Journal of Transport Geography 67 (2018) 1–11

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Determining transit service coverage by non-motorized accessibility to transit: Case study of applying GPS data in Cincinnati metropolitan area

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ARTICLE INFO

Keywords:
Transit service coverage
Non-motorized accessibility to transit
Transit catchment area

ABSTRACT

To more effectively expand transit service coverage through promoting bicycling, a practical approach is presented in the paper for estimating the coverage of transit service accessible by non-motorized modes (i.e. walking and bicycling). The non-motorized accessibility to transit is determined by the connectivity and facilities of non-motorized network. Using the data from 2009 to 2010 GPS-based Household Travel Survey in the Cincinnati metropolitan area, the study examines distance thresholds of such non-motorized transit access trips and identifies the spatial boundary and geographic area of transit catchment areas in the Geographic Information System environment. Results suggest that bicycle enables people to access the transit service. The bicycle-transit catchment area is estimated as 1.7 and 2.3 times of the size of pedestrian-transit catchment area at home and activity ends respectively. As a result, more households and employment can reach the transit service via bicycling than walking (52.45% vs. 36.72% for households and 47.82%. vs. 33.07% for employment in the study area). Suburbs, where near half of population and employment situate, are comparatively underserved. Especially, only 27.14% % of the disadvantaged population in suburbs, can access transit by walking, but the percent is increased to 50.96% if using a bicycle. Besides the distance threshold, the non-motorized accessibility to transit is found to be a significant factor determining transit catchment areas. The transit service area can be expanded if a safer and more comfortable bicycling environment is available. Those findings can also be further used as references in the transit-oriented development planning.

1. Introduction

Transit has been widely viewed as a sustainable means for reducing congestion, saving the use of public space, alleviating environmental issues caused by automobiles, and providing an affordable transportation to public, especially disadvantaged groups (e.g., low-income households). Determining transit service coverage is essential in predicting potential transit ridership and assessing impacts of transit investments in transit planning. A transit service coverage area, or called as transit catchment area, is commonly measured as the vicinity of a transit stop or station (Andersen and Landex, 2008). One challenge of this estimation lies in the determination of spatial boundaries of transit catchment areas, which is related to the first and last mile problem.

Usually, as most of transit riders are pedestrians or bicyclists at the beginning or end of their transit trips (Bhat et al., 2005), a transit catchment area is conventionally determined by willingness distance or distance threshold to walk (Mistretta et al., 2009). Many research efforts have been spared on the walking distance to transit (El-Geneidy et al., 2014; Foda and Osman, 2010; Kim et al., 2005; Murray and Davis, 2001; Peng et al., 1997). Intuitively, connecting bicycle and transit can effectively expand the transit catchment areas by permitting transit to be accessible from further distances due to bicycle's speed advantage over walking to better address the first and last mile gap. However, comparably detailed findings of bicycling distance are much fewer for bicycle-transit catchment areas (Kittelson and Associates et al., 2013; Krizek et al., 2011). Empirical studies of the extent to which transit service areas are extended by bicycle connections compared with walking are still few in number. On the other hand, besides

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https://doi.org/10.1016/j.jtrangeo.2018.01.002
Received 16 September 2017; Received in revised form 30 November 2017; Accepted 10 January 2018
Available online 19 January 2018
0966-6923/

the distance threshold, the accessibility of non-motorized network is crucial to the geographical scope of transit catchment areas. It's been suggested that a well-designed pedestrian and bicycle network ensures good accessibility to public transit (Dill and Carr, 2003; Furth, 2012; Moudon et al., 2005; Wei et al., 2013). Different roadway facilities would encourage or discourage the distance that a cyclist would be willing to travel. For instance, bicyclists are found to be willing to travel 22% further on a bicycle boulevard than on a route with a bike lane (Broach et al., 2009). Yet impacts of those facilities on non-motorized accessibility to transit and the geographical scope of transit catchment areas still remain unclear.

The walking or bicycling distance to transit is usually calculated with self-reported distance (Flamm and Rivasplata, 2014; Lee et al., 2016) or algorithm-estimated distance using recorded locations and street network (El-Geneidy et al., 2014; Flamm and Rivasplata, 2014). However, neither way provides actual distance accessing the transit service. To address this issue, a solution is recommended with the application of Global Position System (GPS) or GPS-enabled devices (e.g. smartphones) in collecting travel information. The recorded GPS information, including trajectory, speed, and time stamps, can be used to examine routes taken and distance traveled et al.

Based on the discussion above, three questions are raised in the study:

- What is the distance threshold that people are willing to walk and bike to access the transit system?
- How would facilities affect non-motorized accessibility to transit and the geographical scope of transit catchment areas?
- To what extend transit service areas can be expanded if bicycle is used as the access mode to transit compared with walking?

To answer these questions, the paper examines analytical features, including travel distance and durations, of walking and bicycling trips to access transit service (termed as non-motorized transit access trips in this paper) using the data obtained from 2009 to 2010 GPS-based Household Travel Survey (HTS) in the Cincinnati metropolitan area. Distance thresholds of non-motorized access trips are then identified using the 85th percentile length. With the analysis results, a method of measuring transit service coverage with the walking and bicycling accessibility in the Geographic Information System (GIS) environment is presented. The transit service coverage is measured by the number of households and employment within transit catchment areas. Spatial boundaries of pedestrian-transit and bicycle-transit catchment areas are determined based on identified distance thresholds and non-motorized accessibility to transit. The connectivity and quality of non-motorized network are adopted in the calculation of non-motorized accessibility to transit. With those efforts, the proposed questions can be answered. In the end of the paper, we further discuss implications of the results into transportation planning process.

2. Literature review

The identification of transit service areas typically uses routes (Peng et al., 1997; Polzin et al., 2002) or stops (El-Geneidy et al., 2014; Foda and Osman, 2010; Zhao et al., 2003) as the reference of measurement. An empirical study conducted by Horner and Murray (2004) suggested that stops are more appropriate basis than routes for estimating coverage, because stops are the actual locations where passengers access the transit system. A commonly recommended walking distance to access either a stop or line in transit planning is 0.25 mile (or 400 m) (Kim et al., 2005; Kittelson and Associates et al., 2013; Murray and Davis, 2001). Meanwhile, there is a substantial body of research devoted to refining the recommend value. Rietveld (2000) summarized that most walking distances are up to about 1.2 km at home ends and 2.2 km at activity ends in Netherlands. Guerra et al. (2012) have concluded findings concerning pedestrian-transit catchments areas in 29 studies and suggested the use of a 0.25-mile catchment area around transit for jobs and a 0.5-mile catchment area for residences. Welch and Mishra (2013) defined a half-mile catchment around each housing unit. Using a detailed Origin-Destination (OD) survey information in Montreal, Canada, El-Geneidy et al. (2014) found that the 85th percentile walking distance to transit service is around 0.5 km for home-based bus trip origins and 1.3 km for home-based commuter rail trip origins. Similar literature on the bicycling distance to transit is much less. Rietveld (2000) found that biking is dominant to access transit between 1.2 and 3.7 km at residential areas in the Netherlands. With on-board travel surveys in three U.S. metropolitan areas, Hochmair (2015) concluded that median bicycle access distances to transit stations are within 1 mile for community hubs and 2 miles for gateway hubs. By surveys conducted in Philadelphia and San Francisco, the average bicycling distances estimated by transit travelers and calculated using Google Maps are 3.08 miles and 2.62 miles, respectively (Flamm and Rivasplata, 2014). Lee et al. (2016) estimated that the access distances in Seoul metropolitan and Daejeon metropolitan areas, Korea are 1.96 km and 2.13 km for home-to-station and station-to-work trips, accordingly.

Most of previous studies examining transit catchment area are based on data collected from traditional travel surveys, such as questionnaire-based interviews (El-Geneidy et al., 2014; Flamm and Rivasplata, 2014; Lee et al., 2016) and travel OD surveys (Rietveld, 2000b). Traditional travel surveys cannot record the actual walking or bicycling distance to access transit. The access distance is commonly obtained from self-reported distance or distance calculated from an algorithm-identified route (such as, the shortest route) with a reported origin/destination and stop location. For example, the access distance was estimated from one's origin to the closest stop using street network and transit stop locations (El-Geneidy et al., 2014; Hochmair, 2015). Google Maps was used to calculate distances based on identified routes by algorithms from recorded ODs in Flamm and Rivasplata's (2014) study. In Crowley et al.'s (2009) study, access distances to bus and streetcar lines were based on estimated straight-line distances to the specified line. However, those estimations don't provide actual stops and distance traveled. This problem can be solved by using GPS travel data that contains detailed travel trajectories. The travel distance and duration of each trip are calculated by projecting GPS points onto road network in the GIS environment. GPS trajectories can be used to examine locations visited (Thierry et al., 2013), identify routes taken (Duncan and Mummery, 2007; Hood et al., 2011), and quantify non-motorized trips (Cho et al., 2011; Rodriguez et al., 2012).

In the estimation of transit catchment areas, some studies delineate geographic areas of transit service coverage based on as-the-crow-flies distance (Kim et al., 2005; Lee et al., 2016; Murray and Davis, 2001; Welch and Mishra, 2013), while others use network distance computed using the street network to reach a transit feature (El-Geneidy et al., 2014; Horner and Murray, 2004; Zhao et al., 2003). The approach using as-the-crow-flies distance to estimate coverage areas, rather than examining the actual street network, is problematic and overestimates coverage areas (Cervero, 2005; Krizek et al., 2011).

Transit is more affordable than private vehicles and it offers great mobility and connectivity benefits for disadvantaged groups. Studies on travel behaviors of disadvantaged groups have indicated that those population rely more significantly on transit than others. For example, Dodson et al. (2010) stated that retired elders and students in secondary and tertiary education have around a quarter their trips made by transit, which is much higher than the average transit share (4.3%) in Gold Coast City, Queensland, Australia. From the 2001 and 2009 U.S. National Household Travel Survey (NHTS), Mattson (2012) found that people from lower-income households are more likely to use public transportation, as are people with medical conditions. A study in Huzhou, China by Cheng et al. (2013) indicated that the predominant motorized mode of low-income people is bus, while it is private cars for the non-low-income. Improving transit service coverage for disadvantaged groups is important to improve their mobility level.

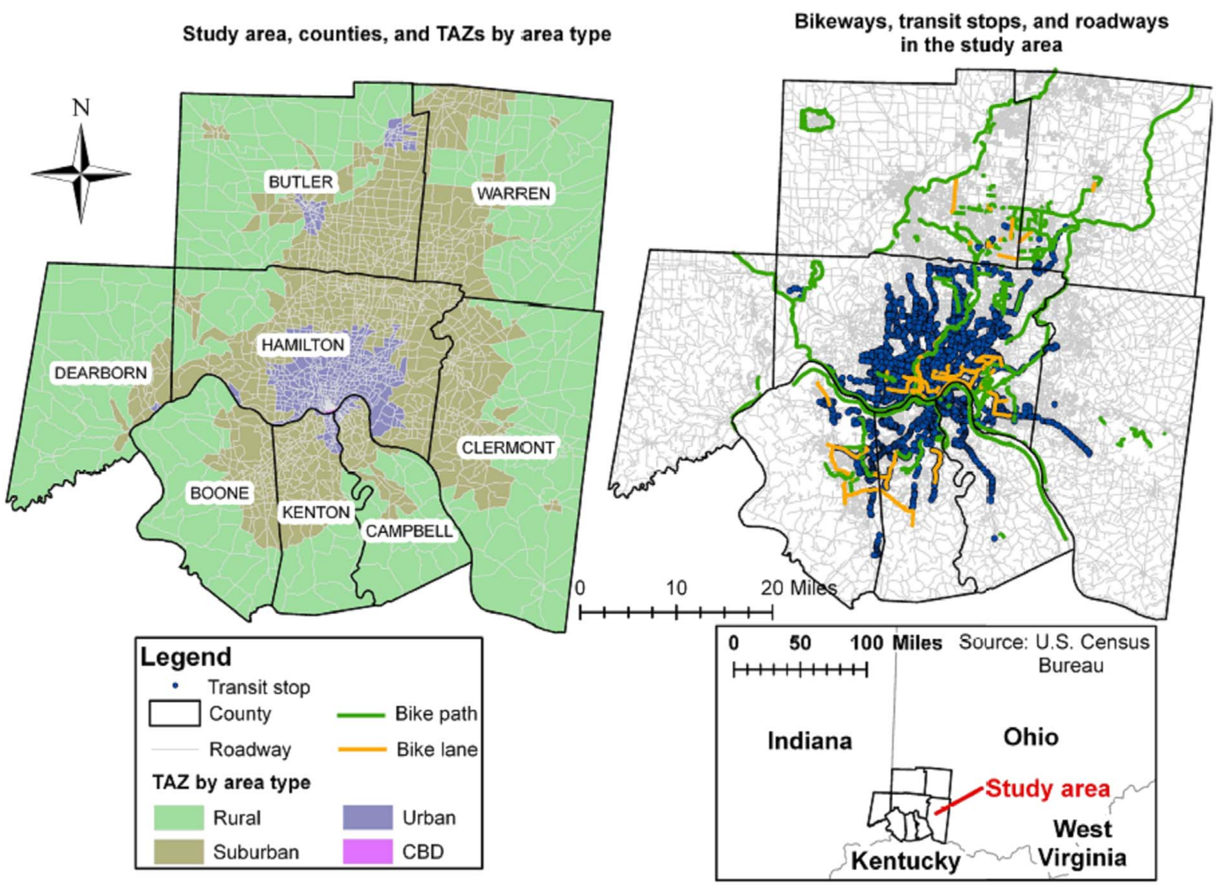

Fig. 1. The study area, roadways, transit stops, and bicycle facilities.

Therefore, disadvantaged groups need particular attention regarding improvements in transit service coverage.

3. Method and data

A common practice in transit planning is to assume that people and jobs are served by transit if they are within a surrounding area where a transit stop is accessible by walking or bicycling. The estimation of transit service coverage involves two procedures: (1) identifying the service coverage area that is accessible by pedestrians and bicyclists and (2) estimating the population and jobs within the service area.

3.1. Data

3.1.1. Study area and GPS-based household travel survey

The Cincinnati metropolitan area is targeted as the study area, which includes counties in the U.S. states of Ohio, Kentucky, and Indiana around the Ohio city of Cincinnati. Traffic analysis zones (TAZs), which is used as the analysis geographic unit, are classified by area type including central business district (CBD), urban, suburban, and rural. The study area boundary and TAZs are shown in Fig. 1. Meanwhile, in the figure, the existing transit stops, bike paths and lanes, and roadways are illustrated as well. There are around 80 bus routes and over 7800 bus stops serving the area. The total length of bike amenities is about 189 miles. Bicycling in the area rely heavily on the general road network. Bike paths and lanes link up to some extent, but it's not a dense bicycle network with complete routes approaching transit service in most cases.

The 2009–2010 Cincinnati GPS-based HTS is adopted as the data source for examining non-motorized transit access trips. This survey was conducted by the Ohio Department of Transportation (ODOT) Research Division in cooperation with the Ohio-Kentucky-Indiana (OKI) Council of Governments. In the survey, GPS data loggers were equipped to all members of a recruited household over 12 years of age for a three-day recording period (Wargelin et al., 2012). A total of 2059 households, sampled across the area provided fully completed GPS data. The data was collected on a second-by-second basis, and 77,209 trips in all modes of travel, including auto, bus, bicycle, walk, and others, were recorded.

3.1.2. Non-motorized transit access trips

There are 1330 trips identified as non-motorized transit access trips, in which 84% are walking trips and only 16% are bicycle trips. Analytical features, including the distribution and average length, of these non-motorized transit access trips by different area type, per capita household vehicle ownership, and per capita household income are further investigated. Results are presented as follows.

(a) Trip distribution and average trip length by area type

Fig. 2 shows the distribution and average distance of non-motorized trips by area type. Over half of those non-motorized transit access trips, i.e. 56% of walking trips and 61% of bicycling trips, are undertaken in the suburban area. About 32% of walking trips and 30% of bicycling trips take place in the urban area. The trip percentage in the rural area is 12% and 8% for walking and bicycling trips. Only a very small portion ($<$ 1%) of trips take place in CBD for both modes. Fig. 2(c) and (d) show the average trip length of transit access trips in different areas by walking and bicycling correspondingly. The average trip length inclines as the area type varies from CBD to rural. Following this trend, we conclude that the more scattered population and employment in an area are, the longer distance people would have to travel to access

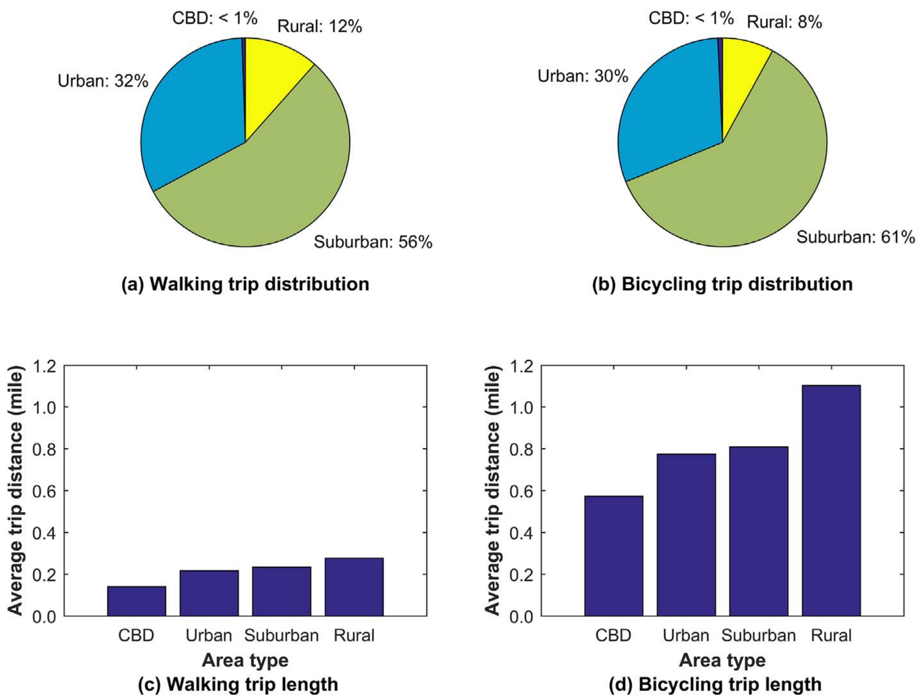

Fig. 2. Non-motorized transit access trip distribution and average length by area type.

transit.

(b) Trip distribution and average trip length by per capita household vehicle ownership

To examine the impact of household vehicle ownership on non-motorized transit access trips, households are classified into four categories according to the per capita average household vehicle ownership, i.e. < 0.33, ≥ 0.33 and < 0.5, ≥ 0.5 and < 1, and ≥ 1. The per capita average household vehicle ownership is calculated as the total number of household vehicles divided by the number of persons in a household. For instance, a household in the category < 0.33 means that on average a vehicle is shared by three persons in the household. Fig. 3 shows the distribution and average distance of non-motorized trips by per capita average household vehicle ownership. The percentages shown in Fig. 3 suggest that families with more household members and less vehicles tend to use transit more frequently. People from those households tend to travel further to access transit, because limited number of vehicles is available to them in their households.

(c) Trip distribution and average trip length by per capita household income

In the GPS-based HTS, household income is categorized into less than $25,000, $25,000 to $49,999, $50,000 to $74,999, and $75,000 or above. The per capital household income is computed by dividing the total household income by the number of persons in a household. The per capital household income is classified into four categories: less than

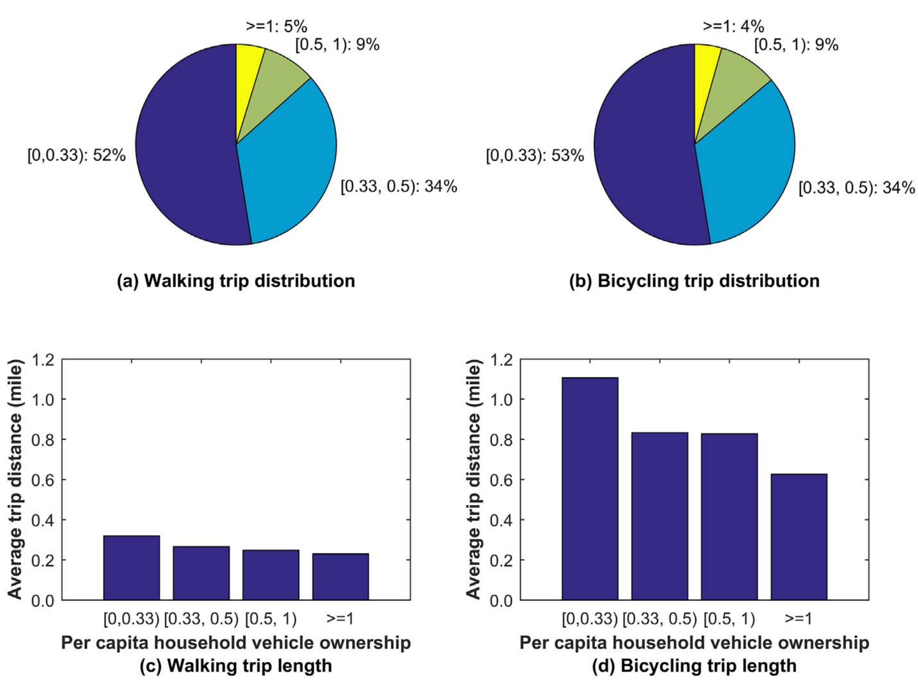

Fig. 3. Non-motorized transit access trip distribution and average length by per capita household vehicles ownership.

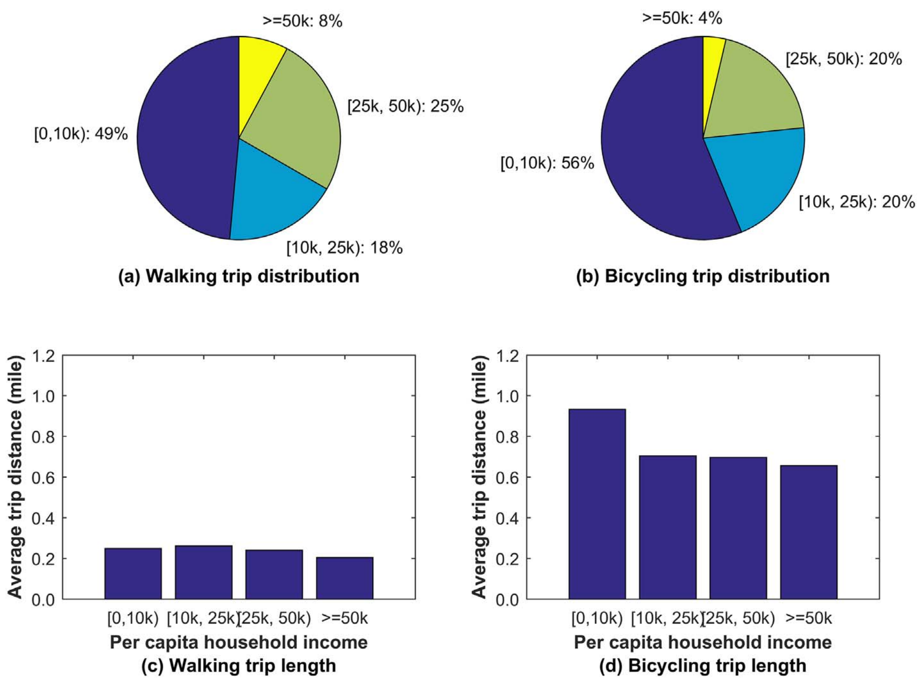

Fig. 4. Non-motorized transit access trip distribution and average length by per capita household income.

$10,000 ([0, 10 k]), $10,000 to $24,999 ([10 k, 25 k)), $25,000 to $ 49,999 ([25 k, 50 k)), and $ 500,000 above (≥ 50 k). Fig. 4 presents the results of non-motorized transit access trip distribution and average distance by the per capita household income. It is noticed that people with lower per capital household income use transit system more often. Moreover, they travel longer distance to transit compared to other income groups. As transit provides a more affordable mobility choice to public, low-income population would be more likely to take the transit even if they have to walk or bicycle further to a transit stop.

3.1.3. Distance thresholds

The 85th percentile distance is applied as threshold that people are willing to walk or bicycle to reach the transit service (El-Geneidy et al., 2014). The statistical features of non-motorized transit access trip length at home and activity (or non-home) ends are enlisted in Table 1. The 85th percentile walking distances are 0.59 mile and 0.34 mile at home and activity ends respectively; the 85th percentile bicycling distances are 1.59 and 1.43 accordingly at home and activity ends. The results suggest that 1) transit users are willing to walk or bicycle further at home ends than at activity ends and 2) bicycle enables people from further areas to access the transit service. The 85th walking distances at both home and activity ends are larger than the commonly used 0.25-mile walking distance in practice (Kittelson and Associates et al., 2013).

It is worth mentioning that the result shown in Table 1 is based on the 2009–2010 GPS-based HTS data in Cincinnati area, Ohio. Dolati (2014) used the NHTS, which was collected nationwide in 2009 by the Federal Highway Administration to find out the average bicycling distance is 2.61 miles, much larger than the result in Table 1. The NHTS datasets include the data from an interview-based survey started in 2001 and combined data from both Nationwide Personal Travel Survey and the American Travel Survey (Dolati, 2014; Edwards et al., 2012). However, no associations between the bicycling distance and transit line or stops are addressed in Dolati's study. The Mobike bike-sharing big data shows that shared bicycles have apparently become the major first and last mile bridge by extending the 800-m (half-mile) walking distance in the transit-oriented planning to 2–3 km (1.24–1.86 mile) for a 10-min access service circle to transit stops (Fang, 2017). This result is very consistent with the Cincinnati's HTS findings.

The distribution of walking and bicycling distances to access transit is illustrated in Fig. 5(a) and (b). As the access distance increases, the number of walking and bicycling trips declines. This trend affirms the sensitivity of residents to distance accessing transit service. At home ends, walking is the most important access mode for distances up to about 0.75 mile; biking is dominant between 0.75 and 3.00 miles. At activity ends, walking is dominant up to about 0.5 mile, and bicycling is the dominant mode for further distances. The findings can effectively help planners determine the potential ridership for those transit users who are willing and able to bicycle on the origin/destination/both ends of their trips.

Table 2 illustrates the results of walking and bicycling durations to transit. The average duration of bicycle trips is less than that of walking trips at home ends. At home ends, 85% of all walking trips are traveling within 11.71 min, and the 85th percentile cycling duration is 13.94 min; while at activity ends, the 85th duration of walking and bicycling trips are 9.99 min and 11.10 min accordingly. With the travel distance and duration, average walking and cycling speeds are calculated as 3.1 mile/h and 9.7 mile/h accordingly. Due to the speed advantage of bicycling over walking, riding a bicycle to transit stops can make the first and last miles easier and less costly in terms of travel time. Connecting bicycle with transit could allow transit services to be accessible from more distant areas.

Table 1
Statistics of travel distances of non-motorized transit access trips.

Statistical features of non-motorized trip length (mile)	Home ends		Activity ends	
	Walking	Bicycling	Walking	Bicycling
Mean	0.36	0.96	0.22	0.76
Median	0.36	0.73	0.18	0.60
85th	0.59	1.60	0.34	1.44
Min	0.07	0.07	0.02	0.04
Max	0.92	2.89	0.94	2.66
Standard deviation	0.21	0.72	0.16	0.65

3.2. Identifying transit catchment area

3.2.1. Non-motorized accessibility to transit

The non-motorized accessibility to transit is largely determined by the connectivity and facilities of non-motorized network. Roadways

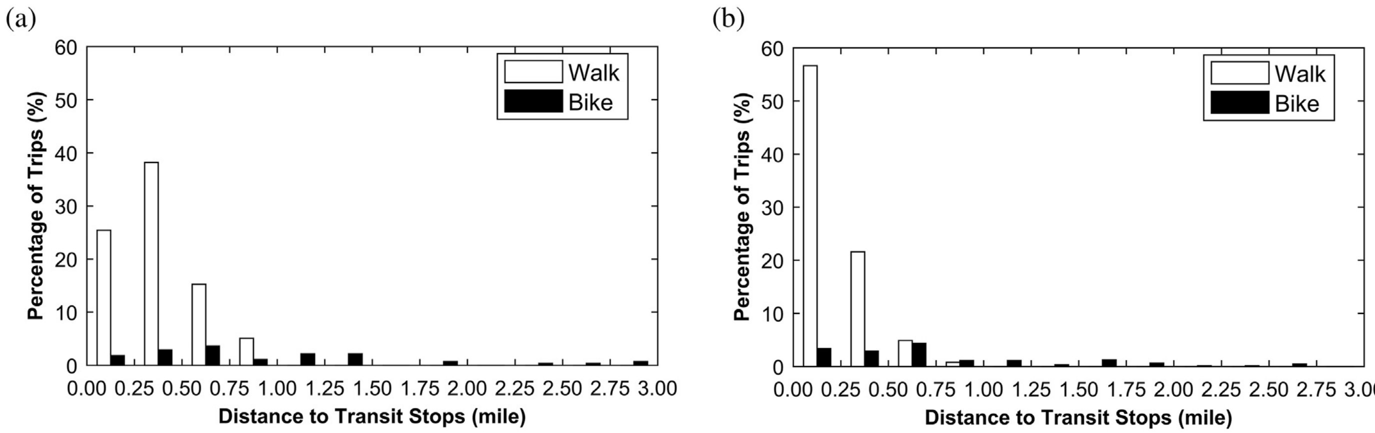

Fig. 5. Distribution of travel distance of non-motorized transit access trips.

Table 2
Statistics of travel durations of non-motorized transit access trips.

Trip duration (min)	Home ends		Activity ends	
	Walking	Bicycling	Walking	Bicycling
Mean	8.58	6.79	5.99	5.98
Median	8.28	5.25	5.41	4.87
85th	13.95	11.71	9.99	11.11
Min	1.78	0.38	0.83	0.37
Max	19.47	19.75	19.98	18.98
Standard deviation	4.50	4.91	3.75	4.81

without any curb, shoulder, and sidewalk are among the most hostile to pedestrians (Evans et al., 1997). All local streets with a speed limit of 20 mile/h or higher but with sidewalks are accessible for pedestrian, except for limited-access roads, such as freeways (Tal and Handy, 2012). Bicyclists prefer to travel on a safer environment, and they have a strong preference for on-street bicycle facilities (Royal and Miller-Steiger, 2008). While on auto-dependent road networks where no or only a few on-street bicycle facilities are available, bicyclists can share routes with automobile users. Different roadway facilities may discourage the distance that a cyclist would be willing to travel (Broach et al., 2009). The effective length, developed by McNeil (2011), is introduced to represent the distance that an average cyclist would be willing to travel on a certain type of road segment. The effective length is produced by actual length divided by the distance threshold multiplier, which is calculated by Eq. (1).

$$L_{e,i} = L_i/\delta_X \tag{1}$$

where,

$L_{e,\,i}$ is effective length of road segment i;
L_i is the actual length of road segment i;
δ_X is the distance threshold multiplier of road segment i, and the value for δ_X is determined by road type: 1.00 for bike lanes, 1.22 for bicycle boulevards, 1.35 for bike paths, 1.00 for local streets, 0.82 for minor arterials, 0.42 for major arterials, 0.14 for highways, and not accessible for freeways.

3.2.2. Catchment area

A transit catchment area is measured as the area within a spatial boundary that transit service can be accessed by bicycle or walking. This spatial boundary is determined by the distance threshold and non-motorized accessibility. The network distance approach is used in the paper to estimate catchment areas as it is capable of reflecting the configuration, connectivity, and quality of non-motorized network.

Transit catchment areas are identified using the network analysis operation in GIS by constructing lines of equal network distance around each transit stop. In the operation, accessible paths to transit stops are searched, and the effective distance is calculated instead of actual network distance when calculating accessible routes. Using GPS trajectories, the travel distance of non-motorized transit access trips is calculated by projecting GPS points onto road network in the GIS environment.

3.3. Estimating population and employment under transit service coverage

Once catchment areas are identified, the number of population and employment served by transit service can be further determined by using the social-demographic data. Using the GIS functions, the population is calculated by overlaying the catchment area on the geographic analysis polygons with social-demographic data. TAZs are adopted as geographic analysis polygons in the paper. The population (P_s) and employment (E_s) served by a transit stop s are equal to the sum of the population and employment in each of the intersecting areas accordingly. Calculations are given as Eqs. (2) and (3).

$$P_s = \sum\nolimits_j P_{sj} \tag{2}$$

$$E_s = \sum\nolimits_j E_{sj} \tag{3}$$

where,

P_{sj} is the population in the intersecting area j that is near transit stop s;
E_{sj} is the employment in the intersecting area j that is near transit stop s;
j is the analysis zone intersecting either fully or partially with the catchment area of transit stop s.

A commonly known area ratio approach is used to estimate P_{sj} and E_{sj}. This approach is represented as Eqs. (4) and (5) (Bhat et al., 2005).

$$P_{sj} = P_j A_{sj}/A_j \tag{4}$$

$$E_{sj} = E_j A_{sj}/A_j \tag{5}$$

where,

A_{sj} is the area of intersection between the catchment area of stop s and zone j;
A_j is the area of zone j;
P_j is the population of zone j;
E_j is the employment of zone j.

Table 3
Statistics of transit catchment areas by transit access modes at home and activity ends.

Statistical results	Catchment area (mile^2)			
	Home ends		Activity ends	
	Walking	Bicycling	Walking	Bicycling
Total	225.42	398.61	171.59	381.29
Maximum	1.36	2.74	1.14	2.61
Minimum	0.018	0.012	0.011	0.012
Mean	0.18	0.32	0.14	0.31
Standard deviation	0.14	0.29	0.09	0.27

4. Analysis

4.1. Area covered by transit service

Based on current transportation network and existing pedestrian and bicycle facilities in Cincinnati metropolitan area, transit service coverage areas for residential and employment are calculated using the 85th percentile distance at home and activity ends, relatively. Table 3 shows statistical features of calculated transit catchment areas that are accessed by walking and bicycling. At home ends, the total and average transit coverage areas via bicycle connections are about 1.7 and 2.2 times of the areas accessed by walking at home and activity ends, accordingly. It is clear that bicycle provides a larger coverage than walking due to its advantage to connect the first and last miles. On the other hand, the standard deviations show that variation of the catchment area size by bicycle is much larger than that by walking. This is primarily because of the disparity between the connectivity and quality of bicycle access to transit around bus stops. People in areas surrounding transit stops that lack on-street bike facilities or preferred roadways (e.g. low-traffic-volume streets) tend to travel shorter to access transit. The non-motorized infrastructure plays an important role in encouraging pedestrian and bicycle trips, and investments in non-motorized travel environment would improve non-motorized accessibility and increase transit ridership.

Table 4 presents the geographic size of each area type in the study area and the percentage of area covered by transit service in each area. Results show that the CBD and urban areas are well covered by transit service either by pedestrian or bicycle connections, while the suburban and rural areas are comparatively underserved. The estimated transit catchment areas at home and activity ends serve as a basis for calculating the number of households and employment within transit service coverage accordingly.

4.2. Households and employment covered by transit service

Using the census data in the year of 2010 and projected social-demographic data in 2040 by OKI, along with estimated transit catchment areas, the number of households and employment with accessible transit service through walking and bicycling in Cincinnati metropolitan area are estimated with the method introduced in section 3.3.

Table 4
Pedestrian- and bicycle-transit catchment areas at home and activity ends by area type.

Area type	Area (mile^2)	Percent of area covered by transit service			
		Home ends		Activity ends	
		Walking	Bicycling	Walking	Bicycling
CBD	0.90	95.05%	99.74%	85.55%	97.86%
Urban	131.05	69.91%	80.21%	56.20%	79.67%
Suburban	895.51	14.43%	31.16%	10.62%	29.40%
Rural	1637.05	0.23%	0.84%	0.13%	0.78%
Total	2664.51	8.46%	14.96%	6.44%	14.31%

Table 5 enlists the total number of households by area type and the percentage of households with accessible transit service in each area. In 2010, most of the households in the Cincinnati metropolitan area are distributed in the urban and suburban area, which consists 87.6% of all population, while only 0.3% and 11.1% of the households are located in the CBD and rural areas. According to Table 5, most households in CBD and urban areas can easily access transit either by walking or bicycling. Only 24.73% of households in the suburban area can access transit by walking, and the percentage is increased to 45.36% if riding a bicycle to access transit. The coverage percentage in the rural area is even lower, which is largely resulted from the dispersed population. There is a projected 14.14% growth in the total number of households by 2040. The projection shows a decentralized trend in population as 48.52% and 47.76% of the total increased households is predicted to be located in suburban and rural areas. This decentralization would reduce the number of households with transit coverage, which is reduced by 4.03% and 5.63% for walking and bicycling connections accordingly.

The number of jobs with accessible transit service in the Cincinnati metropolitan area is presented in Table 6. Similar to the population, in 2010, most jobs in CBD and urban areas are able to access to transit either by walking or bicycling. The suburbs, where over 50% of the total jobs in the study area situated, only around 25.32% of the jobs can access transit by walking. Though the coverage percentage can be increased to 55.95% if using bicycling, more efforts are still required to promote non-motorized access to transit. Alike the population projection, there is a predicted decentralization trend in employment by 2040. Following this trend, the total number of jobs covered by transit is expected to be decreased by 1.2% and 1.1% for walking and bicycling access modes respectively.

4.3. Disadvantaged groups covered by transit service

OKI has defined five categories of the disadvantaged population including disabled, elderly, minority, poverty, and zero-car, in accordance with federal and state Environmental Justice (EJ) guidelines. Table 7 enlists the average population of disadvantaged groups from 2009 to 2013 by area type. In total, 42.72% and 48.76% of the total disadvantaged population live in urban and suburban areas relatively. For each disadvantaged group, about 86–94% of them are in the urban and suburban areas. There is a great need for providing basic transit amenities and convenient non-motorized connections to disadvantaged groups in those two areas.

Fig. 6 shows the percentage of the disadvantaged population that can access transit via walking and bicycling by area type in Cincinnati metropolitan area. For all area types, the bicycle provides a larger coverage of accessible transit service than walking. Comparing among Fig. 6(a–d), the transit coverages in suburban and rural areas are lower than those in CBD and urban areas. Fig. 6(c) shows that on average 27.14% % of the disadvantaged population can access transit by walking and 50.96% of them are covered if riding a bicycle. As over half of the disadvantaged population live in suburbs, providing more accessible transit service to these groups in suburbs is of great benefit to improving EJ and sustainable transportation.

5. Discussion

5.1. Improving bicycle and pedestrian environments

Improving the bicycle and pedestrian environments is a desirable method for enhancing the non-motorized transit access and promoting transit ridership. The introduction of bikeways and sidewalks to the auto-dominant or auto-dependent streetscapes, complete with street furniture, landscaping, pedestrian-scaled lighting, and other features, makes roadways more inviting for people to travel by bicycle or on foot.

Table 5
Households covered by transit service in Cincinnati metropolitan area.

Area type	Number of households (2010)	Percentage of households covered (by access mode)		Number of households (2040)	Percentage of households covered (by access mode)	
		Walking	Bicycling		Walking	Bicycling
CBD	2523	89.23%	88.96%	4063	92.09%	91.51%
Urban	222,540	83.17%	87.48%	225,136	83.14%	87.64%
Suburban	465,661	24.73%	45.36%	519,513	22.92%	42.63%
Rural	94,053	1.30%	3.10%	147,061	1.45%	3.50%
Total	784,777	40.47%	52.45%	895,773	36.44%	47.82%

Table 6
Number of employment covered by transit service in Cincinnati metropolitan area.

Area type	Number of jobs (2010)	Percentage of jobs covered (by access mode)		Number of jobs (2040)	Percentage of jobs covered (by access mode)	
		Walking	Bicycling		Walking	Bicycling
CBD	67,774	82.74%	89.05%	73,882	82.70%	88.98%
Urban	289,485	71.54%	87.14%	301,937	71.49%	87.11%
Suburban	570,718	25.32%	55.95%	640,874	24.62%	54.68%
Rural	41,954	1.31%	4.54%	49,354	1.68%	5.68%
Total	969,931	42.50%	44.26%	1,066,047	41.30%	43.36%

Table 7
Disadvantaged population in Cincinnati metropolitan area by area type (unit: persons).

Area type	Population by group				
	Disabled	Elderly	Minority	Poverty	Zero-car
CBD	361	336	1488	440	523
Urban	48,489	59,185	196,439	132,022	39,662
Suburban	68,409	154,994	183,279	115,654	20,776
Rural	17,739	35,589	12,711	22,414	3275
Total	134,998	250,104	393,917	270,530	64,236

Fig. 7 shows an example of enlargement in transit coverage area if bike lanes were added to existing minor arterials around a bus stop in the downtown Cincinnati. The area around the bus stop covered by transit service is expanded by 42.11% after the implementation of bike lanes. The covered households and jobs are increased by 79.74% and 9.79%, accordingly. Further places from the bus stop can reach the bus service if a safer and more comfortable bicycling environment is available. In addition, the bicycling and walking infrastructure is much less expensive to build and maintain than highways and parking garages.

5.2. Integrating bicycle and transit

Efforts to facilitate integrating bicycle and transit modes are found to be able to enlarge the catchment area for transit (Flamm and Rivasplata, 2014). The predominant approach for integrating bicycle and transit in the U.S. is to bring a bicycle on board transit vehicles. In 2015, about 77% of new U.S. buses were equipped with exterior bicycle racks, up from 32% in 2001 (Neff and Dickens, 2017). Compared with the costs of increasing buses, rail cars, and automobile facilities, it is less inexpensive to install bike racks at transit stops and on buses.

Bicycle racks have been popular with passengers, but they frequently run up against capacity constraints, typically two or three bicycles on a bus's front rack (Krizek et al., 2011). An alternative to bringing a bike on board transit vehicles is bike-sharing programs. Bike sharing programs have been viewed as ways to solve the first and last mile problem and to connect passengers to public transit networks. Traditional docked public bike systems, e.g. Cincinnati Red Bike, provide free or affordable access to bicycles for short-distance trips in an urban area. However, with limits on the number of places where bicycles can be rented or returned, the service can hardly fulfill door-to-door needs. This problem can be solved with the emerging dock-less bike-sharing programs, such as Mobike and Ofo in China, Bluegogo and Spin in U.S. The dock-less bike sharing provides flexible connections between origins/destinations and transit service, thus allowing a shared door-to-door mobility for many utilitarian trips.

5.3. Promoting bicycle-based transit-oriented development

Studies have shown that land use significantly impacts traffic mobility and an effective approach to reduce vehicle travel is through land use planning (Banister, 1997; Newman and Kenworthy, 2006; Wei et al., 2017). Transit-oriented development (TOD) is a strategy that attracts more people and jobs situate within walking or bicycling distance to transit to promote transit ridership and mobility. Planners and researchers use transit catchment areas as geographic units for designing TOD. TOD involves very well the number of population and jobs within transit catchment areas. A common consideration is that the larger the catchment area is and the denser the population and jobs are, the higher the transit travel potential is (Andersen and Landex, 2008). The more people residing and/or employed around transit stations, the greater the probability that the service will be used.

With the 2010 and projected 2040 social-demographic data in Cincinnati metropolitan area, the improvement in transit service coverage from the TOD is discussed here. The density elasticity of households/employment covered by transit service is used to measure responses in transit service coverage to changes in households/employment densities of transit catchment areas. Table 8 illustrates the results of elasticities. For example, a value 0.22 of the density elasticity of households indicates that 1% increase in the household density of pedestrian-transit catchment areas results in 0.22% increase in the total number of households covered by transit. Using bicycle-transit catchment areas as TOD zoning units allows more population, especially families with no cars, to access a wider variety of services and opportunities by transit. In the land use and transportation planning, connecting jobs, schools, and services with communities through transit, accompanied with safe, direct, and comfortable bicycle access to transit at communities and other activity ends, would increase the safety and number of bicycle-transit trips.

In the bicycle-based TOD development, the availability of secure and convenient parking is critical for better integration of bicycle and public transit system. Improving the availability of parking near transit stops is beneficial to promoting bicycle-transit travels (Pucher and Buehler, 2009), and good-quality bicycle parking facilities are most useful to regular commuters (Bachand-Marleau et al., 2011). Priority siting of parking amenities near the transit loading zone allows bicycle-transit users to be free from carrying bicycles up or down stairs or through large crowds of transit travelers, and this is especially helpful to children, female, and elders. Facilities, including lockers, bicycle cages, and storage rooms, for long-term parking (usually four or more hours), and bicycle racks for short-term parking should be provided associated with travel demand. Bicycling could be off-limits to some

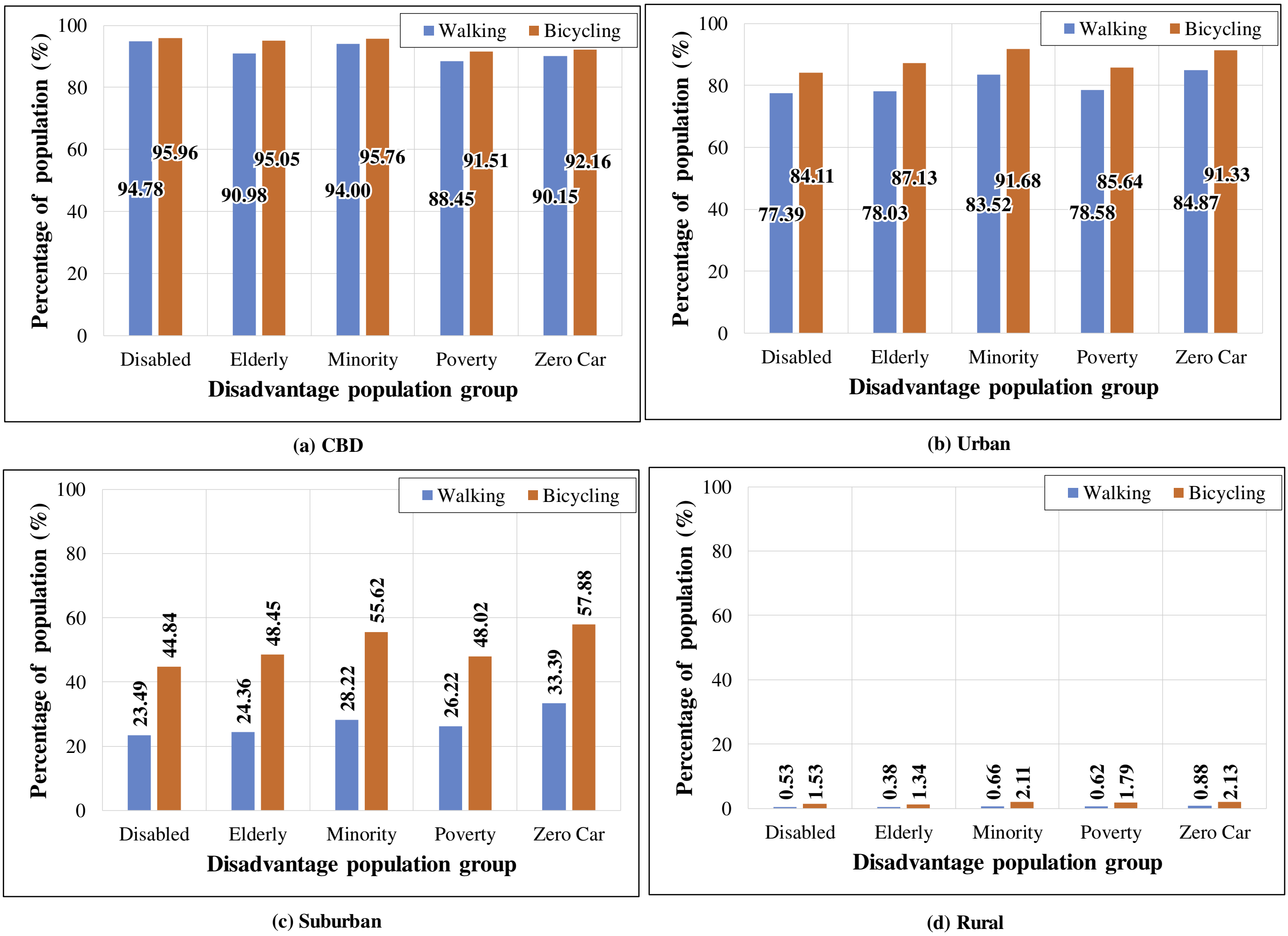

Fig. 6. Percentage of disadvantaged population covered by transit service in different areas.

people who need to tote kids around, providing a kid's seat on bikes may be a possible solution to expand the use of bicycle and enhance bicycle-transit integration. A kid-friendly bike sharing providing tiny bikes and helmets for toddlers, e.g. Vélib in Paris, French, allows kids to ride with families and encourage more kids to bicycle. By introducing the very young generation to the green transportation, it's beneficial to preparing for the future of a more sustainable society.

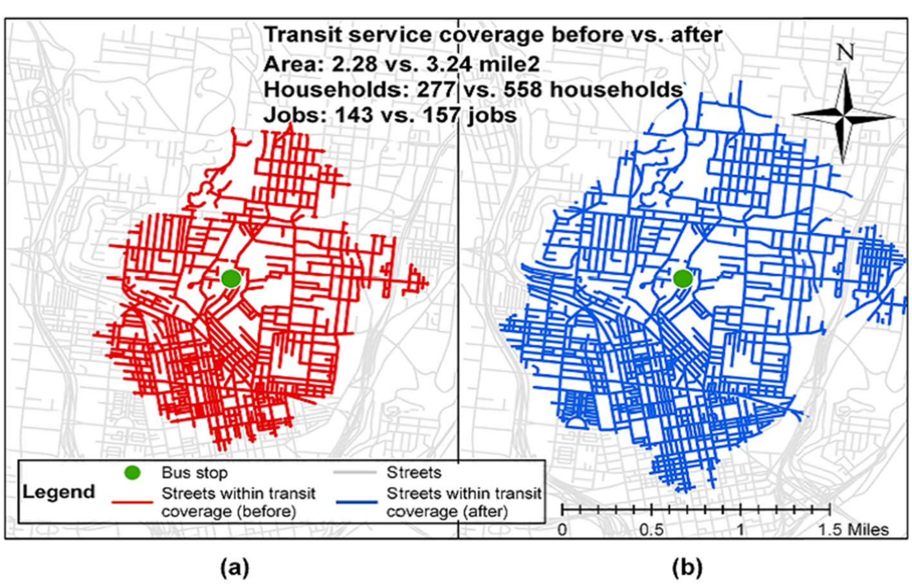

Fig. 7. Streets within transit coverage area before (a) and after (b) bicycle lane were introduced.

Table 8
Household/Employment density elasticity of population/employment covered by transit service in the Cincinnati metropolitan area.

Social-demographics		Pedestrian-based TOD development		Bicycle-based TOD development	
		Density	Elasticity	Density	Elasticity
2010	Households	2.13 households/acre	0.22	1.61 households/acre	0.38
	Employment	3.73 jobs/acre	0.07	2.67 jobs/acre	0.14
2040	Households	2.19 households/acre	0.21	1.68 households/acre	0.36
	Employment	3.99 jobs/acre	0.06	2.88 jobs/acre	0.12

6. Conclusion and future research

In the paper, a method using GPS trip data to measure the transit system coverage is presented. This method is able to identify transit coverage area and measure the population and employment with accessible transit service via non-motorized transportation. The results can further be used as a reference to spot underserve areas by transit and estimate the transit demand for planning purpose. Several conclusion and findings can be drawn from the paper:

1) People from further distance areas are able to reach transit service if using bicycles than walking, and they are willing to travel longer access distance to transit at home ends than activity ends. In the Cincinnati metropolitan area, at home ends, the spatial boundaries of transit catchment areas are 0.59 mile for pedestrians and 1.59 miles for bicyclists; at activity ends, the distance thresholds are 0.34 mile for walking and 1.34 mile for bicycling. The average size of bicycle-transit catchment areas is about 1.7 and 2.2 times of the average size of pedestrian-transit catchment area at home and activity ends, accordingly. Correspondingly, more households and employment can reach transit service accessing by bicycling than walking (52.45% vs. 36.72% for households, 47.82%. vs. 33.07% for employment).
2) Instead of focusing on dense areas, agencies would benefit more by promoting integrated non-motorized and transit environment in suburban and low-density areas. The suburban area where over half of the households and jobs situate is underserved as only about 25% of households and 22% of the jobs are within a walkable distance to access transit. The percentages of both households and bicycle covered can be improved by > 20% if passengers bike to transit stops instead of walk. Similarly, the coverage of the disadvantaged population in suburbs can be improved from 27.14% % to 50.96% if using a bicycle.
3) A safer and convenient pedestrian and bicycle environment can improve non-motorized connectivity to transit, and thereby expanding transit catchment areas. TODs encourage more households and employment to locate near transit service. Using bicycle-transit catchment areas as the geographic units of TOD zoning to promote bicycle-based TOD, allows more population, especially families with one less car or no cars, with access to a wider variety of services and opportunities by transit.

In the future research, route choices of non-motorized trips can be further investigated to reveal pedestrians' and bicyclists' route preferences on-road facility type and quality, which helps to provide a more accurate measure of transit catchment areas. On the other hand, the approach to identify transit catchment areas can be applied in the calculation of transit accessibility.

Reference

Andersen, J.L.E., Landex, A., 2008. Catchment areas for public transport. In: Brebbia, C.A. (Ed.), Urban Transport XIV: Urban Transport and the Environment in the 21st Century. WIT Press, Ashurst, Southampton, pp. 175–184.
Bachand-Marleau, J., Larsen, J., El-Geneidy, A., 2011. Much-anticipated marriage of cycling and transit: how will it work? Transp. Res. Rec. J. Transp. Res. Board 109–117.
Banister, D., 1997. Reducing the need to travel. Environ. Plan. B Plan. Des. 24, 437449.
Bhat, C.R., Guo, J.Y., Sen, S., Weston, L., 2005. Measuring Access to Public Transportation Services: Review of Customer-oriented Transit Performance Measures and Methods of Transit Submarket Identification. Centre for Transportation Research University of Texas, Austin, TX Available at: http://ctr.utexas.edu/wp-content/uploads/pubs/0_5178_1.pdf.
Broach, J., Gliebe, J., Dill, J., 2009. Development of a multi-class bicyclist route choice model using revealed preference data. In: 12th International Conference on Travel Behavior Research. Jaipur, India, December 13–16, 2009.
Cervero, R., 2005. Accessible Cities and Regions: A Framework for Sustainable Transport and Urbanism in the 21st Century. UC Berkeley Center for Future Urban Transport: A Volvo Center of Excellence, Berkeley, CA Available at: https://doi.org/UCB-ITS-VWP-2005-3.
Cheng, L., Bi, X., Chen, X., Li, L., 2013. Travel behavior of the urban low-income in China: case study of Huzhou City. Proc. Soc. Behav. Sci. 96, 231–242.
Cho, G.H., Rodríguez, D.A., Evenson, K.R., 2011. Identifying walking trips using GPS data. Med. Sci. Sports Exerc. 43, 365–372.
Crowley, D., Shalaby, A., Zarei, H., 2009. Access walking distance, transit use, and transit-oriented development in North York City Center, Toronto, Canada. Transp. Res. Rec. J. Transp. Res. Board 2110, 96–105.
Dill, J., Carr, T., 2003. Bicycle commuting and facilities in major U.S. cities: if you build them, commuters will use them. Transp. Res. Rec. J. Transp. Res. Board 1828, 116–123.
Dodson, J., Burke, M., Evans, R., Gleeson, B., Sipe, N., 2010. Travel behavior patterns of different socially disadvantaged groups analysis of household travel survey data for a dispersed metropolitan area. Transp. Res. Rec. J. Transp. Res. Board 2163, 24–31.
Dolati, H., 2014. Biking Distance: Exploring Gender, Race, and Climate. M.S. Thesis The Ohio State University Available at: https://etd.ohiolink.edu/!etd.send_file%3Faccession%3Dosu1388725654%26disposition%3Dinline.
Duncan, M.J., Mummery, W.K., 2007. GIS or GPS? A comparison of two methods for assessing route taken during active transport. Am. J. Prev. Med. 33, 51–53.
Edwards, S., Ivey, S.S., Lipinski, M., Golias, M.M., 2012. Bicycle and pedestrian studies based on data from National Household Travel Survey. Transp. Res. Rec. J. Transp. Res. Board 2299, 150–156.
El-Geneidy, A., Grimsrud, M., Wasfi, R., Tétreault, P., Surprenant-Legault, J., 2014. New evidence on walking distances to transit stops: identifying redundancies and gaps using variable service areas. Transportation (Amst) 41, 193–210.
Evans, J., Perincherry, V., Douglas, G., 1997. Transit friendliness factor: approach to quantifying transit access environment in a transportation planning model. Transp. Res. Rec. J. Transp. Res. Board 1604, 32–39.
Fang, W., 2017. Understanding transit-oriented development through bike-sharing big data. [WWW Document]. Sustain. Cities blog. URL http://blogs.worldbank.org/sustainablecities/understanding-transit-oriented-development-through-bike-sharing-big-data (accessed 11.25.17).
Flamm, B., Rivasplata, C., 2014. Perceptions of Bicycle-friendly Policy Impacts on Accessibility to Transit Services: The First and Last Mile Bridge. MinetaTransportation Institute, San Jose, CA Available at: http://transweb.sjsu.edu/PDFs/research/1104-bicycle-policy-transit-accessibility-first-last-mile.pdf.
Foda, M., Osman, A., 2010. Using GIS for measuring transit stop accessibility considering actual pedestrian road network. J. Public Transp. 13, 23–40.
Furth, P.G., 2012. Bicycling infrastructure for mass cycling: a transatlantic comparison. In: Pucher, J., Buehler, R. (Eds.), City Cycling. MIT Press, pp. 105–140 (Cambridge, MA).
Guerra, E., Cervero, R., Tischler, D., 2012. Half-mile circle does it best represent transit station catchments? Transp. Res. Rec. J. Transp. Res. Board 2276, 101–109.
Hochmair, H.H., 2015. Assessment of bicycle service areas around transit stations. Int. J. Sustain. Transp. 9, 15–29.
Hood, J., Sall, E., Charlton, B., 2011. A GPS-based bicycle route choice model for San Francisco, California. Transp. Lett. Int. J. Transp. Res. 3, 63–75.
Horner, M.W., Murray, A.T., 2004. Spatial representation and scale impacts in transit service assessment. Environ. Plan. B Plan. Des. 31, 785–797.
Kim, J., Kim, J., Jun, M., Kho, S., 2005. Determination of a bus service coverage area reflecting passenger attributes. J. East. Asia Soc. Transp. Stud. 6, 529–543.
Kittelson & Associates, Inc, Brinckerhoff, P., KFH Group, Inc, Texas A&M Transportation Institute, Arup, 2013. Transit capacity and quality of service manual. In: Transit Cooperative Highway Research Program (TCRP) Report 165, Third ed. Transportation Research Board, Washington, DC Available at: 10.17226/24766.
Krizek, K., Stonebraker, E., Tribbey, S., 2011. Bicycling Access and Egress to Transit: Informing the Possibilities. Mineta Transportation Institute, San Jose, CA Available at: http://transweb.sjsu.edu/PDFs/research/2825_bicycling_access.pdf.
Lee, J., Choi, K., Leem, Y., 2016. Bicycle-based transit-oriented development as an

alternative to overcome the criticisms of the conventional transit-oriented development. Int. J. Sustain. Transp. 10, 975–984.
Mattson, J.W., 2012. Travel Behavior and Mobility of Transportation-disadvantaged Populations: Evidence from the National Household Travel Survey. Upper Great Plains Transportation Institute, Fargo, ND Available at: http://www.ugpti.org/pubs/pdf/DP258.pdf.
McNeil, N., 2011. Bikeability and the 20-min neighborhood. Transp. Res. Rec. J. Transp. Res. Board 2247, 53–63.
Mistretta, M., Goodwill, J.A., Gregg, R., De Annuntis, C., 2009. Best Practices in Transit Service Planning. University of Southe Florida Center for Transit Research, Tampa, FL Available at: http://www.fdot.gov/research/Completed_Proj/Summary_PTO/FDOT_BD549_38_rpt.pdf.
Moudon, A.V., Lee, C., Cheadle, A.D., Collier, C.W., Johnson, D., Schmid, T.L., Weather, R.D., 2005. Cycling and the built environment, a U.S. perspective. Transp. Res. Part D Transp. Environ. 10, 245–261.
Murray, A.T., Davis, R., 2001. Equity in regional service provision. J. Reg. Sci. 41, 577–600.
Neff, J., Dickens, M., 2017. 2016 Public Transportation Fact Book. American Public Transportation Association, Washington, DC Available at: http://www.apta.com/resources/statistics/Documents/FactBook/2016-APTA-Fact-Book.pdf.
Newman, P., Kenworthy, J., 2006. Urban design to reduce automobile dependence. Op. An Int. J. Suburb. Metrop. Stud. 2, 35–52.
Peng, Z., Dueker, K.J., Strathman, J., Hopper, J., 1997. A simultaneous route-level transit patronage model: demand, supply, and inter-route relationship. Transportation (Amst) 24, 159–181.
Polzin, S.E., Pendyala, R.M., Navari, S., 2002. Development of time-of-day-based transit accessibility analysis tool. Transp. Res. Rec. J. Transp. Res. Board 1799, 35–41.
Pucher, J., Buehler, R., 2009. Integrating bicycling and public transport in North America. J. Public Transp. 12, 79–104.
Rietveld, P., 2000. The accessibility of railway stations: the role of the bicycle in The Netherlands. Transp. Res. Part D Transp. Environ. 5, 71–75.
Rodriguez, D., Cho, G.-H., Elder, J.P., Conway, T.L., Evenson, K.R., Ghosh-Dastidar, B., Shay, E., Cohen, D., Veblen-Mortenson, S., Pickrell, J., Lytle, L., 2012. Identifying walking trips from GPS and accelerometer data in adolescent females. J. Phys. Act. Health 9, 421–431.
Royal, D., Miller-Steiger, D., 2008. National Survey of Bicyclist and Pedestrian Attitudes and Behavior, Volume II: Findings Report. National Highway Traffic Safety Administration, Washington, DC Available at: https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/811841b.pdf.
Tal, G., Handy, S., 2012. Measuring nonmotorized accessibility and connectivity in a robust pedestrian network. Transp. Res. Rec. J. Transp. Res. Board 2299, 48–56.
Thierry, B., Chaix, B., Kestens, Y., 2013. Detecting activity locations from raw GPS data: a novel kernel-based algorithm. Int. J. Health Geogr. 12, 14.
Wargelin, L., Stopher, P., Minser, J., Tierney, K., Rhindress, M., O'Connor, S., 2012. GPS-based Household Interview Survey for the Cincinnati Ohio Region. Ohio Department of Transportation, Columbus, OH Available at: https://www.dot.state.oh.us/Divisions/Planning/SPR/Research/reportsandplans/Reports/2012/Planning/134421_FR.pdf.
Wei, H., Ai, Q., Ramirez-Bernal, M.F., 2013. Bicycle Trip Forecasting Model: Cincinnati Metropolitan Case Study. Ohio Department of Transportation, Columbus, OH Available at: http://www.dot.state.oh.us/Divisions/Planning/SPR/Research/reportsandplans/Reports/2013/Planning/134641_FR.pdf.
Wei, H., Zuo, T., Liu, H., Yang, Y.J., 2017. Integrating land use and socioeconomic factors into scenario-based travel demand and carbon emission impact study. Urban Rail Transit. 3, 3–14.
Welch, T.F., Mishra, S., 2013. A measure of equity for public transit connectivity. J. Transp. Geogr. 33, 29–41.
Zhao, F., Chow, L.F., Li, M.T., Gan, A., Ubaka, I., 2003. Forecasting transit walk accessibility: regression model alternative to the buffer method. Transp. Res. Rec. J. Transp. Res. Board 1835 (16).