e-bikes to public transit and to conventional bicycles considering travel time and physical energy expenditure as two measures. The methods are applied to four Japanese cities to assess applicability on two scales, namely a community-wide scale and a city-wide scale.

Results

On the community-wide scale, e-bikes are applicable to areas with steep road gradients, areas with geographical obstacles requiring detours, and areas lacking public transportation. E-bike applicable communities with high likely e-bike demand are selected. On the city-wide scale, e-bikes are applicable to short distance trips in cities with well-developed transit systems, with applicable travel time and physical energy expenditure range of 65 min and 1.25 MET-h round trip, respectively. E-bikes are a promising alternative means of transport in local cities; they also have limitation in terms of physical energy expenditure compared to transit.

Conclusions

The indices can be valuable tools providing urban planners with knowledge about e-bikes on a community-wide scale and a city-wide scale.

Keywords

E-bike, Bicycle, Travel time, Physical energy expenditure

1. Introduction

Electric bikes (e-bikes) present 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, and are user-friendly for 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, concerns remain 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), the use of lead-acid batteries in e-bikes (Cherry et al., 2009), and the hesitation to promote its use for public transportation for the fear that it will decrease transit ridership.

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 uangzhou and partially prohibited in Shenzhen and Beijing (uangzhou Municipal People's overnment, 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 have 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 further increase in the use of e-bikes in the future.

In Japan, the legally permitted e-bikes are the electric-power-assisted bicycle. They constitute 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). E-bikes are expected to help promote sightseeing and improve the mobility of local citizens; thus, e-bike rentals have been introduced in 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 overnment, 2017).

When establishing a city's transportation system, it is necessary to provide services that meet various demands and to mitigate inadequate mobility by integrating numerous strategies. A deeper understanding of e-bikes as an active transportation mode is necessary for effective future planning. This study aims to provide some insights into the e-bike potential and limitations when introduced into the existing urban transportation system.

This paper is structured as follows. Section 2 reviews the existing literature on this topic. Section 3 explains the study methodology, including the three main indices. In Section 4, the methodology is applied in four Japanese cities. The discussion of the results is provided in Section 5 and the conclusions are summarized in Section 6.

2. Literature review

2.1. Bicycling convenience evaluation

There are various measures to assess the performance of transportation modes, 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).

Many methods have been 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 previous studies 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 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 were performed by 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.

2.2. Physical energy expenditure in e-biking

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 the reviewed studies reported that e-biking can contribute to at least moderate intensity physical activity (i.e., 3–6 metabolic equivalent of task (MET)), which is sufficient to meet physical activity guidelines (Table 1). In terms of cost, a comparison of e-biking and 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.

Table 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)
ojanovic 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 selected 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.

2.3. Research objectives

This research aims to evaluate e-bike convenience for local users when introduced into the existing urban transportation system to inform policy decisions for integrating e-bikes into urban transportation systems. 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 determined by comparing it to existing transportation modes. Therefore, we define e-bike applicability as the change of convenience due to the introduction of e-bikes into the existing urban transportation system, and we propose an assessment methodology based on the comparisons.

In this research, 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 is a maximum of two when the speed is less than 10 km/h, and this rate gradually decreases as the speed increases and becomes 0 at 24 km/h (*Regulation for Enforcement of the Road Traffic Act*, 2018). The two alternative transport modes selected for comparison are: (1) conventional bicycles, the antecedent of e-bikes, and the mode to be possibly 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 the travel time and energy expenditure.

This study aims to explore e-bike's applicability in the transportation system within the urban environment, specifically by answering two questions. (1) Where can e-bikes improve resident mobility compared to bicycles and transit (community-wide scale)? (2) How significant is the improvement in different cities (city-wide scale)?

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 of traveling by bicycle, e-bike, and public transportation.

3. Methods

This study mainly proposes three indices: overall convenience index (Section 3.1), index of e-bike convenience on a community-wide scale (Section 3.5), and on a city-wide scale (Section 3.6). The data source and processing of the base map are presented in Section 3.2. The two evaluation components, travel time and physical energy expenditure will be explained in Sections 3.3 and 3.4, respectively.

3.1. Overall convenience index

To denote the convenience of a transport mode for a user in a community, a service area was 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 costs are travel time and energy expenditure, which are the components used for comparison. These two components were selected 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 (Section 2.3), we considered energy expenditure as a cost from the Japanese perspective. Although 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, we speculate that being able to ride with less effort is an important characteristic in e-biking.

The following components were not considered in the calculations presented here: (1) contributions from dedicated cycling paths and traffic volume, owing to lack of actual measured data from e-bike users; (2) charging station locations, because the maximum calculation range in this study (approximately 18 km) was 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, owing to difficulty in finding their location data and the consideration that their users can park them almost anywhere.

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

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. 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.

According to the studied modes, three sets of road network were built: bicycling network, e-biking network, and transit network. The two former networks share the same form, referred to as 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 "motorway," "footway," and "pedestrian" are excluded, referring to the definition in OSM (OpenStreetMap, 2018), whereas those labeled "path," "track," "steps," and "bridleway" are excluded because they are considered to be unsuitable for cycling after visually checking oogle 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. 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 in 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, that is intercity bullet train lines, are removed from the railway data. From bus route data, segments longer than 5 km between bus stops are treated as high-speed bus routes and removed from the analysis.

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

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:

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

3.3. Travel time settings

For every resulting cycling network link, speed is assigned in relation to gradient according to empirical data from Inagaki et al. (2011). Note that in this study, e-biking speeds are shown to be lower than bicycling speeds for uphill segments, whereas Inagaki et al. (2011) stated that there is no significant difference between e-biking and conventional bicycling in all three scenarios; they speculated that the difference may result from the feature of e-bikes and 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 uphill and downhill 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 e-bike riders may slow down to achieve a higher assist ratio when e-biking uphill. In studies conducted in the United States (Langford et al., 2017), Germany (Sperlich et al., 2012), and Switzerland (Gojanovic et al., 2011), e-bikes were reported to have higher speeds than bicycling in both flat and uphill segments. A Japanese study (Takaishi et al., 2012) reported that e-bikes with assist-on have higher speeds in uphill segments but lower speed in flat segments than those with assist-off.

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 and Yamamoto (2011), in which the energy was measured when the speed was fixed at 50 m/min. When the gradient was less than 4%, the energy in walking at a speed of 2.5 m/h on a level and firm surface (NIHN, 2012) was adopted. Therefore, the walking speed was set to 4.0 km/h and 3.0 km/h, respectively. For the bus and railway links, the scheduled speed was adopted and waiting time at bus stops or railway stations was not considered (Table 2).

Table 2
Velocity settings of transportation methods.

Cycling speed (km/h)				Transit speed (km/h)			
Gradient	Conventional bicycle [a]	E-bike [a]	At signal (s)	Gradient	Walking	Bus [d] (schedule speed)	Railway [e] (schedule speed)
Uphill ≧2%	14.0	13.6		Uphill ≧4%	3.0 [b]		
<2%	14.3	14.4	24	<4%	4.0 [c]	11.0	43.4
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 and Yamamoto (2011)
c: corresponds to physical activity data in National Institute of Health and Nutrition (2012)
d: from Toei Transportation (2017)
e: calculated based on MLIT (2016) and Toei Transportation (2017)

3.4. Physical energy expenditure settings

Physical energy expenditure (EE) was quantified in this study. We used MET-h as the unit of expenditure for a transportation mode user. MET is a unit of physical activity (PA) that measures 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 was 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 (Fig. 1.) was obtained from existing studies (Ainsworth et al., 2011; Hagiwara and 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 3.), 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.

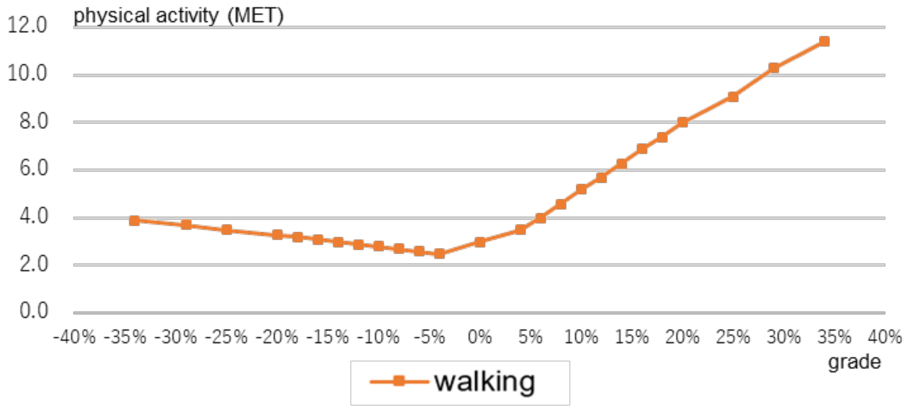

Fig. 1. Calculated physical activity values (MET) for walking by gradient (gradient ≧4%: calculated based on Hagiwara and Yamamoto (2011); gradient <4%: based on NIHN (2012)).

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. (1) (Parkin and Rotheram, 2010; Wilson et al., 2004), considering the air resistance, slope resistance, rolling resistance, and average bump resistance:

$$W_1 = \frac{C_v}{\eta_{\mathrm{mech}}}\left[Mg\left(C_r + \frac{s}{100}\right) + 0.5C_D A\rho(C_v + C_w)^2\right] \tag{1}$$

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. In terms of the other factors, we 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 was neglected in this study.

Second, to calculate e-biking physical activity, we considered the assistance ratio, which is the ratio of the engine output to the personal output. The measured assistance ratio can be summarized as given in Eq. (2) based on prior research (Japan Bicycle Promotion Institute, 2016):

$$a = \begin{cases} 1.4, 0 \le C_v < 10 \\ 1.4 - 0.1(C_v - 10), 10 \le C_v \end{cases} \tag{2}$$

where C_v is the speed of the bicycle (m/s). Then, the human output in e-biking (W_0) is calculated based on W_1 using Eq. (3):

$$W_0 = \frac{W_1}{(1+a)}. \tag{3}$$

Third, the oxygen consumption rate (VO_2) is calculated using Eq. (4) according to Zoladz et al. (1995):

$$VO_{2m} = 450.00 + 9.7067\, W_m \tag{4}$$

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. Results smaller than 1.5 MET are manually changed to 1.5 MET since that is the value corresponding to inactivity.

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

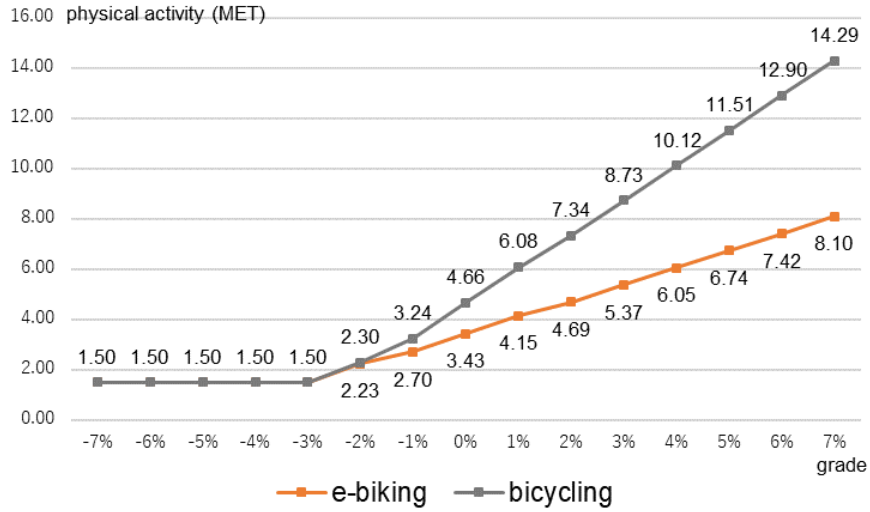

Fig. 2. Calculation results of physical activity values (MET) in bicycling and e-biking by gradient.

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 (MA) equation in Kwok and Yeh (2004), the index bike-service area gap (BA) is proposed to denote the e-bike applicability on a community-wide scale:

$$BA_{mi}^{k} = \frac{S_{0i}^{k} - S_{mi}^{k}}{S_{0i}^{k} + S_{mi}^{k}}, m \neq 0 \tag{5}$$

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

To illustrate the BA results, we 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 BAs are illustrated in Figs. 3(b) and (c).

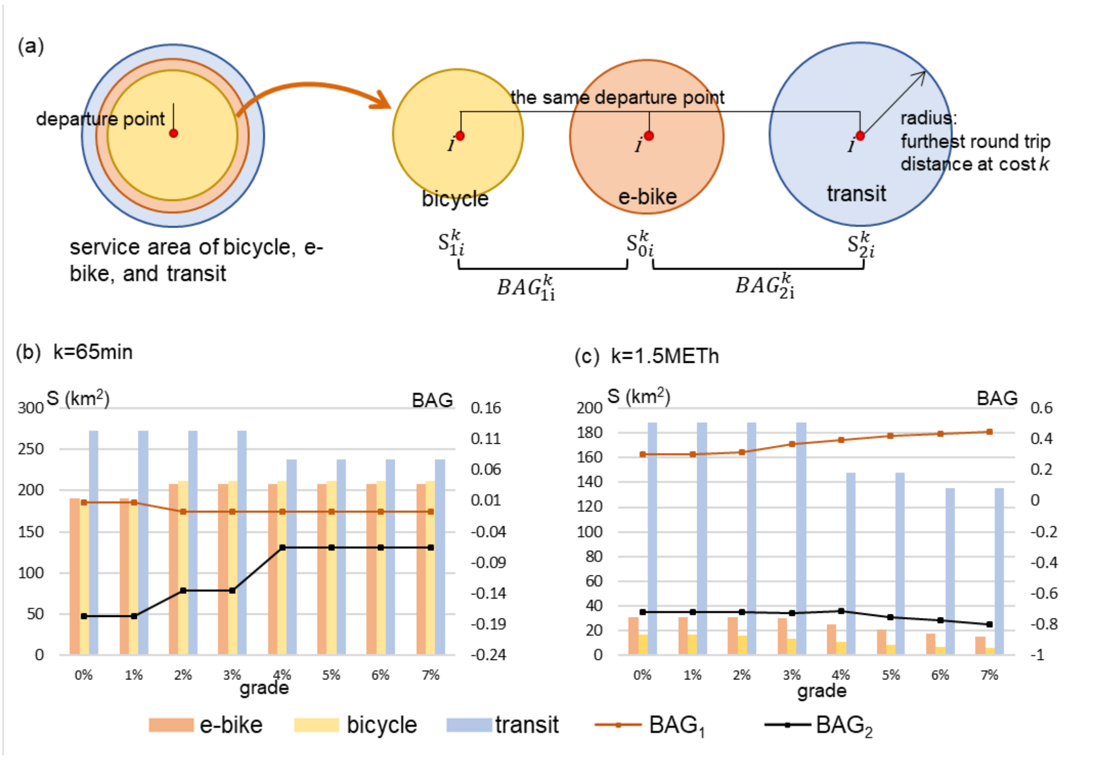

Fig. 3. Simplified version of S and BA calculation: (a) related factors; (b) results when k=65 min; (c) results when k=1.5 MET-h.

3.6 E-bike applicability index (city)

The index average of BAG (ABAG) is proposed based on the BA, denoting the e-bike applicability on a city-wide scale, and is calculated using Eq. (6):

$$ABAG_m^k = \frac{\sum_{i=1}^{N}(p_i BAG_{mi}^k)}{\sum_{i=1}^{N} p_i}, m \neq 0 \tag{6}$$

where N is the number of communities and p_i is the population in community i. The ABAG variation 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. Case studies

In this section, the methods described in Section 3 are applied to four Japanese cities to answer the question of where e-bikes have the potential to improve the mobility of residents, and to explore e-bike applicability in cities with different characteristics.

4.1. Cities studied

The four cities selected for the case study were the 23 Special-ward Area (Tokyo), Osaka City, Nagasaki City, and Tsukuba City. These cities, summarized in Table 3, were selected based on the e-bike applicability relevant factors, density of public transportation lines, and grade of road segments. Tokyo was selected because of its high density of public transportation lines, Nagasaki City was selected because of its typical steep grade of roads, and Osaka City and Tsukuba City, with mild grade of roads and a lower density of public transportation lines, were selected for comparison.

Table 3
Descriptive statistics of the four case study cities.

City	Land area (km^2)	Population		Number of communities	Average road gradient (%)	Transit line density [a] (km/km^2)	Cycling road density (km/km^2)
		Number	Density (pop./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 both counted.

4.2. Improvement compared to transit and bicycle

The BA was calculated to identify where e-bikes can improve the resident mobility compared to transit and bicycle. Different from the simplified version presented in Section 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, e-bikes tend to be more applicable to communities with lower transit line density as expected (Fig. 4). This tendency can be observed in the four case study cities in Fig. 5. The well-developed transit system in the central parts of Osaka and Tokyo and the relatively high transit line densities in southeast Tsukuba and central Nagasaki tend to make e-bikes not applicable to these areas, but applicable to the fringe areas.

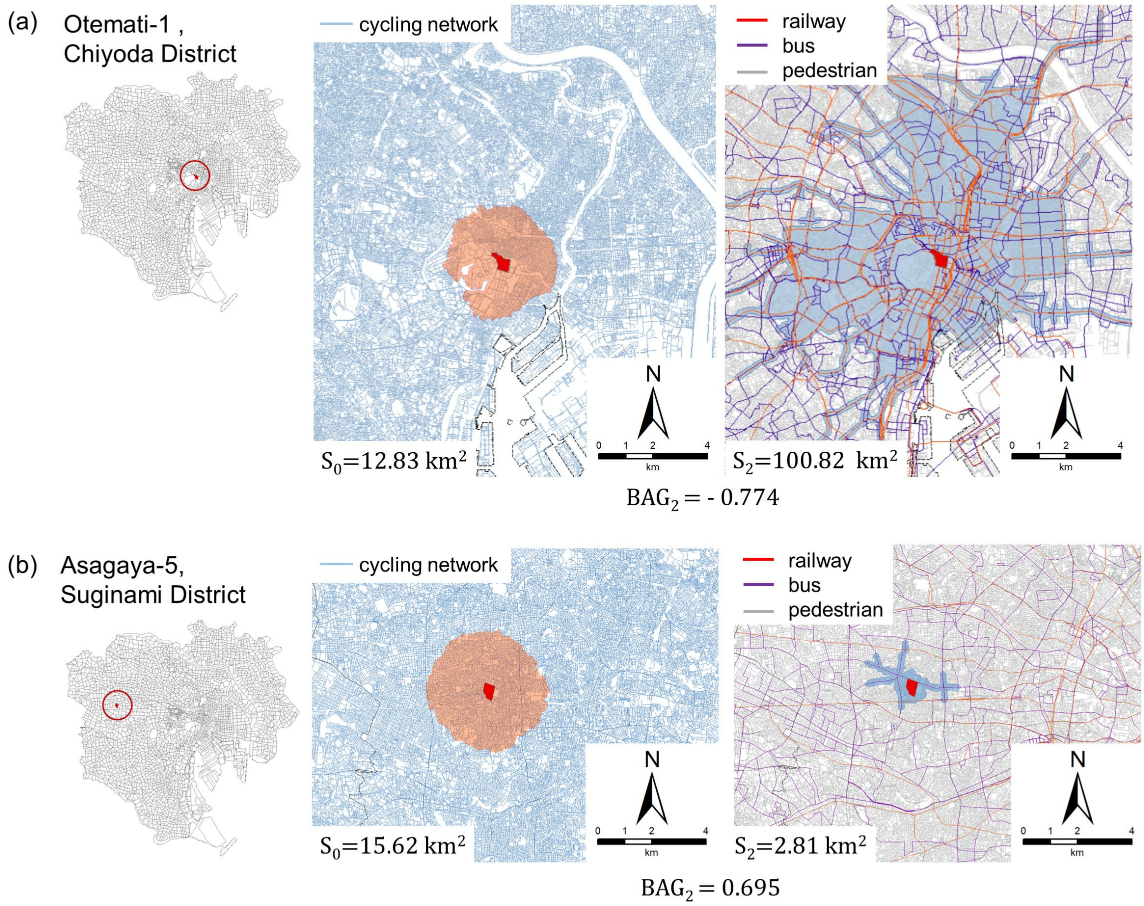

Fig. 4. Example of resulting S and BA in Tokyo, when m=2 and k=1.25 MET -h.

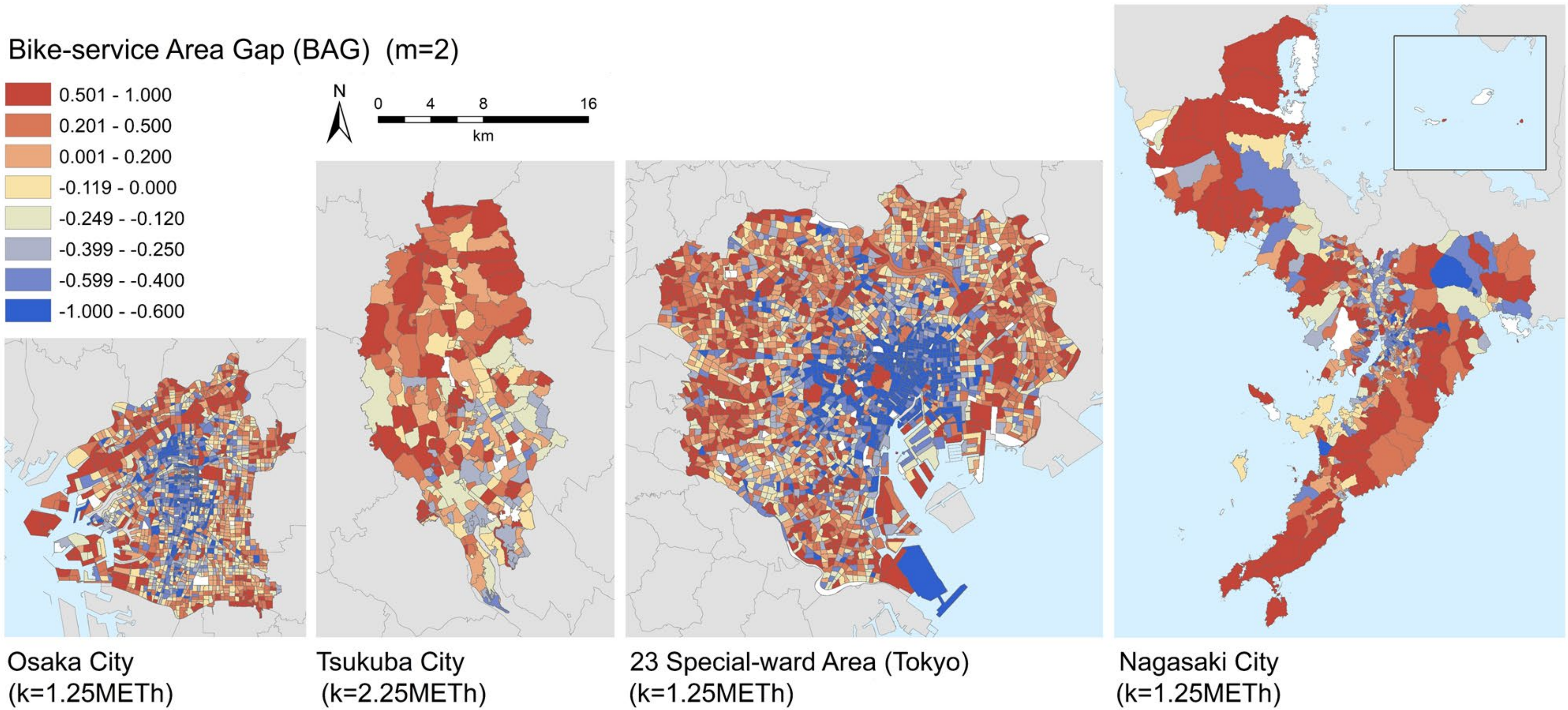

Fig. Results[a] of the BA (m= 2) in Osaka, Tsukuba, Tokyo, and Nagasaki.

[a] To compare the results with the same legend, figures are shown when the average values of BAs are near 0.

When compared to bicycles in terms of physical energy expenditure, the results show that e-bikes can improve their mobility anywhere, but particularly when the roads are steeper (Figs. 6(a) and (b)), or with geographical obstacles requiring a detour (Figs. 6(a) and (c)). Considering a riverside community as an example (Fig. 6(c)), as the road density decreases, whether a vehicle can reach and cross a bridge can considerably affect the size of the service area. Since e-bikes are more likely to cross bridges than conventional ones, the same physical energy is exerted.

The same tendency seen in the communities can be observed in the cities (Fig. 7). The effects of steep roads occur in the southwest and north parts of Tsukuba, central and west parts of Tokyo, and the outskirts of Nagasaki. The red area in the southwest seaside and stripe-like areas in the northern part going east-to-west in Osaka and the red strip in northeast and southwest in Tokyo suggest the impact exerted by wide rivers. Similar impacts from large parks can be observed in Osakajo Park (Osaka) and Yoyogi Park (Tokyo). Otherwise, the cycling road density can also affect the results. Areas with low cycling road density can lead to marginal difference between e-biking and bicycling, thus minimal applicability of e-bikes over bicycles.

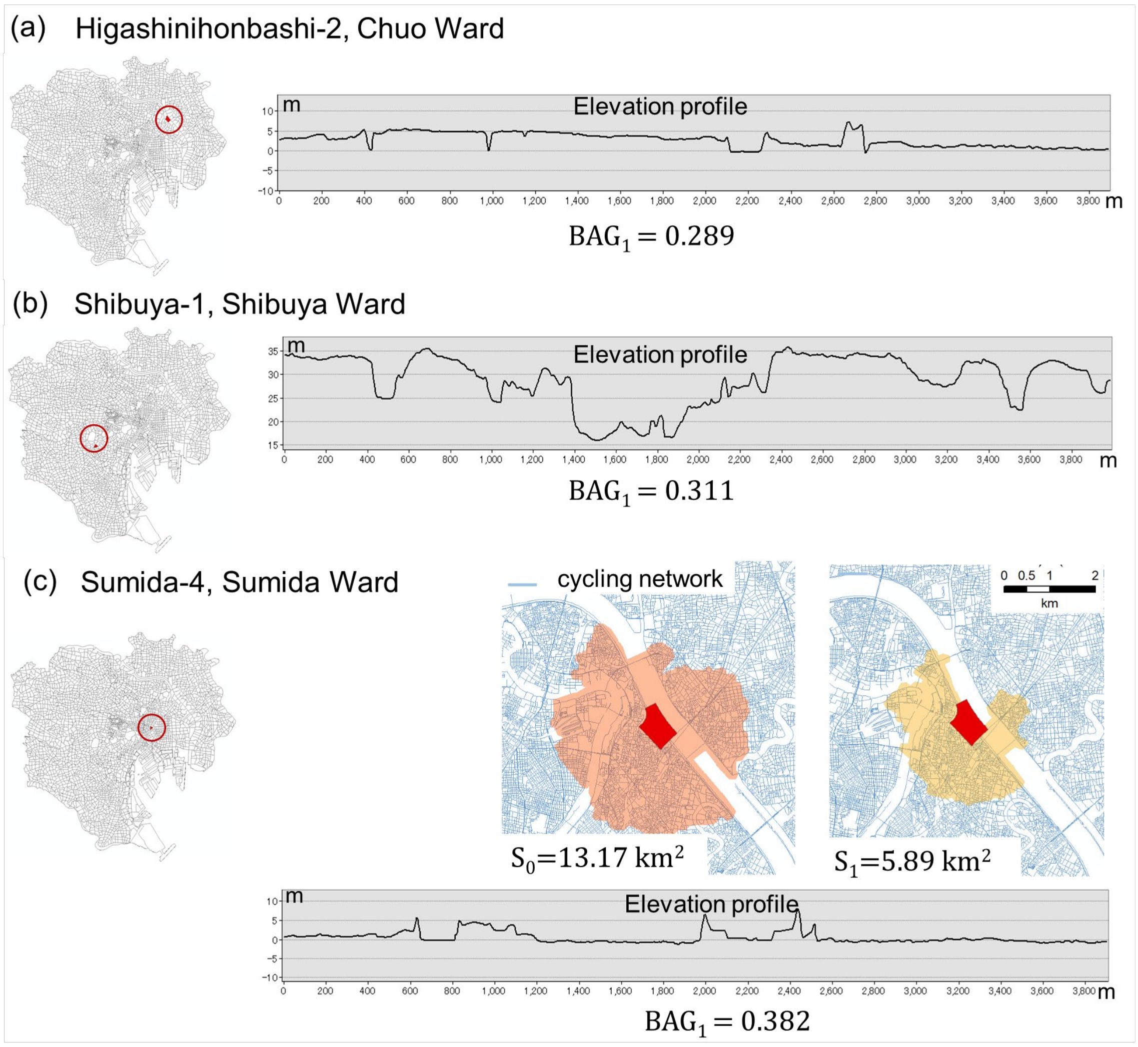

Fig. 6. Example of resulting S and BA in Tokyo (m=1, k=1.25 MET-h) and elevation profile of e-bike service area.

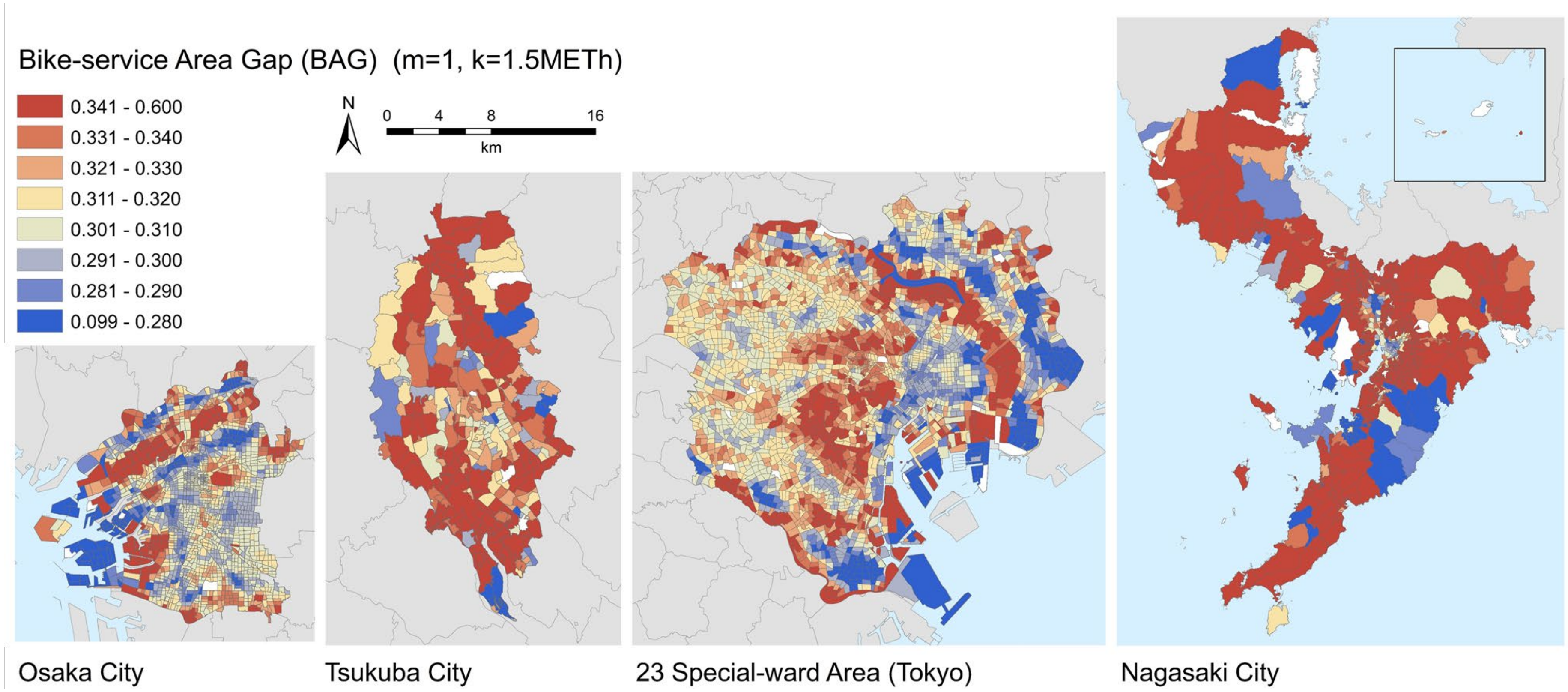

Fig. Results of the BA (m=1, k=1.5 MET-h) in Osaka, Tsukuba, Tokyo, and Nagasaki.

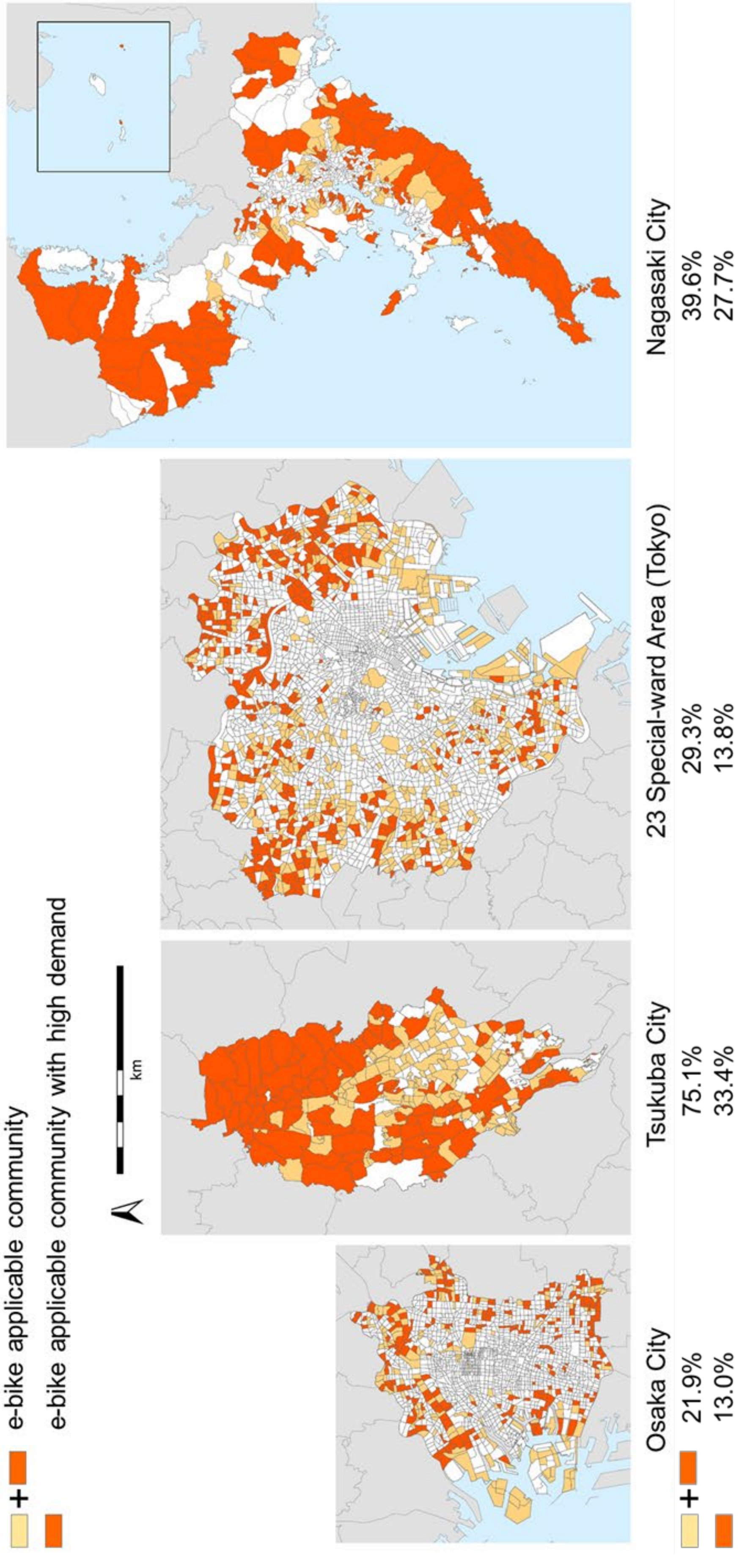

Fig. 8 E-bike applicable communities in Osaka, Tsukuba, Tokyo, and Nagasaki.

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. We assume that half of the daily activity, 1.5 MET-h, is attributed to transportation. Thus, the criterion for an e-bike applicable community was set to $\mathrm{BA}_{1}^{1.5\,\mathrm{MET-h}} \geq 0$ and $\mathrm{BA}_{2}^{1.5\,\mathrm{MET-h}} \geq 0$. The travel time range was not used since it was 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 were 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. Considering the accessibility of data, we used the ratio of the elderly above 70 years old to children under 5 years old in the population as an indicator of potential users, and a ratio higher than 20% is assumed to be high. The results are shown in Fig. 8.

4.4. E-bike applicability in different cities

To investigate the e-bike applicability in different cities, the ABAG values were calculated and plotted. The terrain characteristic tends to be the determinant compared to conventional bicycles (Figs. 9(a) and (b)). In terms of travel time, the increased terrain has a negative correlation with e-bike advantage over conventional bicycle (Fig. 9(a)). In a hilly city with an average grade over 2%, e-bikes can lose their advantage in speed since the e-bike riders may slow down to achieve a higher assist ratio when e-biking uphill. Regarding energy expenditure, the e-bike advantage over bicycles gradually increases as energy expenditure increases before reaching and remaining at its peak. Hilly terrain has a positive impact on e-bike advantage ($\mathrm{ABA}_{1}^{\mathrm{time}}$) as shown in Fig. 9(b).

Compared to public transportation in terms of time ($\mathrm{ABA}_{2}^{\mathrm{time}}$), cities with well-built transit systems (Tokyo and Osaka) have an e-bike applicable time range under 65 min, whereas the ranges are wider in local cities, showing stronger competitiveness over transit, as shown in Fig. 9(c). In terms of energy expenditure ($\mathrm{ABA}_{2}^{\mathrm{energy}}$) in Fig. 9(d), cities with high transit density (Tokyo and Osaka) and hilly terrain (Nagasaki) have similar applicable energy ranges, which are smaller than that in a local city with flat terrain (Tsukuba). Note that e-bike applicable ranges are smaller when physical energy is considered. For instance, assuming cycling roads are flat, the corresponding time at the applicable physical energy ranges in Fig. 9(d) are 22 min (1.25 MET-h) and 39 min (2.25 MET-h), which are shorter than the 65-min time range when only travel time is considered.

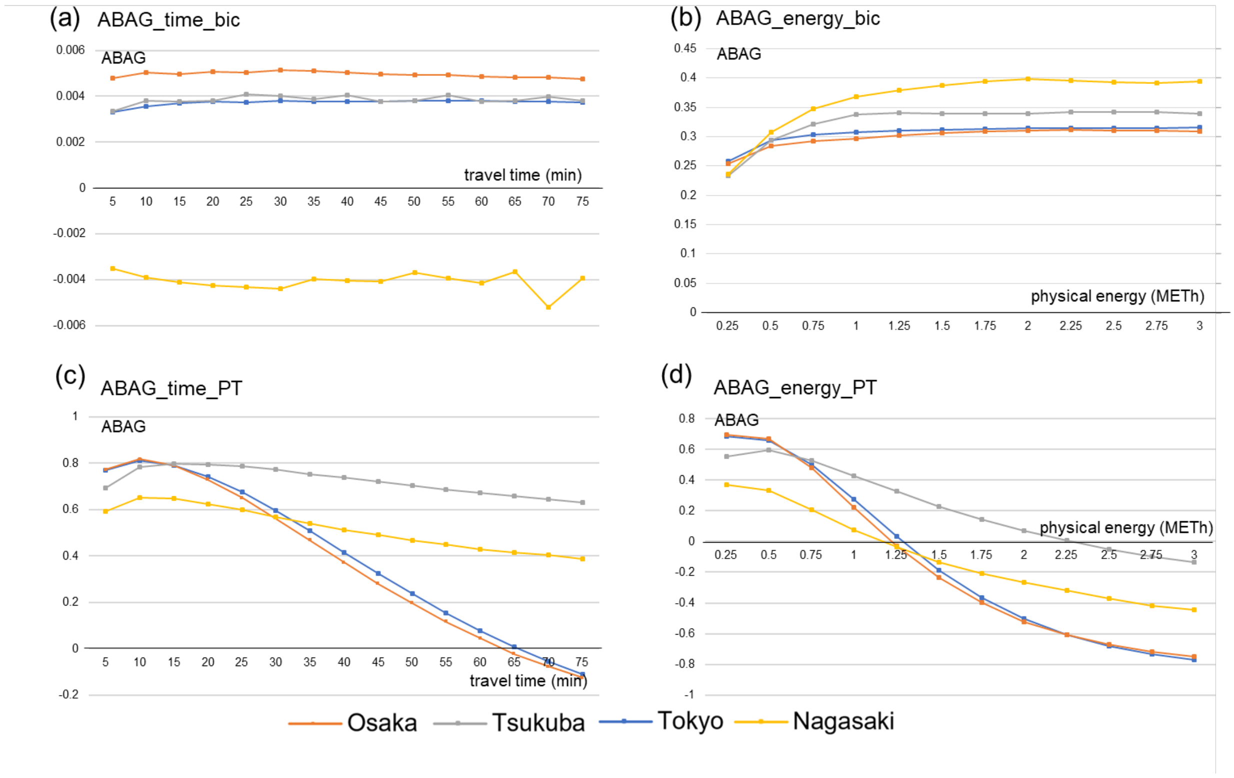

Fig. 9. Results of the ABA in Osaka, Tsukuba, Tokyo, and Nagasaki.

5. Discussion

With the research goal to evaluate e-bike potential and limitations for local users, we 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 of e-bikes and existing transportation modes. This study extends 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.

Although the results from the case study reported herein are specific to four cities in Japan, the estimation methodology and findings are indicative of convenience improvement that may arise as a result of e-bike introduction in other cities or countries. 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). On the community-wide scale, e-bike applicable communities with high likely demand can be selected after exploring the mobility improvement of e-bikes compared to bicycles or transit, respectively. The selected communities imply where the infrastructure supporting e-biking can be established, and where the ports for an e-bike rental system can be built efficiently to improve resident mobility, as some suburban areas lack public transportation due to financial limitations.

On the city-wide scale, this method provides general information about e-bike applicability in cities with different environments, including road gradient and transit density. The results suggest that e-bikes can support their users for short trips in cities with well-built transit lines, and they can be accepted as a promising solution to ensure convenience in local cities without well-built transit systems. The advantage of e-bikes in terms of conserving the user's effort is most significant in hilly cities. The limitation that e-bikes require considerably more physical energy than transit is highlighted, suggesting that from the perspective of the welfare of individuals with physical limitations, policy-makers must be cautious when considering e-bikes as substitute for public transportation.

Although, information used in the extraction of high e-bike demand districts may be specific to Japan, 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 cities in developing countries, 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 rail. 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.

6. Conclusions

Aiming to inform policy decisions about integrating e-bikes into urban transportation systems, we defined e-bike applicability as the change of convenience due to the introduction of e-bikes, and developed indices by comparing the convenience of e-bikes to public transportation and to conventional bicycles in terms of travel time and physical energy expenditure. Then, the method was applied to four Japanese cities as a case study.

The indices can be valuable tools to provide 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, results show that (1) when compared to conventional bicycles, e-bikes are applicable to areas with steeper road grades or with geographical obstacles requiring a detour and (2) when compared to transit, e-bikes are applicable to areas lacking public transportation, such as fringe areas in large cities or local cities. The e-bike applicable communities and those with high likely e-bike demand were selected to inform policy decisions about where to establish infrastructure to support e-biking. With regard to the second question about e-bike applicability in different cities, results show that (1) e-bikes are used 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, respectively; (2) e-bikes are promising alternative means of transport in local cities; and (3) e-bikes have limitation in terms of physical energy expenditure compared to transit.

The limitations of this research that could be addressed in future evaluations of e-bike applicability include calculating the physical activity benefits (improvements to mood and well-being) and the perceived costs of the exercise provided by bicycling and e-biking, as well as examining the economic, environmental, and traffic safety impacts of increased e-bike uptake.

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