Journal of Transport Geography 42 (2015) 72–83

Contents lists available at ScienceDirect

Journal of Transport Geography

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

Spatiotemporal accessibility to supermarkets using public transit: an interaction potential approach in Cincinnati, Ohio

Michael J. Widener [a,*], Steven Farber [b], Tijs Neutens [c], Mark Horner [d]

[a] Department of Geography, University of Cincinnati, 2825 Academia Way, BRN 401E, Cincinnati, OH 45221-0131, United States
[b] Department of Human Geography, University of Toronto Scarborough, 1265 Military Trail, Toronto, ON M1C 1A4, Canada
[c] Department of Geography, Ghent University, Krijgslaan 281, S8, 9000 Ghent, Belgium
[d] Department of Geography, The Florida State University, 323 Bellamy Building, Tallahassee, FL 32306-2190, United States

ARTICLE INFO

Keywords:
Accessibility
Food deserts
Transit
Nutrition
Interaction potential
Mobility

ABSTRACT

Improving nutrition in urban regions involves understanding which neighborhoods and populations lack access to stores that sell healthy foods, such as fruits and vegetables. To this end, recent work has focused on mapping regions without access to places like supermarkets, often terming them 'food deserts'. Until recently, this work has not considered residents' mobility as facilitated by transportation systems, and even among those that do, few have considered alternative forms of transportation, like public transit, opting for automobile-oriented travel assumptions. This paper analyzes people's spatio-temporal constraints to accessing supermarkets, and focuses on the transit commuting population. Analysis of commute data from Cincinnati, Ohio shows there are a significant number of residents that have improved access to supermarkets when a grocery shopping trip is made on the way home from work, than if they were to depart from their home location. These results extend previous work showing relatively few automobile commuting residents have better access to supermarkets given their work locations.

1. Introduction

Over the past two decades, there has been strong interest in mapping urban neighborhoods' level of access to healthy foods. This work is part of a broader trend, whereby researchers seek to understand the links between environmental conditions and urban structure, diets lacking recommended levels of nutrition, and undesirable health outcomes (McKinnon et al., 2009). In both academic and popular venues, these efforts commonly fall under the umbrella of "food desert" research (Barclay, 2013; Shaw, 2006a; Walker et al., 2010).

While definitions vary, food deserts are generally described as regions that do not have spatial access to healthy food (Walker et al., 2010). This lack of access is thought to have a negative effect on the overall nutrition of diets consumed by residents of food deserts. Unhealthy diets are associated with a higher risk of suffering from a number of chronic diseases including diabetes, hypertension, certain types of cancer, and cardiovascular disease (Bazzano et al., 2002; He et al., 2004; Higdon et al., 2007; Hung et al., 2004; Joshipura et al., 2001; Leal and Chaix, 2011; Smith-Warner et al., 2001).

Despite the attention given to this important topic, studies have not conclusively linked poor health outcomes, or even lack of access to healthy foods, to residing in regions considered food deserts (An and Sturm, 2012; Cummins et al., 2014; Raja et al., 2008; Short et al., 2007; Widener et al., 2011; Wrigley, 2002). A potential reason for this is that food desert maps over-generalize spatial aspects of the food environment, while ignoring the actual mobility patterns of individual residents (Widener and Shannon, 2014). Census geographies used to define food deserts are home to relatively large populations with diverse characteristics. The individual spatial, economic, social, and transportation contexts of residents in these spatial units encourage or dissuade them from maintaining healthy diets, making it difficult to decisively consider the entire area as being with or without access. A second related reason is that most food desert metrics, with the notable exceptions of recent research by Horner and Wood (2014), Widener et al. (2013, 2011), and Salze et al. (2011), consider the urban environment to be static. However, cities are very dynamic systems. People move throughout the day, changing their levels of access to various goods and services as they participate in their daily activities.

* Corresponding author. Tel.: +1 513 556 2849; fax: +1 513 556 3370.
E-mail addresses: michael.widener@uc.edu (M.J. Widener), steven.farber@utoronto.ca (S. Farber), tijs.neutens@ugent.be (T. Neutens), mhorner@fsu.edu (M. Horner).

http://dx.doi.org/10.1016/j.jtrangeo.2014.11.004
0966-6923/

In this research we address both of the aforementioned issues in the food deserts literature by presenting a spatiotemporal interaction measure to examine how movements of people using bus transit affect their spatial accessibility in the mid-size Midwestern city of Cincinnati, Ohio. We depart from previous literature and focus on public transit, a transport mode that is often ignored in empirical work on spatial access to healthy food. Not only are the movements of transit users constrained by the system's spatiotemporal structure, they also face additional spatial, economic, and social constraints (Garrett and Taylor, 1999) that can adversely affect their ability to purchase and consume healthy foods. The issue of daily movements is addressed by replicating a previously-established method used to study spatiotemporal access to healthy foods for residents that commute via automobile (Widener et al., 2013). It is possible that a person's movements throughout the course of the day will give rise to better access to goods or services at different times. Using data from the local metropolitan planning organization (MPO), an interaction potential metric (Farber et al., 2013) is derived for the transit population that provides information on both the temporal and spatial characteristics of access to healthy food stores, given their daily commuting patterns. Such an analysis provides a more detailed account of this population's accessibility, thereby improving researchers' ability to measure health outcomes and implement interventions in a targeted and effective manner. From a transportation perspective, this approach indicates how well transit systems serve the needs of their patrons and how this might be measured using accessibility to healthy food as an indicator.

2. Background

Researchers commonly identify food deserts by measuring travel costs from administrative areal units (e.g. census tracts) to food vendors considered to carry healthy food (Larsen and Gilliland, 2008; Widener et al., 2012). Perhaps the most visible definitions of food deserts are those presented by the US Department of Agriculture (USDA) Economic Research Service's Food Access Research Atlas – previously known as the ''Food Desert Locator'' (USDA ERS, 2013). This tool offers thresholds for customizing food desert definitions, but typically considers distance to stores and indicators of socioeconomic status. For example, the default food access measure is calculated using the following definition,

> *"A low-income tract with at least 500 people or 33 percent of the population living more than 1 mile (urban areas) or more than 10 miles (rural areas) from the nearest supermarket, supercenter, or large grocery store."*

where a low-income tract is defined as a tract with a poverty rate at ''20 percent or greater; or the tract's median family income is less than or equal to 80 percent of the State-wide median family income; or the tract is in a metropolitan area and has a median family income less than or equal to 80 percent of the metropolitan area's median family income'' (USDA ERS, 2013). Food vendor locations come from a list that combines data from government records on stores that are authorized to receive Supplemental Nutrition Assistance Program benefits (formerly known as food stamps) and a proprietary collection compiled by Trade Dimensions TDLinx. More on the USDA's methods and alternative measures can be found at their website (USDA ERS, 2013).

While some of the USDA's food accessibility measures include variables like vehicle availability that hint at the level of mobility in a census tract, movement patterns of residents are not captured. In the broader accessibility literature however, recent research has increasingly attempted to incorporate the mobility and time geographical constraints associated with urban life via an array of spa-

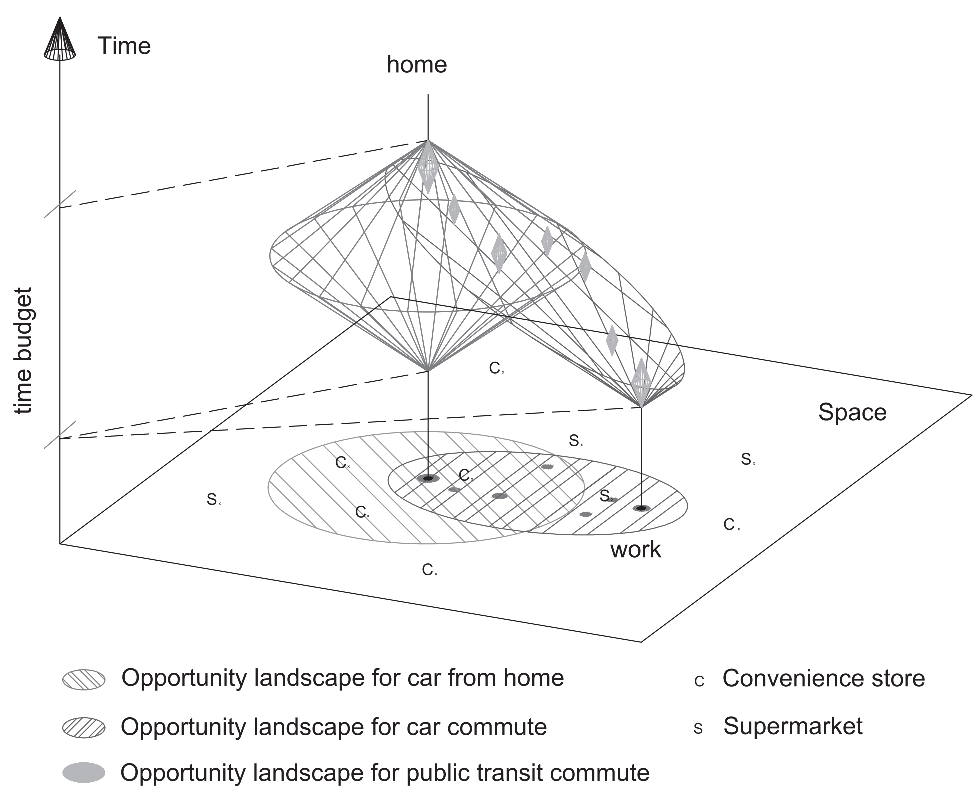

Fig. 1. This example illustrates how a time budget and the use of transit can change the accessibility picture of access to different food store opportunities.

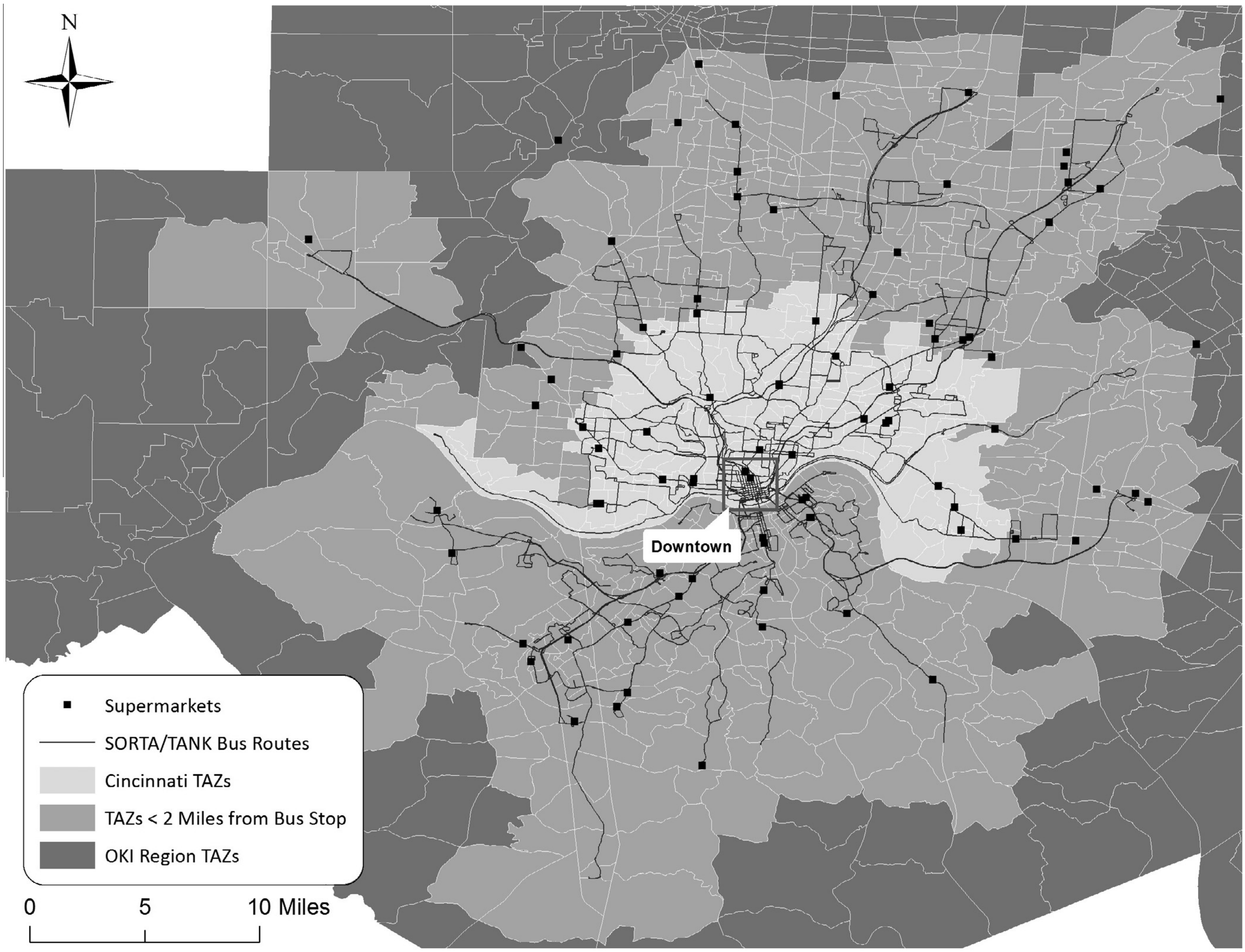

Fig. 2. Study area.

tial and temporal methods. These could be brought to bear on studies of food accessibility.

The use of spatiotemporal measures in accessibility research is well established. For example, Miller (2007) argues for a more "people-based" geographic information science (GIScience) that harnesses new technologies, like smart-phones, to better describe individuals' access to opportunities and activities across time. Similarly, Kwan (2012) explores the uncertain geographic context problem, which accounts for the temporal and spatial uncertainties present in many datasets. The importance of the time-geographic perspective to transportation geography has also been examined by Shaw (2006b), who comments on the implicitly dynamic nature of transportation and calls for further integration of space–time methods into transportation research. More recently, and echoing some of Shaw's sentiments, Richardson (2013) has documented the emergence of real-time spatiotemporal analysis using GIScientific tools, noting the vast potential for such methods.

Among the first studies to discuss the personal constraints inherent to the time-geographic framework in tandem with the implications for transit-based accessibility, O'Sullivan et al. (2000) detailed a method for generating isochrones delimiting transit service regimes using geographic information system (GIS). Given a fixed time budget, O'Sullivan et al. accounted for the sub-components of transit-based trips, including walking and wait time, in addition to in-vehicle travel time. From this, they produced maps displaying areas that are reachable from a particular origin given a fixed travel budget. As O'Sullivan et al. did not incorporate measures of travel demand into their study, Polzin et al. (2002) developed a tool to measure accessibility as afforded by public transit, taking into account both the supply and demand for transit services, recognizing these quantities vary spatially and temporally throughout the day. Horner and Mefford (2005) also employed an isochrone-based approach in their exploration of bus transit service equity in Austin, TX. Their study sought to determine whether individuals of different socioeconomic groups have differential access to opportunities, in this case, jobs via the transit system. Focusing on the issue of spatial scale, Lee (2005) described a parcel-level methodology for capturing transit accessibility with GIS whose results can be communicated with policymakers and stakeholder communities. Burns and Inglis (2007) extended previous work by O'Sullivan et al. and other researchers to estimate accessibility to fast food options in Melbourne, Australia and combine these estimates with information on relative deprivation indices. Cheng and Agrawal (2010), for their part, implemented a measure of accessibility similar to that of O'Sullivan et al. (2000) and demonstrated its applicability with spatial data from Santa Clara, CA. Likewise, Lei and Church (2010) also implemented a transit based accessibility approach similar to O'Sullivan et al. which showed the differential accessibility experienced by those with access to bus vs. car, and locations

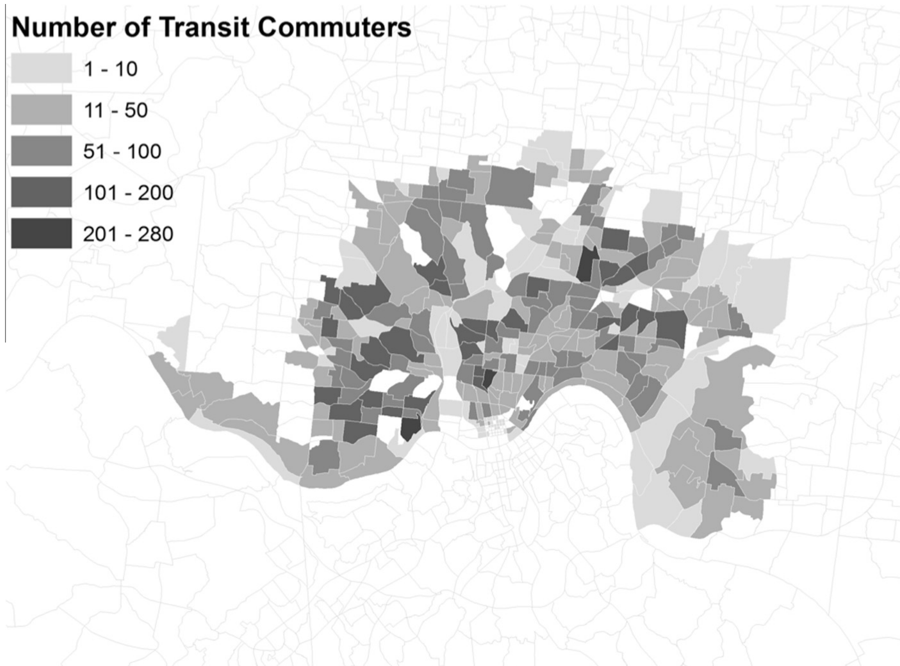

Fig. 3. Spatial distribution of transit commuters in Cincinnati.

where bus and auto travel times are at least competitive. Finally, Mavoa et al. (2012) built on past work to create a multimodal transit network in Auckland, NZ which was used to estimate a series of accessibility measures.

While there has been substantial work in the area of transit accessibility, few of these studies attempt to control for the time geographical constraints on the daily lives of transit users, namely, where people live and work, and the need for them to travel between these two places. Moreover, none of this research has been integrated with questions of food accessibility. Using commuting flow data from the regional metropolitan planning organization (MPO), our approach addresses this gap by investigating the ease with which transit riders can make a grocery stop on their way home from work.

3. Method

This study adopts methods described in Widener et al. (2013) by utilizing an interaction potential measure to quantify access levels to healthy food vendors in Cincinnati. The interaction potential metric is derived using an approximation of the typical time–space constraints on the transit commuting population leaving from work, as well as an analog measure where trips begin at a residents' home. Commuting flow data provide information on residents' patterns of movement, from home to work locations, and vice versa. While these data do not capture the entirety of residents' urban mobility, they do provide a basis for understanding common and frequent movements (Horner, 2004).

With these movements, it is possible to analyze the amount of time a resident has to "interact" with healthy food stores (i.e. grocery shop) given a time budget, the transit network, and the transit schedule. Specifically, we measure the level of accessibility of a resident who works at location j and lives at location i to a healthy food store k as the time remaining after accounting for the time it takes to travel to and from the food store. The interaction potential measure is described mathematically in the next subsection. Fig. 1 illustrates the time geographical underpinnings of our approach. The figure represents the home-based opportunity landscape for car users and the post-work opportunity landscape for car and transit commuters by means of space–time prisms (Miller, 1991). Note that for transit commuters the space–time opportunities to access food stores occur at multiple discontinuous locations and time windows depending on stop locations and timetables of public transport.

In this research, home and work locations are generalized to the centroid of the containing transportation analysis zones (TAZs), as no higher resolution data are available. This study focuses on transit commuters who reside in one of 359 "home" TAZs in the city of Cincinnati and work in one of 1140 "work" TAZs in the greater Cincinnati metropolitan region. Work TAZs farther than two miles from a bus stop were removed. This was to limit the computational burden of including TAZs too far away from the transit network to feasibly attract commuters by transit. Additionally, this two-mile cutoff more than accounts for the recommended 1/4th of a mile radius around a transit stop frequently considered accessible by walking (Murray and Wu, 2003). Healthy food stores are geocoded to the address level, and include national and regional chain supermarkets and grocers like Kroger, Remke Markets, and IGA, in addition to the daily and open-year-round Findlay Market. Addresses for these stores are obtained from Orbis (2012) and crosschecked with Google Maps and on-the-ground checking. For consistency with previous work, these healthy food stores are henceforth referred to as "supermarkets" (Widener et al., 2013). While it is possible other food vendors sell healthy foods, previous research points to supermarkets as offering more consistent stocks and cheaper prices than alternative vendors like bodegas (Horowitz et al., 2004; Widener et al., 2011). Fig. 2 displays the study area's TAZs, supermarkets, and the merged bus routes of Southwest Ohio Regional Transit Authority (SORTA) and Transit Authority of Northern Kentucky (TANK), which both service downtown Cincinnati.

The commuting flows of transit riders between home and work TAZs from 2005 are obtained from the local metropolitan planning organization (MPO), OKI Regional Council of Governments. Fig. 3 displays the spatial distribution of the 13,669 transit commuters in Cincinnati TAZs. MPO data are used for comparative purposes; the same dataset was used in previous research exploring the interaction potential of automobile commuters to supermarkets

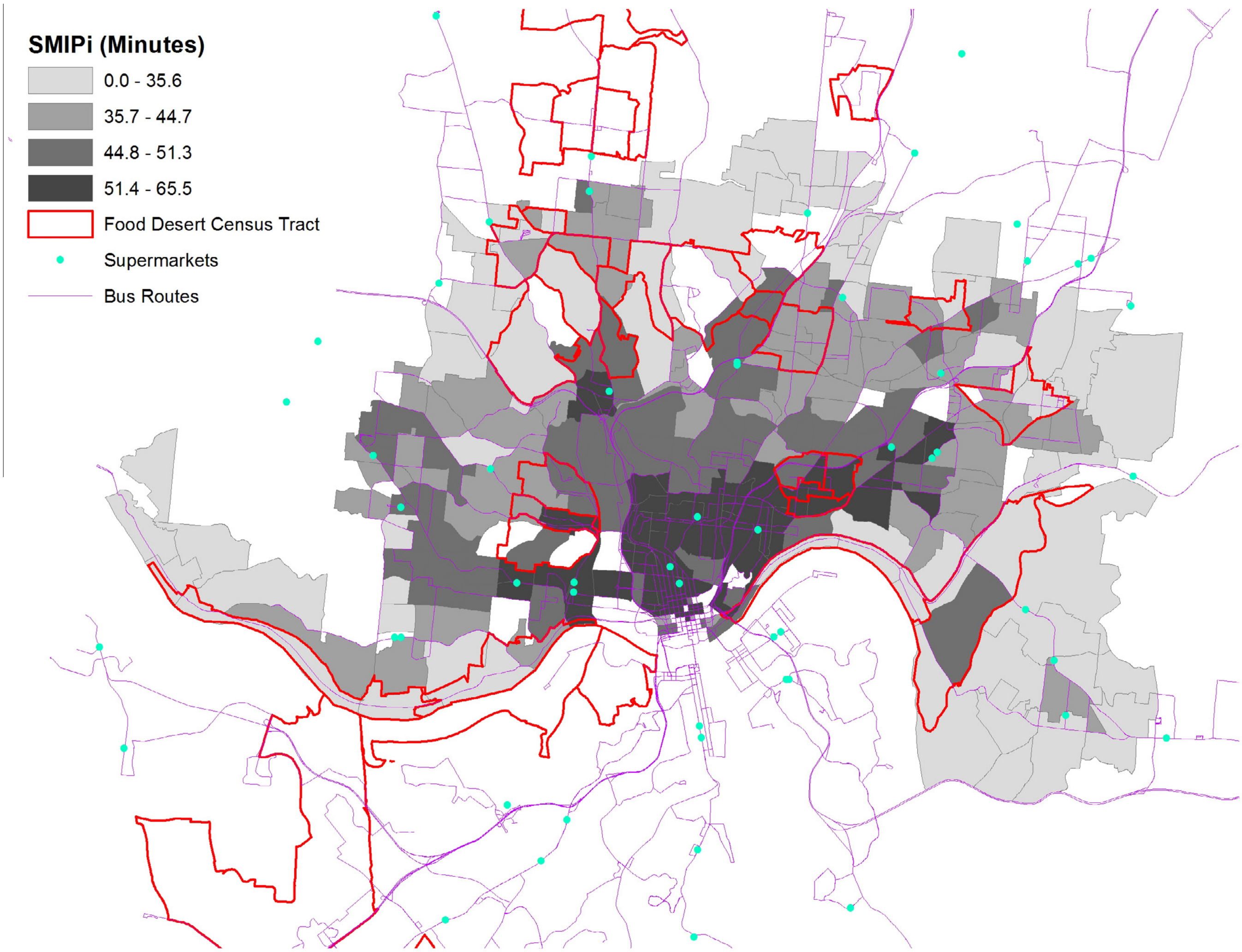

Fig. 4. *$SMIP_i$* scores in minutes.

in the Cincinnati metropolitan region. One major difference between the methods used in this paper and Widener et al.'s research on automobile commuters is that MPO data on travel time estimates between TAZs are not utilized. This is done because transit travel times are highly sensitive to departure times and available transfers, making calculating the travel cost from one location to another more complex than the shortest-path approach implicit in the methods used for automobiles. To compute travel costs on the transit network, General Transit Feed Specification (GTFS) data were obtained from the two major transit authorities that operate in the Cincinnati metropolitan region: SORTA and TANK. GTFS data are a standardized way for describing public transit routes, stops, and schedule information. Generally, GTFS data consist of a series of text files that provide information on transit stop locations, scheduled arrivals and departures, vehicle identification and routes, as well as other relevant information such as price and accessibility. More on the standard can be found at the developer documentation page maintained by Google (2013). By linking information within these files together and connecting them to a GIS, it is possible to compute shortest path routes across the transit network, subject to the unique transit system's schedule.

A custom script is then used to add the GTFS datasets to a Network Dataset in ArcGIS [http://transit.melindamorang.com/], which allows for the use of transit networks (as described by GTFS data) with the standard suite of ArcGIS Network Analyst Tools. The tools are in turn used to estimate travel times between all j–k–i triplets (representing a trip from work, j, to a supermarket, k, to home, i) given a departure time from work of 5 pm using a Monday bus schedule. The custom script accounts for ingress and egress walking, waiting, and transfer times. Moreover, if walking between locations is faster than taking transit, then the travel times reflect the walking time along the street network. These transit/walk travel times, henceforth referred to as transit travel times, are then used to compute accessibility metrics per the details provided in the next section.

3.1. Defining interaction potential measures

The interaction potential measure provides a convenient way to express space–time constraints in an accessibility score. Originally developed to gauge the level of social interaction possible between two or more people in urban environments (Farber et al., 2013), interaction potential metrics have since been adopted as a way to understand the level of access a mobile person has to a brick-and-mortar grocery store (Widener et al., 2013). In the latter case, the interaction measure is termed "SMIP" for Super Market Interaction Potential and defined as follows for an individual living in TAZ i, working in TAZ j, and shopping at a supermarket k:

$$SMIP_{ijk} = max(0, D_{ijk} - A_{ijk}), \tag{1}$$

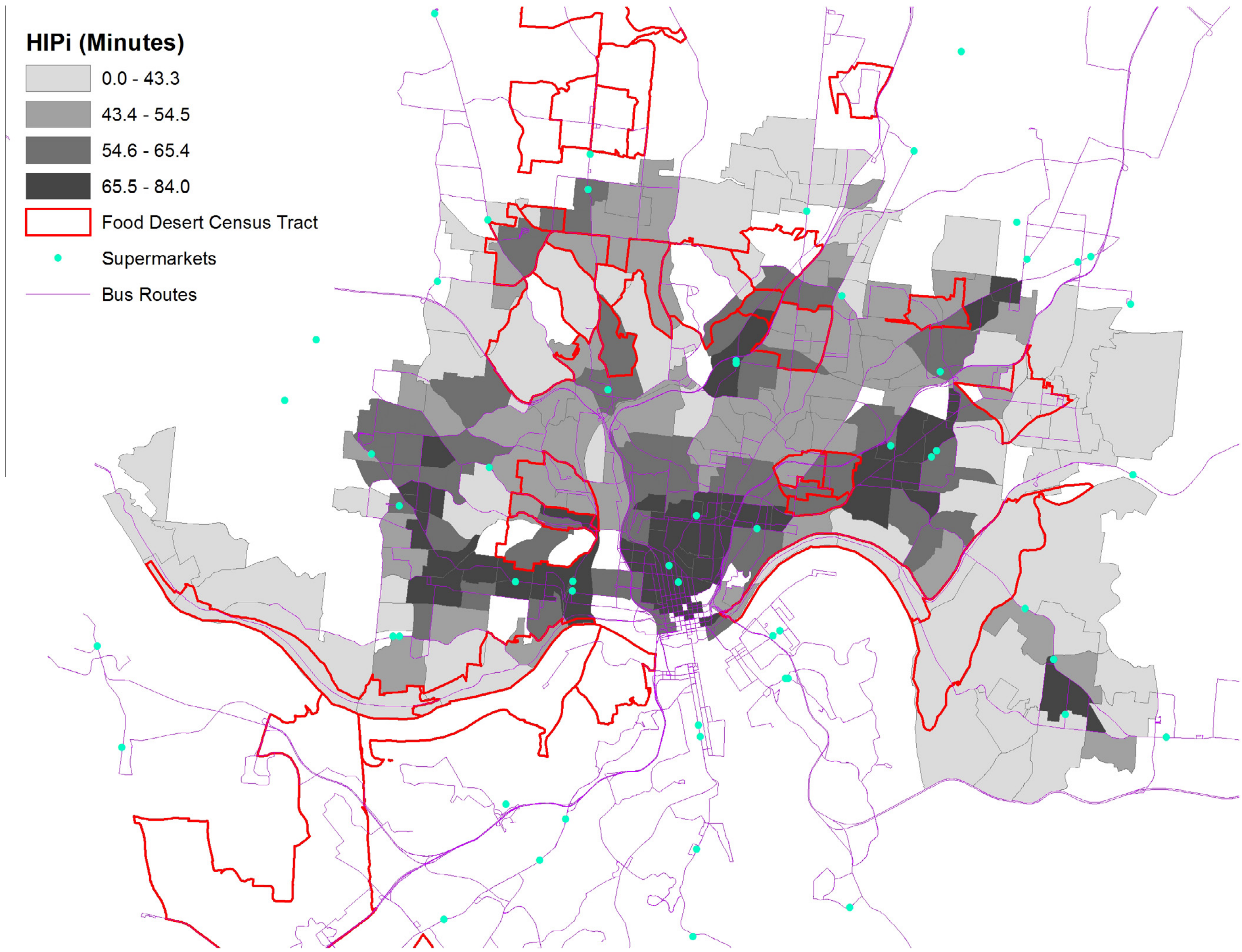

Fig. 5. HIP_i scores in minutes.

where D_{ijk} is the latest possible departure time from the supermarket and A_{ijk} is the earliest possible arrival time at the supermarket. D_{ijk} and A_{ijk} are computed under the time constraints of a 5 pm departure from work, and a required 7 pm arrival at home, which define a 120 min time budget. A time budget of 120 min is chosen because it allows for the average time spent grocery shopping of approximately 47 min, as found in the American Time Use Survey (USDA ERS, 2008), while still allowing for 73 min for driving from work to the supermarket and then from the supermarket to home. The max(0,−) function ensures non-negative interaction scores for inaccessible supermarkets.

Eq. (1) provides a result that is specific to a person working at location j, shopping at supermarket k, and living at location i. A measure that provides more information about the level of access for all of the transit riders in a TAZ i can be derived by calculating the SMIP_i statistic:

$$SMIP_i = \sum_j P_j^i \frac{\sum_{k \in K} SMIP_{ijk}}{n}, \tag{2}$$

where P_j^i is the proportion of transit commuters in TAZ i that work in zone j, K is the set of supermarkets, and n is equal to the size of set K. So as to remain consistent with previous work (Widener et al., 2013), the number n of supermarkets to consider is chosen to be five in this paper and K is assumed to contain those supermarkets that result in the largest $SMIP_{ijk}$ values for commuters in zone i that work in zone j. The resulting $SMIP_i$ value thus gives the average time residents in TAZ i have to shop after work at the five most accessible supermarkets while travelling by public transit. This reflects the assumption that only a limited number of supermarkets must be accessible in order to provide adequate access to healthy foods.

In order to compare the SMIP to the level of access residents have if they originate and end their supermarket trip from their home TAZ, the home-to-supermarket interaction potential measure (HIP) is derived as follows:

$$HIP_{ik} = max(0, D_{ik} - A_{ik}), \tag{3}$$

where all terms are defined as above. An analog to $SMIP_i$ is also computed for the home-to-supermarket case:

$$HIP_i = \frac{\sum_{k \in K} HIP_{ik}}{n}. \tag{4}$$

As with Eq. (2), K is the set of supermarkets that result in the largest HIP_{ik} values for residents living in zone i and n is equal to the size of the set K. HIP_i provides a useful indicator of the level of service available at a TAZ i given a departure time and time budget. As Widener et al. (2013) note, HIP_i scores also align conceptually with previous home-based food desert measures. The minimum attainable $SMIP$ or HIP of 0 is attained when no super-

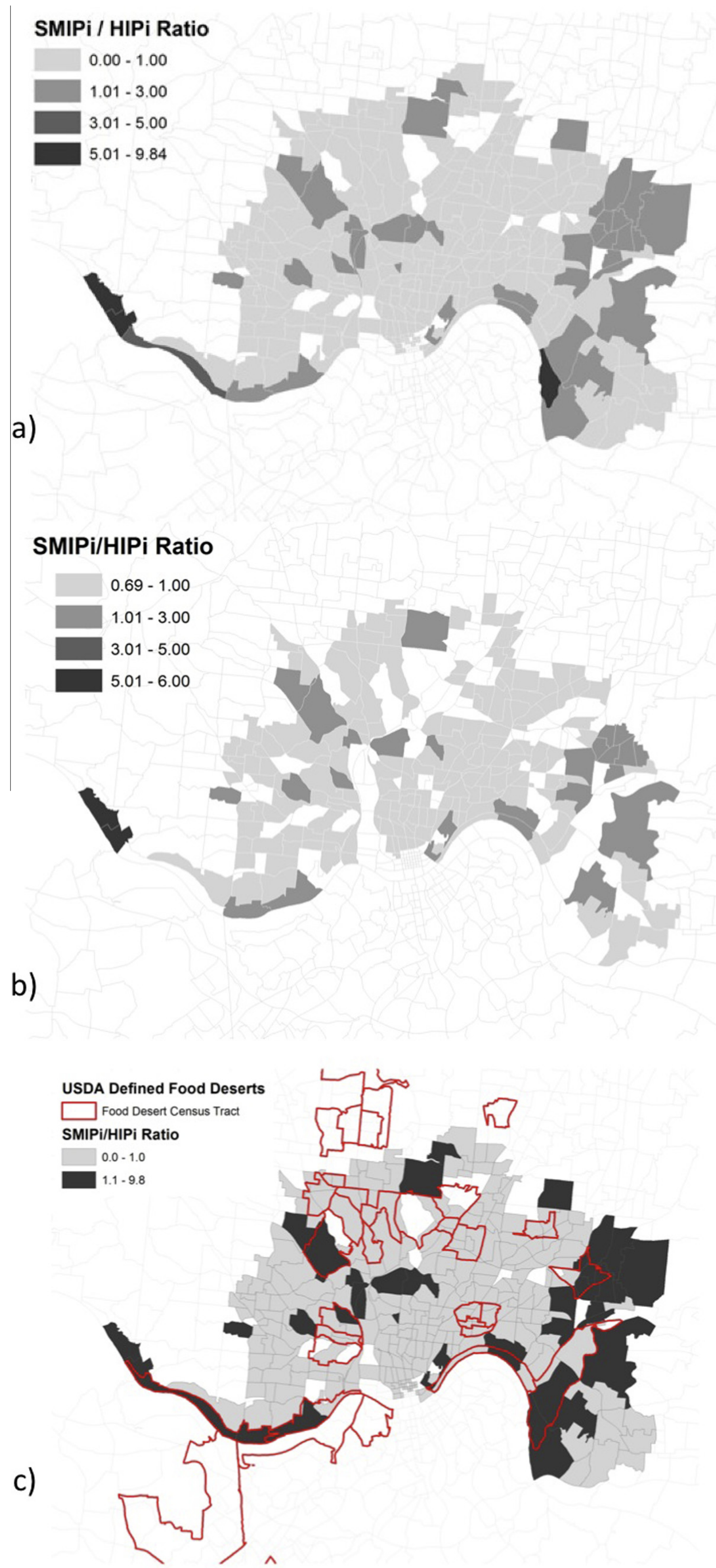

Fig. 6. $SMIP_i/HIP_i$ ratios for (a) all TAZs and (b) for TAZs with 10 or more transit riders. Map (c) shows the locations of food deserts census tracts layered over every TAZs with a $SMIP_i/HIP_i$ ratio greater than one.

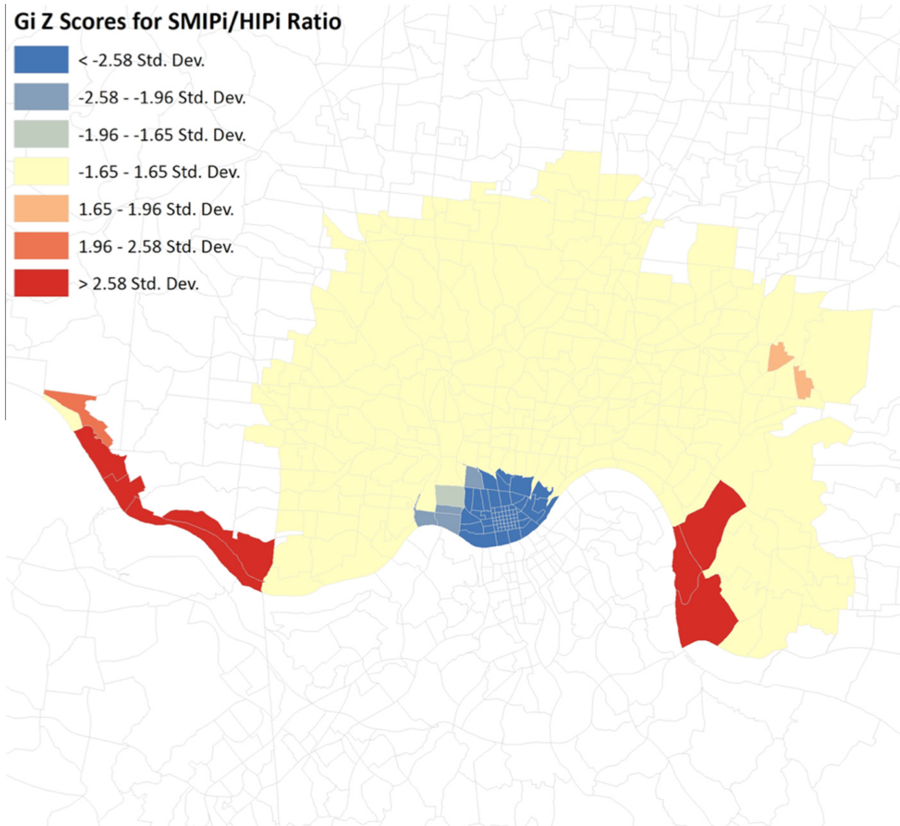

Fig. 7. Map of $SMIP_i/HIP_i$ ratio values G_i^* z-scores. Larger positive values indicate clustered regions where access to supermarkets is improved when departing from work. Negative values indicate clustered regions where access to supermarkets is better when departing from home.

markets are accessible within the time budget. The maximum score is the same as the time budget used in the analysis, when people live, work, and shop, all at the same location.

4. Results

$SMIP_i$ and HIP_i scores are calculated for all TAZs in the city of Cincinnati, with the exception of TAZs without any transit commuters, and their results are plotted for further analysis. The spatial distribution of $SMIP_i$ scores is found in Fig. 4. Given the 120 min time budget, scores range from 0, where residents work and live in locations that make it impossible to divert to a supermarket without exceeding the time budget, to approximately 66 min, where residents' wait time, walk time, and bus ride time to and from the five nearest supermarket average 54 min. $SMIP_i$ scores are relatively high downtown and in TAZs northeast of downtown. This likely reflects this region's transit network and supermarket density. Other TAZs near supermarkets and transit stops have similarly high $SMIP_i$ scores.

HIP_i values are mapped in Fig. 5. Overall, HIP_i scores tend to be larger than their $SMIP_i$ counterparts. However there are still three TAZs with a value of 0, where a trip to and from a supermarket via transit, leaving at 5 pm on a weekday exceeds two hours. The maximum HIP_i score is approximately 85 min; nearly 20 min more than the maximum $SMIP_i$ score. The spatial distribution of HIP_i scores resembles the $SMIP_i$ scores, with relatively high values downtown and northeast of downtown. However, there are a number of TAZs west of downtown, which contain a bus line with stops near a number of supermarkets, that also have high scores.

To understand if residents' movements positively affect their access to supermarkets, the ratios of TAZ's $SMIP_i$ and HIP_i scores are mapped (Fig. 6). Ratio values equal to one indicate a resident has the same level of access to supermarkets via transit whether leaving from their work or home location, TAZs with ratio values less than one indicate more access when departing from home, while TAZs with ratio values greater than one indicate more access when departing from work. For example, a TAZ with a $SMIP_i/HIP_i$ ratio of 2 means that residents on average have twice as much time to shop at a supermarket when departing from work than from home. A total of 43 TAZs, accounting for 1229 transit commuters, see an improvement in access to supermarkets given their commutes (Fig. 6a). The number of TAZs with a $SMIP_i/HIP_i$ ratio greater than one found in this study is significantly higher than the two TAZs found in the automobile commuter study (Widener et al., 2013). Even when only considering TAZs with more than 10 transit commuters, 28 out 233 TAZs see improved access given transit commutes, with some zones seeing an improvement of greater than five times the accessibility score derived given a shopping trip that originates at home (Fig. 6b). Fig. 6c shows that many TAZs with $SMIP_i/HIP_i$ ratios greater than one overlap with USDA designated food desert census tracts. Of the 28 TAZs with transit commuter populations greater than 10 and $SMIP_i/HIP_i$ ratios over one, 20 intersect a food desert tract. This implies that some residents of regions considered food deserts gain access to supermarkets via their transit commute.

Using the Getis-Ord G_i^* statistic, it is possible to identify spatial clusters of high and low $SMIP_i/HIP_i$ ratios. Fig. 7 shows that there are three identifiable hotspot regions where accessibility to supermarkets improves with trips originating from work, and one coldspot region with better access from home departures. Downtown Cincinnati makes up the coldspot, which makes sense given the relative density of bus service and supermarkets. The three regions that see the greatest improvements in access with departures from work include parts of the southwest and east of the city.

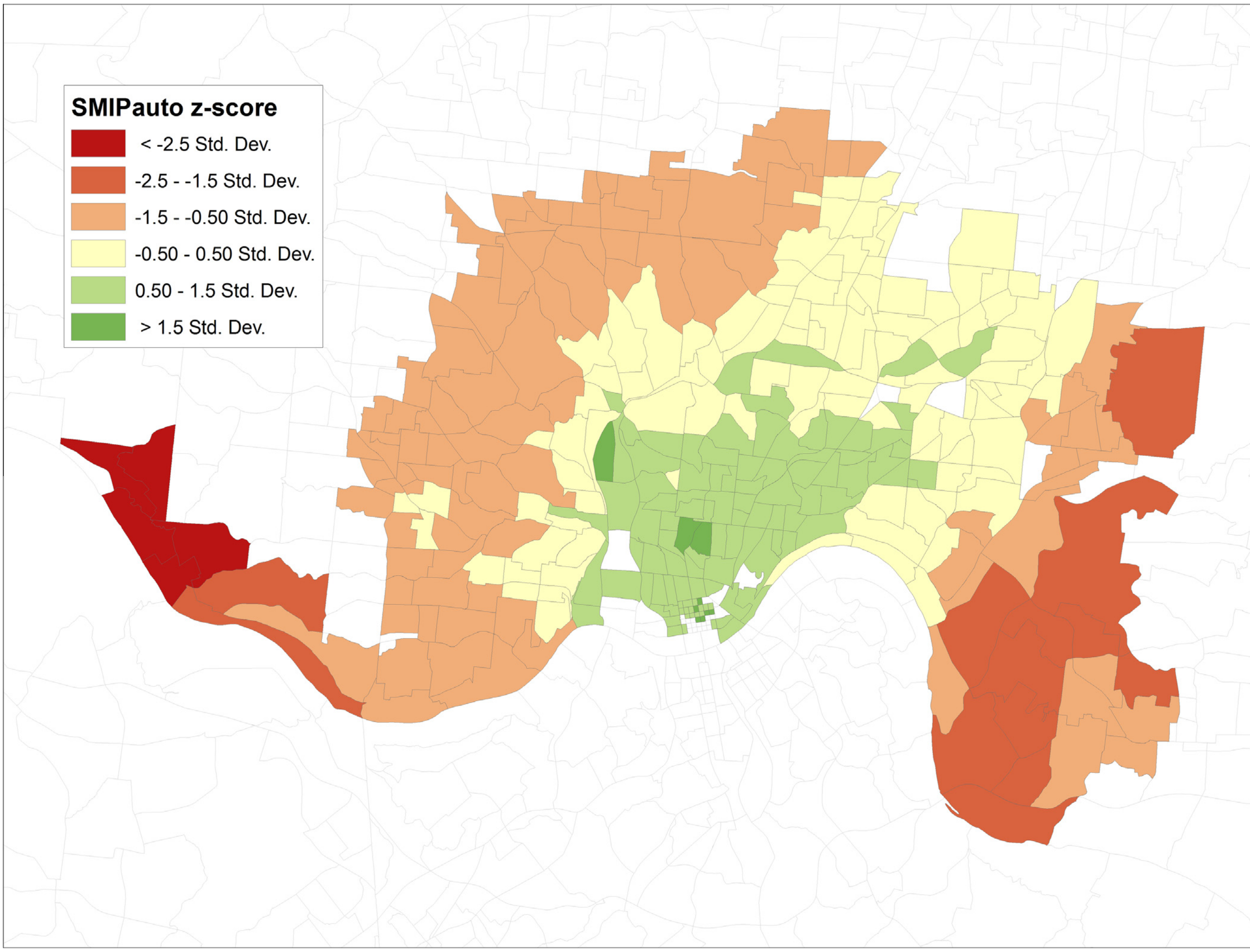

Fig. 8. Map of $SMIP_i^{auto}/SMIP_i^{bus}$ ratio scores.

4.1. Comparison to interaction potential scores for auto commuters and users

A direct comparison to interaction potential scores derived by Widener et al. (2013) for automobile users unsurprisingly reveals that driving results in more access to supermarkets for all TAZs, for both the $SMIP_i$ and HIP_i measures. To summarize these measures, the mean $SMIP_i^{bus}$ score is 43.20 min ($\sigma = 11.86$) while the $SMIP_i^{auto}$ score is 98.95 min ($\sigma = 4.21$). Likewise, the mean HIP_i^{bus} is 53.33 min ($\sigma = 18.38$) while the HIP_i^{auto} is 106.96 min ($\sigma = 3.94$). Interestingly, not only are the average access scores for transit much lower than for automobile, the amount of variability is much higher. This indicates that the benefit of accessibility is far more unevenly distributed among the population, echoing recent findings made by social justice proponents studying modal equity (Golub and Martens, 2014).

As a spatial comparison of these raw interaction potential values would prove to be rather uninteresting due to the vast advantage afforded to those with automobile access, it is more telling to compare the relative accessibility afforded to TAZs by the two different modes using standardized representations of the interaction potential measures. In other words: do TAZs with interaction potential scores that are higher for one mode also see increased interaction potential scores for the other? To answer this question we present two maps that compare the $SMIP_i$ z-scores.

Generally, there is a positive association between the standardized scores (Pearson's correlation of 0.77 for $SMIP_i$ and 0.83 for HIP_i). This implies that commuters who live in TAZs with high $SMIP_i^{auto}$ or HIP_i^{auto} scores tend to have better $SMIP_i^{bus}$ and HIP_i^{bus} scores, respectively. However, when observing the spatial pattern of the standard scores, an interesting pattern emerges. Figs. 8 and 9 display the z-scores of $SMIP_i$ values for automobile and transit commuters. For auto commuters (Fig. 8), the best access stretches from the central part of the city toward the northeast, paralleling the two major interstate highways in the region (I-75 and I-71). For transit commuters (Fig. 9), the best access is again found in the central part of Cincinnati, but higher $SMIP_i$ scores radiate out from the center more evenly. This likely relates to the hub-and-spoke design of the bus network in the city. The analysis of HIP_i z-scores shows similar patterns.

Ultimately, this comparative analysis, included for the sake of completeness, shows that on the whole TAZs will have similar levels of accessibility to supermarkets via both automobile and bus after controlling for the two modes' innate speed differences. However, there are some areas, particularly the west-side of the city, that have better relative access via transit than they do via automobile.

4.2. Relationships between accessibility scores and sociodemographic variables

To understand the relationships between sociodemographic variables and the two interaction potential measures, two spatial error models are computed with $SMIP_i$ and HIP_i as dependent variables. The sociodemographic data available at the TAZ level include

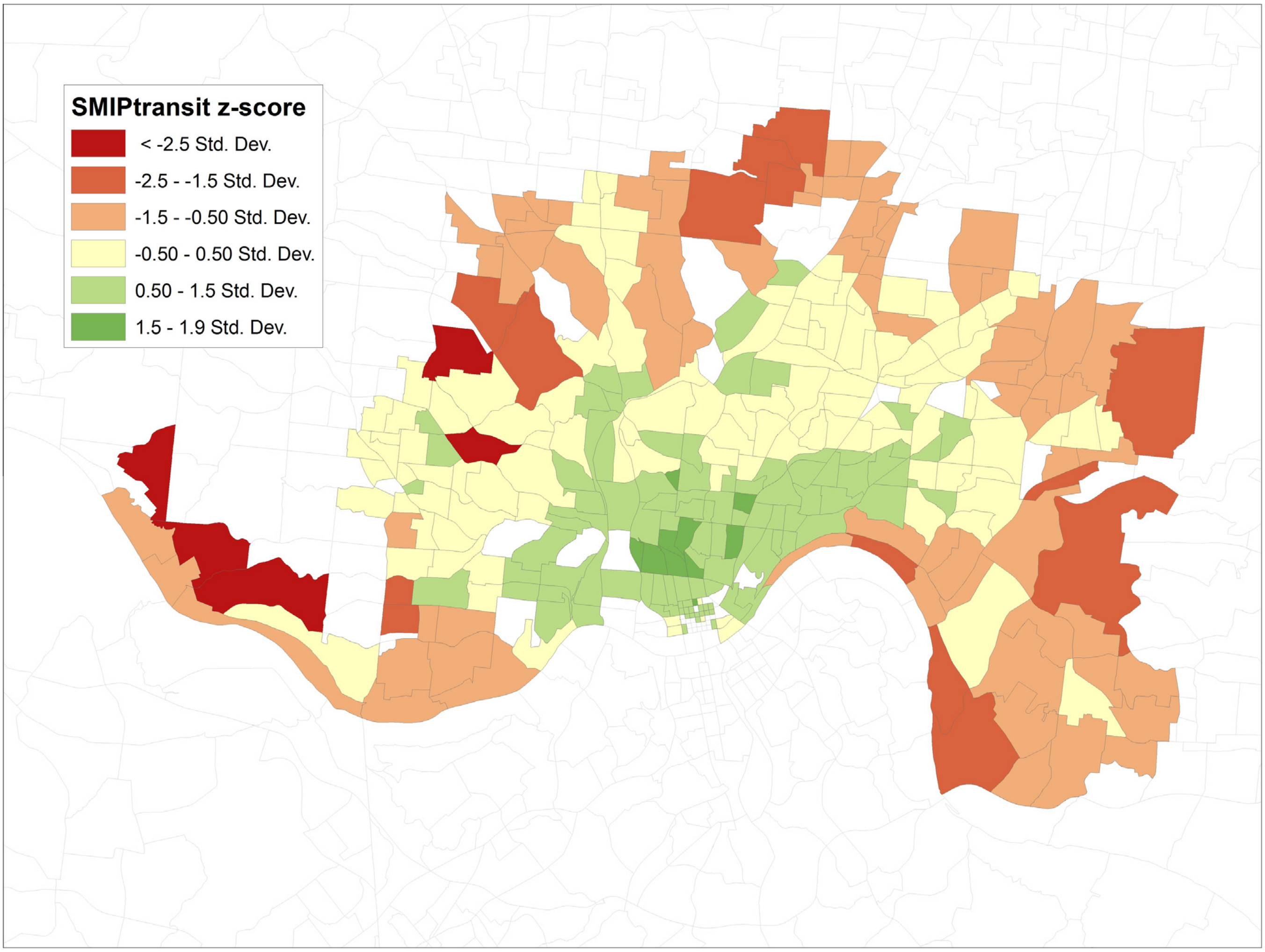

Fig. 9. Map of HIP_i^{auto}/HIP_i^{bus} ratio scores.

Table 1
$SMIP_i$ and HIP_i regression analysis.

	Coefficients	
Dependent Variable	$SMIP_i$	HIP_i
(Intercept)	28.90666***	53.51120***
Median TAZ Income	−0.00008	−0.00006
Num. Transit Commuters	0.10548***	0.02164*
Ratio of Pop in Labor Force	17.34452**	15.82357***
Ratio of HHs with Vehicles	−1.00081	−6.59802**
Lambda	0.61356***	0.87171***
pseudo-R^2	0.3954	0.7831

Significance codes:
*** 0.01.
** 0.05.
* 0.10.

median TAZ income, number of transit commuters, the ratio of a TAZ's population in the labor force, and the ratio of HHs with vehicles. The resulting significant and positive lambda values imply both models have patterns of dependence between errors for adjacent TAZs.

In the SMIPi and HIPi models there are negative relationships between the interaction potential measures and median income and the ratio of vehicle ownership, as well as positive relationships between the labor force population ratio and the number of transit commuters (Table 1). These results show that as both income and vehicle ownership decrease, there is increased access to supermarkets via transit, indicating that no systemic income-inequities are present. However, a closer inspection of the spatial distribution of low $SMIP_i$ and HIP_i scores reveals that exceptions to this general trend exist. For example, Fig. 10 shows the location of TAZs with a median income less than 30,000 dollars and a HIP_i score less than 40 min. All of these TAZs are near USDA designated food desert tracts, but three of the seven are not within these tracts. This indicates that there are regions with low access via transit and low income that are not considered in the USDA's typology.

Quite interestingly, the goodness-of-fit in the HIP_i model is far stronger than the $SMIP_i$ model as indicated by the squared correlation coefficient between estimated and observed values of accessibility (pseudo R^2). This may indicate that socioeconomic conditions of the home neighborhood only explain a small fragment of the total variation in accessibility outcomes once basic daily mobility patterns are introduced into the accessibility metric. This points to the importance of a more complete, mobility-based measure of accessibility, and also may explain why previous studies investigating outcomes of poor, home-based accessibility to supermarkets, have failed to find consistency in their results.

5. Discussion

When considering the population of transit commuters in Cincinnati, there are many opportunities for improved access to supermarkets given the geography of work locations. This finding is important since the transit-dependent population is more at risk of having limited access to healthy foods, given that their

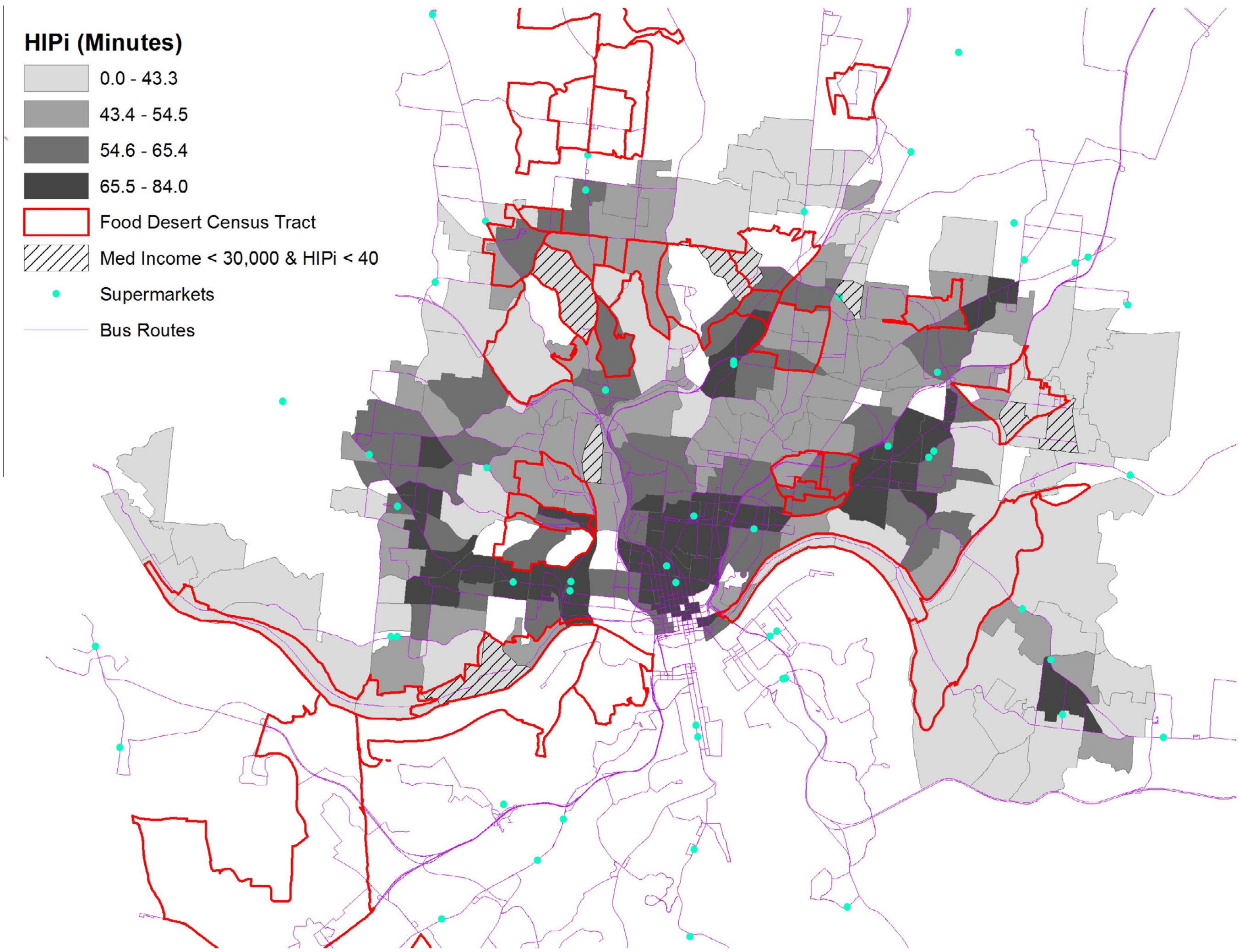

Fig. 10. Low income and low-access TAZs.

movements are constrained by the structure of the transit system. Beyond the spatial constraints, it is also the case that many transit riders in Cincinnati, and other cities, have additional financial and social obstacles to overcome (Garrett and Taylor, 1999). It is possible that the differences in accessibility, which manifest when considering mobility, could have some bearing on the inconsistent findings of previous studies seeking to link health outcomes to residing in food deserts (An and Sturm, 2012; Short et al., 2007; Wrigley, 2002).

Additionally, the findings of this research can be directly applied to intervention strategies in Cincinnati. In particular, these results suggest that transit riders in three particular regions could experience improved access to supermarkets given $SMIP_i$ scores. Those three regions are Sayler Park and Riverside (west of downtown), the East End (east of downtown), and Oakley (northeast of downtown). All three benefit from relatively frequent bus service that runs by a number of supermarkets. The city of Cincinnati could potentially work with the transit authority to encourage transit riders in these neighborhoods to consider chaining a grocery-shopping trip onto their other tasks. This could be accomplished through added amenities on transit vehicles (e.g. improved storage spaces for bags), discounted fares for riders making a shopping stop, marketing campaigns that advertise the possibility of trip chaining, or even supplying supermarkets with real-time transit feed information to keep transit riders informed of the schedule. For those locations with low interaction potential scores it is important to explore the trade offs of improving access by either upgrading transit services or incentivizing the opening of a new healthy food store.

While the findings of this study are encouraging, there are limitations. First, the number of commuters who rely on transit is relatively low when compared to automobile commuters. There are approximately 150,000 automobile commuters, while there are only roughly 13,600 transit commuters. It is also unknown whether or not the transit commuters have access to a vehicle. A second limitation is that commuting patterns are not completely representative of the transit-dependent populations' daily movements, since many non-workers have low-incomes and ride transit for non-work reasons. A third limitation is related to the aggregated nature of the data used for this research. This is an important, but common issue affecting many accessibility analyses (Hewko et al., 2002). In the case of this research, TAZs can be large and the simplified representations of origins and destinations as TAZ centroids will have an effect on the travel and time cost calculations. However, at the time of analysis, the MPO transit commuting dataset used here provided the best data available. Future work should consider more disaggregate representations of the transit commuting population to explore whether the findings of this project hold. Nevertheless, trying to perform spatially representative analyses using detailed disaggregate survey data is extremely difficult due to costs associated with data collection. A fourth limitation worth noting is the use of a standard time budget for all commuters. Obviously, time budgets will vary from person to person, but given a lack of data on this matter, we believe the assumption of 120 min described in Section 3.1 is reasonable and provides the opportunity to compare access across regions relative to a known standard. Additionally, the choice of a standard time budget does not take away from the overall methodological and philosophical contribution of the research. Finally, this analysis does not consider the possibility of the division of household tasks among household members. It is possible that the commuter has a partner who purchases groceries.

Despite these limitations, this analysis shows that there are ample opportunities for transit planners to capitalize on existing commuting patterns, or provide better transit infrastructure to commuters in order to improve accessibility to healthy foods. Additionally, this paper documents a novel methodology for describing food accessibility landscapes that can be used with a variety of data, including high-resolution individual-level activity patterns. Future work should link these interaction potential scores with individual-level behavioral outcomes to understand the relationship between spatiotemporal accessibility and grocery shopping practices.

Acknowledgements

The authors would like to thank Melinda Morang at ESRI for her time answering questions about the transit network analyst extension, and Andrew Rohne at OKI Regional Council of Governments for providing Cincinnati-area commuting data. Parts of this research are based upon work supported by the National Science Foundation (NSF) under Grant No. 1339462. Steven Farber is grateful for support from the National Institute for Transportation and Communities grant number 662. Tijs Neutens gratefully acknowledges the financial support by the Research Foundation Flanders. Mark Horner would like to acknowledge a grant (BCS-1062924) made to him by the NSF which facilitated his collaboration on this project. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

References

An, R., Sturm, R., 2012. School and residential neighborhood food environment and diet among California youth. Am. J. Prev. Med. 42, 129–135.

Barclay, E., 2013. Can Star Power Make New Orleans' Food Deserts Bloom. National Public Radio. http://www.npr.org/blogs/thesalt/2013/05/15/183992818/can-star-power-make-new-orleans-food-deserts-bloom>.

Bazzano, L., He, J., Ogden, L., Loria, C., Vupputuri, S., Myers, L., et al., 2002. Fruit and vegetable intake and risk of cardiovascular disease in US adults: the first National Health and Nutrition Examination Survey Epidemiologic Follow-up Study. Am. J. Clin. Nutr. 76, 93.

Burns, C.M., Inglis, A.D., 2007. Measuring food access in Melbourne: access to healthy and fast foods by car, bus and foot in an urban municipality in Melbourne. Health Place 13, 877–885.

Cheng, C.-L., Agrawal, A.W., 2010. TTSAT: a new approach to mapping transit accessibility. J. Public Transp. 13, 55.

Cummins, S., Flint, E., Matthews, S.A., 2014. New neighborhood grocery store increased awareness of food but did not alter dietary habits or obesity. Health Aff. 33, 283–291.

Farber, S., Neutens, T., Miller, H., Li, X., 2013. The social interaction potential of metropolitan regions: a time-geographic measurement approach using joint accessibility. Ann. Assoc. Am. Geogr. 103, 483–504.

Garrett, M., Taylor, B., 1999. Reconsidering social equity in public transit. Berkeley Plann. J. 13, 6–27.

Golub, A., Martens, K., 2014. Using principles of justice to assess the modal equity of regional transportation plans. J. Transp. Geogr. 41, 10–20.

Google, 2013. What is GTFS? https://developers.google.com/transit/gtfs/>.

He, K., Hu, F., Colditz, G., Manson, J., Willett, W., Liu, S., 2004. Changes in intake of fruits and vegetables in relation to risk of obesity and weight gain among middle-aged women. Int. J. Obes. 28, 1569–1574.

Hewko, J., Smoyer-Tomic, K.E., Hodgson, M.J., 2002. Measuring neighborhood spatial accessibility to urban amenities: does aggregation error matter. Environ. Plann. A 34, 1185–1206.

Higdon, J., Delage, B., Williams, D., Dashwood, R., 2007. Cruciferous vegetables and human cancer risk: epidemiologic evidence and mechanistic basis. Pharmacol. Res. 55, 224–236.

Horner, M.W., 2004. Spatial dimensions of urban commuting: a review of major issues and their implications for future geographic research. Profess. Geograp. 56, 160–173.

Horner, M.W., Mefford, J.N., 2005. Examining the spatial and social variation in employment accessibility: a case study of bus transit in Austin, Texas. Access to Destinations, pp. 193–214.

Horner, M.W., Wood, B.S., 2014. Capturing individuals' food environments using flexible space-time accessibility measures. Appl. Geogr. 51, 99–107.

Horowitz, C.R., Colson, K.A., Hebert, P.L., Lancaster, K., 2004. Barriers to buying healthy foods for people with diabetes: evidence of environmental disparities. Am. J. Public Health 94, 1549–1554.

Hung, H.C., Joshipura, K.J., Jiang, R., Hu, F.B., Hunter, D., Smith-Warner, S.A., et al., 2004. Fruit and vegetable intake and risk of major chronic disease. J. Natl Cancer Inst. 96, 1577–1584.

Joshipura, K., Hu, F., Manson, J., Stampfer, M., Rimm, E., Speizer, F., et al., 2001. The effect of fruit and vegetable intake on risk for coronary heart disease. Ann. Intern. Med. 134, 1106.

Kwan, M.P., 2012. The uncertain geographic context problem. Ann. Assoc. Am. Geogr. 102 (5), 958–968.

Larsen, K., Gilliland, J., 2008. Mapping the evolution of 'food deserts' in a Canadian city: supermarket accessibility in London, Ontario, 1961–2005. Int. J. Health Geogr. 7, 1–16.

Leal, C., Chaix, B., 2011. The influence of geographic life environments on cardiometabolic risk factors: a systematic review, a methodological assessment and a research agenda. Obes. Rev. 12, 217–230.

Lee, B.H.-Y., 2005. Parcel-level measure of public transit accessibility to destinations. Access to Destinations, pp. 215–242.

Lei, T.L., Church, R.L., 2010. Mapping transit-based access: integrating GIS, routes and schedules. Int. J. Geogr. Inform. Sci. 24, 283–304.

Mavoa, S., Witten, K., McCreanor, T., O'Sullivan, D., 2012. GIS based destination accessibility via public transit and walking in Auckland, New Zealand. J. Transp. Geogr. 20, 15–22.

McKinnon, R.A., Reedy, J., Morrissette, M.A., Lytle, L.A., Yaroch, A.L., 2009. Measures of the food environment: a compilation of the literature, 1990–2007. Am. J. Prev. Med. 36, 124–133.

Miller, H.J., 1991. Modelling accessibility using space-time prism concepts within geographical information systems. Int. J. Geogr. Inform. Syst. 5, 287–301.

Miller, H.J., 2007. Place-based versus people-based geographic information science. Geogr. Compass 1 (3), 503–535.

Murray, A.T., Wu, X., 2003. Accessibility tradeoffs in public transit planning. J. Geogr. Syst. 5 (1), 93–107.

O'Sullivan, D., Morrison, A., Shearer, J., 2000. Using desktop GIS for the investigation of accessibility by public transport: an isochrone approach. Int. J. Geogr. Inform. Sci. 14, 85–104.

Orbis, 2012. Company Information. Bureau Van Dijk. http://www.bvdinfo.com/products/company-information/international/orbis>.

Polzin, S., Pendyala, R., Navari, S., 2002. Development of time-of-day-based transit accessibility analysis tool. Transp. Res. Record: J. Transp. Res. Board 1799, 35–41.

Raja, S., Ma, C., Yadav, P., 2008. Beyond food deserts: measuring and mapping racial disparities in neighborhood food environments. J. Plann. Edu. Res. 27, 469–482.

Richardson, D.B., 2013. Real-time space-time integration in GIScience and geography: space-time integration in geography and GIScience. Ann. Assoc. Am. Geogr. 103 (5), 1062–1071.

Salze, P., Banos, A., Oppert, J.M., Charreire, H., Casey, R., Simon, C., et al., 2011. Estimating spatial accessibility to facilities on the regional scale: an extended commuting-based interaction potential model. Int. J. Health Geogr. 10 (2), 1–16.

Shaw, H., 2006a. Food deserts: towards the development of a classification. Geogr. Ann.: Series B, Human Geogr. 88, 231–247.

Shaw, S.L., 2006b. What about "time" in transportation geography? J. Transp. Geogr. 14 (3), 237–240.

Short, A., Guthman, J., Raskin, S., 2007. Food deserts, oases, or mirages? small markets and community food security in the San Francisco Bay Area. J. Plann. Edu. Res. 26, 352–364.

Smith-Warner, S., Spiegelman, D., Yaun, S., Adami, H., Beeson, W., van den Brandt, P., et al., 2001. Intake of fruits and vegetables and risk of breast cancer: a pooled analysis of cohort studies. J. Am. Med. Assoc. 285, 769–776.

USDA ERS, 2008. Eating and Health Module (ATUS). http://www.ers.usda.gov/data-products/eating-and-health-module-(atus).aspx>.

USDA ERS, 2013. Food Access Research Atlas. http://www.ers.usda.gov/data-products/food-access-research-atlas.aspx>.

Walker, R.E., Keane, C.R., Burke, J.G., 2010. Disparities and access to healthy food in the United States: a review of food deserts literature. Health Place 16, 876–884.

Widener, M.J., Farber, S., Neutens, T., Horner, M.W., 2013. Using urban commuting data to calculate a spatiotemporal accessibility measure for food environment studies. Health Place 21, 1–9.

Widener, M.J., Metcalf, S.S., Bar-Yam, Y., 2011. Dynamic urban food environments: a temporal analysis of access to healthy foods. Am. J. Prev. Med. 41, 439–441.

Widener, M.J., Metcalf, S.S., Bar-Yam, Y., 2012. Developing a mobile produce distribution system for low-income urban residents in food deserts. J. Urban Health 89, 733–745.

Widener, M.J., Shannon, J., 2014. When are food deserts? integrating time into research on food accessibility. Health Place 30, 1–3.

Wrigley, N., 2002. 'Food deserts' in British cities: policy context and research priorities. Urban Studies 39, 2029–2040.