Article

Urban Analytics and City Science

EPB: Urban Analytics and City Science
2025, Vol. 52(4) 985–1001

DOI: 10.1177/23998083241312369
journals.sagepub.com/home/epb
Sage

How does delivery service change food accessibility: A modified 2-step floating catchment area method

Grace Jia
University of Washington, USA

Ram Pendyala
School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, USA

Cynthia Chen
University of Washington, USA

Abstract

Existing methodology on food accessibility predominately focuses on on-premise services, that is, dine-in and shopping at stores, which assumes a linear distance decay property (the closer, the higher accessibility). Access to delivery services is fundamentally different from that to on-premise stores. Stores with close proximity (within an inner boundary) are less desirable for delivery due to delivery fees, and there is an outer boundary beyond which deliveries are unavailable, both challenging the assumption of increasing impediment with distance. These two boundaries form a donut shape for delivery services. We propose a modified 2-step floating catchment area method that incorporates the donut shape, accounts for both demand and supply, and examines the diversity of food options. Using Seattle as a case study, our results show that delivery services increase restaurant and fast-food accessibility in areas where there is already good accessibility (e.g., downtown Seattle for restaurants and South Seattle for fast-food). Given South Seattle is where low-income and low-access households concentrate, the increase in accessibility to fast-food may not be desired. Interestingly, with delivery services, more low-income or low-access households (those who live far from grocery stores) have better accessibility to fresh produce from grocery stores compared to the rest of the population. And the newly created Supplemental Nutrition Assistance Program (SNAP) online program appears to miss low-access

Corresponding author:
Cynthia Chen, Department of Civil and Environmental Engineering, University of Washington, 201 More Hall, Seattle, WA 98195, USA.
Email: qzchen@uw.edu

Data Availability Statement included at the end of the article

Correction (January 2025): Article has been updated with the author order since its original publication. See correction notice for more details.

households. These findings have important implications for policymakers and stakeholders seeking to improve food accessibility in urban areas through delivery services.

Keywords
Food accessibility, delivery accessibility, 2-step floating catchment area (2SFCA)

Introduction

Access to affordable and nutritious food has become a significant issue in many communities, particularly those with low-income populations (Ploeg et al., 2009). United States Department of Agriculture (USDA) stated that approximately 11.5 million low-income individuals (with incomes at or below 200% of the Federal poverty threshold) have low access to food defined as living more than one mile away from supermarkets or large grocery stores (Ploeg et al., 2009). Among them, 1.9 million do not have access to a vehicle (USDA, 2022). Low-access and lack of a vehicle likely lead to more barriers to accessing healthy food and increased health issues (Higgs and Thomas, 2016). Existing research also found that low-income people spend more at fast-food, convenience stores, US dollar trees, and drugstores compared to the population who live closer or are richer (Kaiser et al., 2019). The reliance on fast-food is also a nationwide trend: U.S. spending on fast-food has risen from US$6 billion to US$110 billion over the last 30 years (Schlosser, 2012), making fast-food an alternative for people's food consumption choices. Similarly, the popularity of prepared meals from restaurants rose as 68% of the adults in the U.S. indicated prepared meals offered convenience over cooking at home (Riehle et al., 2021), though less nutritious compared to cooking fresh groceries.

USDA defines low-access, similar to the existing literature, using the distance from a population location, like the center of a census tract, to the nearest food establishment, such as grocery stores (Kolak et al., 2018). Other existing metrics include, for example, the number of food establishments within a predefined distance threshold from a population location (Berg and Murdoch, 2008; Liese et al., 2007; Morland et al., 2002), gravity-based metrics treating farther food establishments as less-accessible (Chen et al., 2017; Dai and Wang, 2011), and utility-based metrics evaluating how much satisfaction one receives by purchasing from food establishments (Cicia et al., 2002). Each type of metric has its own strength and different use cases. Distance or time-based metrics, such as those based on proximity, offer simple interpretations: shorter distance or time means better accessibility. In contrast, gravity-based metrics require calibration of distance decay functions (Chen, 2019), and utility-based metrics consider people's preferences in purchasing food, food establishment quality, and characteristics, among others. These metrics assume that customers travel from a set location (like home or workplace) to buy food in person.

However, these metrics aren't easily applied to evaluating food access through delivery services, where food comes to the customer instead. Delivery services reduce the dependence on mobility (eliminate travel time) and proximity (distance becomes less significant), and this key feature can be further broken down into three aspects. First, food establishments too close to a population location are not necessarily more accessible, as delivery fees apply despite the short distance. Second, with delivery service, people are no longer constrained by travel time to food establishments, opening a broader range of food choices. Third, existing food accessibility metrics focus solely on the supply side of food establishments (Chen, 2019), and with rising demand for delivered food, the metric should consider both supply and demand sides and competition when establishments can't meet the demand or consumers have many food choices. There is a need to understand how to account for delivery in the methodology and our understanding of food access (O'Hara and Toussaint, 2021; Widener, 2018).

To promote food access and a healthful diet for low-income Americans, USDA launched the Supplemental Nutrition Assistance Program (SNAP), the nation's largest nutrition assistance program (Caswell et al., 2013). In 2022, SNAP announced its investment in the SNAP online program, recognizing online shopping as a vital resource to improve access for SNAP participants (U.S. Department of Agriculture, Food and Nutrition Service, 2022). SNAP online benefits continue to use income as the eligibility criteria: in Washington state, individuals and households should have monthly income (before taxes and reductions) under the gross monthly income standard listed in Washington Administrative Code. Since low-income households do not necessarily experience low-access, as about 41% of USDA defined low-income tracts are low-access, the income-alone criterion may not be appropriate. Furthermore, the criteria do not consider whether a household with limited access to on-premise shopping for food also faces limited access to delivered food.

Thus, two observations can be made regarding delivered food accessibility. First, no existing research has confirmed or refuted that people far from grocery stores (thus low-access) also have low-access to delivered groceries. Second, it would be of interest to evaluate whether the SNAP online program can indeed help individuals lacking access to fresh vegetables through food delivery. Low-income individuals may struggle with ordering delivery if SNAP online benefits do not cover delivery fees and prefer pickup or on-premise purchasing, leading to unrealized SNAP online benefits. On the other hand, low-income individuals living within walking distance (e.g., a 15-min walk to grocery stores) can also buy groceries on-premise. It is thus unclear how SNAP online benefits will affect food access, especially for low-income and low-access households.

In short, the rise of food delivery services motivated this study. More specifically, this study proposes a modified Two-step Floating Catchment Area (2SFCA) method that accounts for the unique features associated with delivery services, investigates how the emergence of delivery service changes the landscape of food access, and examines how the SNAP online program helps food access by low-income and low-access households with delivery service in mind. This study answers the following questions:

1. How to incorporate the key features of delivery service into food accessibility quantification?
2. How does the increase in food accessibility brought by delivery services vary across different population segments in a region? And
3. How is the population with low-access to delivered fresh produce supported by SNAP online benefits?

The evolution of food accessibility metrics

Food accessibility, stemming from the widely explored work on accessibility, refers to the extent of potential opportunities for obtaining food (Ben-Akiva and Lerman, 1979). People recognize the importance of food accessibility because enough and nutritious food options are critical for human survival and well-being. Past studies pointed out that people in rural areas (Chung and Jr., 1999; Larson et al., 2009; Liese et al., 2007; Ploeg et al., 2009), having limited access to transportation (Morland et al., 2002; Ploeg et al., 2009; Racine et al., 2018; Sharkey, 2009), and low-income and minority concentrated (Gordon et al., 2011) communities have less access to food. Spatial factors, such as proximity to residential areas, population density, and service capacity of food establishments, are also influential in determining food access (Charreire et al., 2010; Sharkey, 2009; Silva and Altieri, 2022).

Measurements for food accessibility started with a primitive form of the distance to the closest food establishment from a population location, for example, census tracts (Kolak et al., 2018). Longer distance to the closest establishment implies lower levels of food access. Later, the definition expands to the form of cumulative opportunity, which counts the number of food establishments within a given distance determined by travel time, mode, and speed from an origin or within a given area unit such as a census tract (Berg and Murdoch, 2008; Liese et al., 2007; Morland et al., 2002; Páez et al., 2010; Powell et al., 2007). Commonly, these measurements involve a distance threshold from 0.5 to 15 miles

(Berg and Murdoch, 2008; Larson et al., 2009; Racine et al., 2018; Yang and Diez-Roux, 2012). However, cumulative opportunity does not treat closer options as easier reach than farther options. Thus, gravity-based measures were proposed to discount opportunities that are farther away through distance decay functions (Chen et al., 2017; Dai and Wang, 2011). The discussion quickly evolves to incorporating personal characteristics because one might prefer one option over other options due to factors including income level and service quality (Adamowicz and Swait, 2013; Black et al., 2014). Under this branch, each food option is weighted by the utility, or the overall satisfaction one perceives, and consumers purchase food based on the random utility maximization principle (Cicia et al., 2002). Personal attributes like cultural preferences, service quality, and price sensitivity may lead individuals to opt for farther food establishments, which are challenging to be captured in gravity models. Understanding utility requires detailed data such as survey instruments to estimate preferences for qualitative and quantitative attributes of the food (Cicia et al., 2002), which is more expensive and less accurate to collect compared to census tract and food establishment's coordinates.

Recent literature argue that the existing food accessibility measurements are compromised by focusing only on the supply side, that is, the food establishments and overlooking supply-demand interactions (Bonanno, 2012; Chen and Jia, 2019). Simply speaking, given a set of food establishments, areas with higher population density will compete for food and receive less service quality compared with areas with lower population density. One step forward is calculating the density, or ratio of population to food establishments (Moore et al., 2008), to reflect how much competition for food exists within a place. However, this density metric usually treats all food establishments the same, despite varying capacities or the amount of service provided. A restaurant serving 100 customers simultaneously should be differentiated from other small-scale food stores serving only 10 customers.

To capture the intricacy of local competition between supply and demand, more literature in the last two decades began to explore the Two-step Floating Catchment Area (2SFCA) method, originally proposed by Luo et al. (2003). 2SFCA begins with calculating a supply-to-demand ratio as the establishment's service capacity to the populations attracted to this establishment within a distance threshold. The accessibility of a population location is the sum of supply-to-demand ratios for establishments within this distance threshold. The original 2SFCA model counts every establishment equally like cumulative opportunity models and is later enhanced to incorporate distance decay functions including negative exponential function, power function, generalized logistic function, and kernel density forms such as gaussian, and generalized logistic function (Dai and Wang, 2011; Delamater, 2013; Martínez and Viegas, 2013), to mimic the effect of higher accessibility of nearby services than those farther away in a gradually decaying fashion. A detailed discussion on the applicability and limitations of 24 distance decay functions can be found in Chen and Jia (2019).

The service capacity for each food establishment is usually acquired using a store's square footages (Luo, 2017), sales volume ranges (Jin and Lu, 2022; Kuai and Zhao, 2017), and the proportion of SNAP benefits used in one food category for all establishments belonging to that category (Chen, 2019; Chen and Jia, 2019). However, the use of different units for supply such as square footage units, monetary units, or percentages potentially makes it challenging to interpret the supply–demand ratio and accessibility. For example, when monetary units are used, the supply-to-demand ratio will be in US dollar per person. Thus, a high ratio of US$1,000 per person could either result from the high monetary value associated with the supply or a low demand. Similar can be said about the proportion of SNAP benefits given that there likely exists large variations in how much SNAP benefits are used across different establishments. The use of square footages fares better than the other two and yet they are still in different units from the demand. Ultimately, it is desirable to use the same units for both supply and demand (both in persons) and hence this is the approach adopted in this study.

The existing work on food accessibility is only oriented toward quantifying on-premise accessibility when individuals travel to the food establishment. Food incentive programs, such as SNAP, rely only on on-premise food accessibility findings, or simply by the income level of households to determine the eligibility status. Though a few analyze the SNAP program with spatial and supply-demand perspectives such as Chen (2019), the effect of delivery on food accessibility remains unexplored, with one pointing out that rural, food insecure counties in Washington continue to lack access to grocery delivered to home (Beese et al., 2022). The existing literature on food accessibility metrics often discuss either food quantity or diversity, and yet they can be very different from each other. High level of accessibility to one type of food can be associated with lack of diverse food options; a community may have an abundance of fast-food but lack access to fresh produce. Conversely, diverse food options may not meet population needs if quantity is insufficient. Most literature focuses only on the grocery category, leaving little room to discuss diversity. Some has argued the importance of examining both healthful and less-healthful (but affordable and convenient) food establishments to form a cohesive, comprehensive understanding of food access (Lucan et al., 2018, 2020). Hence, in our study, we look at three food categories: grocery stores, restaurants, and fast food, and examine accessibility in each category and their diversity.

Methodology

This study modified the 2SFCA method, originated from studies on the accessibility of physician services (Luo and Wang, 2003), to quantify and analyze food accessibility through a case study in Seattle, Washington. The modification contributes to the research questions by developing food accessibility metrics for on-premise and delivery services, accounting for supply versus demand and quantity versus diversity.

The original 2SFCA method

2SFCA first calculates the supply-to-demand ratio, R_j, for each physician location j. R_j serves as the physician's capacity (usually counted as the number of physicians) to serve the population in the vicinity. The population can only be served by a physician if the distance, d_{ij}, between the population location i and the physician location $\boldsymbol{j}$ is less than a pre-defined distance threshold $\boldsymbol{r}$. Suppose there are $\boldsymbol{N}$ population locations, and each location has a population size of $P_i, (i = 1, \ldots, N)$. There are M physician locations, each with one physician. Then, R_j is defined by equation (1)[1]:

$$R_j = \frac{supply\,at\,location\,j}{population\,within\,r} = \frac{1}{\sum_{i \in \{N|d_{ij} \le r\}} P_i}. \tag{1}$$

The second step searches all physician locations within the threshold r from population location i. Therefore, the accessibility to physicians for a population location, A_i, is a sum of the supply-to-demand ratios:

$$A_i = \sum_{j \in \{M|d_{ij} \le r\}} R_j. \tag{2}$$

Key features of delivery and their difference from on-premise options

To account for special features delivery, this work uses different catchment areas for food accessibility on-premise and through delivery. With delivery, customers are limited by travel time or distance, so one might enlarge the catchment area and increase the distance threshold for delivery scenario. However, drivers are reluctant to spend more than 15–20 min on the road, and prepared food loses taste after a long trip. Thus, delivery platforms consider 5 miles as a standard delivery distance (Brar and Minaker, 2021). Moreover, the impedance function for delivery service should discourage orders from service locations too close to the customer due to delivery fees. For example, Rodrigue proposed to modify the function to a straight-line function for e-commerce without delivery fee per order (Rodrigue et al., 2017). Given delivery apps' per-order fees, this study designs a donut-shaped catchment area, excluding food outlets too close to the population center. A 1.5-mile distance threshold is set based on a survey indicating a preference for traveling to nearby establishments over ordering delivery (US FOODS, 2019). Therefore, the donut-shaped catchment area has an inner and outer distance threshold of 1.5 miles and 5 miles, respectively. For on-premise food accessibility, literature has shown that the average distance traveled to food outlets varies depending on the type of the food outlets (Kerr et al., 2012). The outer radius for catchment area for grocery stores, fast-food outlets, and restaurants are set at 4.67, 4.96, and 6.10 miles, respectively, according to the finding from Kerr et al. (2012).

The modified 2SFCA method

The first modification is discounting the supply-to-demand ratio for food establishments further away from the population location or cost higher than others. Secondly, this study categorizes food establishments into full-service restaurants, quick-service restaurants, and groceries to analyze accessibility across categories and to examine competition, complementary effects, and the diversity of food choices. Originally conceptualized in the literature in the 1970s (Weibull, 1976), competition arises when customers have multiple service locations to choose from, potentially leading to demand dilution towards locations with lower costs. A recent work measuring job accessibility considers competition via a probabilistic model, comparing location attractiveness using a negative exponential decay function (Cheng and Bertolini, 2013). Third, service capacity can be estimated based on daily customer served, derived from seating capacity (the number of customers a food outlet can accommodate). Fourth, the demand for each food establishment should be carefully addressed to avoid demand and supply inflation, a phenomenon identified by several works (Delamater, 2013; Paez et al., 2019). Demand inflation occurs if the 2SFCA method overestimates the potential population demand where multiple facilities are accessible to a population location. Supply inflation occurs if the 2SFCA assigns supply to all residents from a population location. To account for the above, equation (1) can be modified as follows:

$$R_j = \frac{supply\ at\ location\ j}{population\ attracted\ to\ j} = \frac{cap_j}{\sum_{i \in \{N | r_1 \le d_{ij} \le r_2\}} P_i \times p(d_{ij})}, \tag{3}$$

where cap_j $(j = 1, ..., M)$ being the supply capacity of j^{th} food establishment. r_1 and r_2 represent the inner and outer radius of the donut-shaped catchment area, respectively. Supply capacity, cap_j, is determined by multiplying seating capacity by daily operating hours, assuming customers spend up to 1 hour at the establishment. d_{ij} is the distance from population location i to food establishment j, which represents the cost for customers from location i to be served by j. The longer the distance, the higher the cost. The function $p(d_{ij})$ in the denominator is the fraction of population i choosing location j out of a set of M available options, based on d_{ij}. So, the demand from location i to establishment j is not P_i but $P_i \times p(d_{ij})$. Up to this step, the use of $p(d_{ij})$ in calculating demand and R_j is the same as the row-normalization of the impedance matrix developed by Paez et al. (2019) and addresses demand inflation problem as noted by Paez et al. (2019). The formulation of $p(d_{ij})$ is discussed later in equation (5). An establishment with R_j value of less than 1 offers insufficient service to the demand.

Equation (2) is modified into a category-specific food accessibility for location i, A_{ic}, to facilitate analyzing quantity and diversity:

$$A_{ic} = \sum_{j \in \{M | r_1 \leq d_{ij} \leq r_2 \cap C_j = c\}} R_j \times p(d_{ij}), and \tag{4}$$

$$p(d_{ij}) = \frac{e^{-d_{ij}^2/\beta}}{\sum_q e^{-d_{iq}^2/\beta}}, \tag{5}$$

where $q = \{1, \ldots, j, \ldots, M\} \cap r_1 \leq d_{iq} \leq r_2$, and C_j represents the category of a food establishment j. Food establishments contribute to accessibility based on their relative importance, weighted by a fractional population from location i that will visit each food establishment j. We note that the above formulation defines the supply–to-demand ratio and category-specific food accessibility via delivery. For on-premise establishments, the function $r_1 \leq d_{ij} \leq r_2$ should be changed to $d_{ij} \leq r_2$. Additionally, this study adopts the logit model with Gaussian function as the functional form of $p(d_{ij})$ and uses distance as the only input[2]. Gaussian function has been reported to outperform cumulative opportunity, inverse power-law, kernel density, and negative exponential decay functions. The decay parameter β is derived from the USDA Atlas finding that the maximum travel distance to purchase food is observed to be 20 miles. Therefore, Chen (2019) believed that the critical value $e^{-20^2/\beta}$ equals 0.01 (the value for the Gaussian function approaching 0 (Wan et al., 2012)) and the decay parameter $\beta = -\frac{20^2}{ln\, 0.01} = 86.9$.

$p(d_{ij})$ in equation (4) calculates the food accessibility for location i as a weighted average of $R_j s$, and the weight for each R_j equals the proportion of the population that visits establishment j. This methodology addresses the supply inflation in that the supply from one establishment is only given to those who visits the establishment, not the entire population. Calculating food accessibility in this fashion, similar to Delamater (2013), ensures the total supplies given out from the food establishments equals the total supplies received by the population, and thus the following property holds: $\sum A_i P_i = \sum cap_j$ (see Supplementary Materials Section B for the proof). We note this is different from another line of literature that discusses preserving instead $\sum A_i = \sum R_j$, as proposed by Paez (2019), an approach also used by Pereira (2017) and Desjardins et al. (2022).

Because customers can obtain food from one or more categories, the total food accessibility, A_i, is the summation of all category-specific food options:

$$A_i = \sum_{c=1}^{C} A_{ic}. \tag{6}$$

The diversity of food accessibility comes into play through complementary effects using entropy (Yeh and Li, 2001), and higher diversity means a more balanced food accessibility. The diversity index D_i can be defined as:

$$D_i = -\sum_{c=1}^{C} \frac{A_{ic}}{A_i} \times ln\left(\frac{A_{ic}}{A_i}\right). \tag{7}$$

A_i and D_i are two key metrics that evaluate the census tract's food accessibility's quantity and diversity, respectively. Though much of the literature emphasizes accessing healthy foods from grocery stores in particular, a rising share of literature (Apparicio et al., 2008; Li and Wang, 2022) highlights the importance of diversity as an essential element of local food environment. And they suggest that a good food accessibility metric may not be the proximity to a single food source, albeit healthy, but the availability of different food sources in the residents' daily travel footprint.

Results

The analysis is carried out on a case study in Seattle, Washington, including 135 census tracts, 3,654 full-service restaurants (referred to as restaurants), 389 quick-service restaurants (referred to as fast-foods), and 564 groceries. The justification of selecting this region and data preprocessing can be found in Supplementary Materials section A. And a detailed discussion on supply-to-demand ratios can be found in Supplementary Materials section C. Thus, the rest of this section will focus on food accessibility, the amount of food options relative to the demand in a census tract.

How does the increase in food accessibility brought by delivery service vary across in the study area?

Category-specific food accessibility. Figure 1 presents heat maps illustrating geographic variations in category-specific food accessibility. The 2 × 3 subplot distinguishes between on-premise versus delivery and the category being plotted. A tract is shaded lighter if it has a smaller A_{ic} value compared to darker tracts. There is noticeable difference for the restaurant category comparing the first column. The heat map indicates that downtown Seattle has limited access to delivered restaurant food compared to peripheral areas. This pattern appears to contradict the high concentration

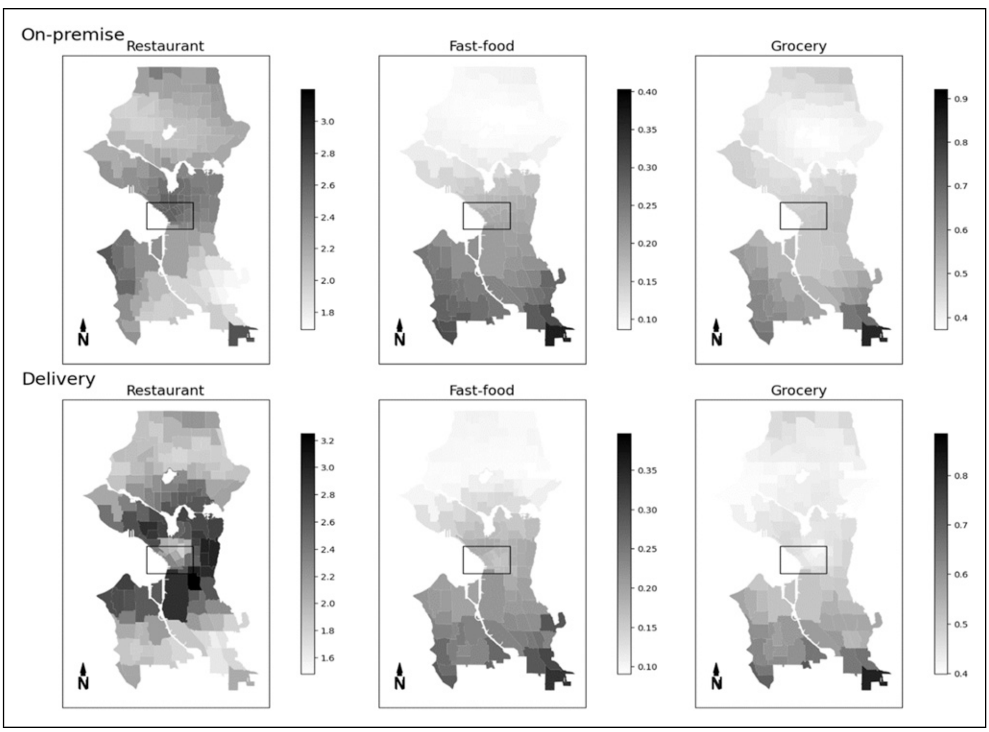

Figure 1. Heat maps for category-specific food accessibility in the study area. Top row: accessibility through on-premise service. Bottom row: Accessibility through delivery service. Downtown Seattle is bounded within the black rectangle.

of restaurants in downtown areas (bounded within the black rectangle in each subplot). However, it is consistent with the donut-shaped catchment area for delivery services, leaving the downtown area with fewer available food establishments to choose from. Since more restaurants are located in downtown, residents there are ensured to have enough food through dine-in option. Heatmaps for fast-food and grocery showed less discrepancy, possibly owing to a much smaller number of establishments. The heatmaps for grocery and fast-food establishments generally display a linear increase from north to south in the study area. Donut-shaped areas around downtown for these two types are less prominent than those for restaurants. Comparing the heatmaps for on-premise and delivery for fast-food and grocery stores, respectively, several observations can be made. First, the south part has better accessibility than the north for both on-premise and delivery. Second, the difference between the north and south parts is more pronounced for fast-food compared to grocery stores. Third, adding the delivery option does not alter the overall pattern: it further enhances fast-food options in the south. Comparing on-premise and delivery heat maps shows increased restaurant food accessibility in the outskirts of downtown, although access to fresh produce is more subject to the number of establishments available in vicinity.

Table 1 reports the summary statistics of on-premise and delivery service's A_{ic}. In all categories, the mean and median of the delivery A_{ic} and on-premise A_{ic} are of similar magnitude. Restaurant and grocery store's food access via delivery have medians that are slightly less than on-premise food access. In general, this indicates that if all food establishments exclusively offer delivery service (e.g., during strict social-distancing policy), customers would have equal amount of food to access compared to on-premise services. However, it is noteworthy that the standard deviation for restaurant-specific food accessibility is much higher than other categories in both delivery and on-premise cases, indicating greater variation in accessing cooked food from restaurants. The restaurant specific food accessibility is also considerably larger than other categories, due to the presence of 3,654 restaurants out of 4,607 establishments in the study area.

Further examining category-specific food accessibility for low-income/non-low-income and low-access/non-low-access (defined by USDA) reflects how delivery improves accessibility in different population segments. Figure 2(a) depicts the grocery specific food accessibility for low-income versus non-low-income tracts and low-access and non-low-access tracts via delivery only. With delivery, non-low-income tracts have a wider range of grocery accessibility, ranging from [0.40, 0.89], whereas low-income tracts can at most have 0.72. Similarly, low-access tracts also have a lower upper-bound, with their maximum grocery access valued at 0.66 compared to 0.89 of the non-low-access tracts. However, the plots suggested that more of the low-income and low-access tracts have higher accessibilities compared to their counterparts. This implies that delivery services

Table 1. Summary statistics for category-specific food accessibility through on-premise service (top) and delivery (bottom).

On-premise	Mean	Median	Standard deviation
Restaurant	2.24	2.21	0.24
Fast-food	0.16	0.15	0.07
Grocery	0.48	0.47	0.09
Delivery	**Mean**	**Median**	**Standard deviation**
Restaurant	2.23	2.11	0.39
Fast-food	0.16	0.16	0.06
Grocery	0.48	0.45	0.09

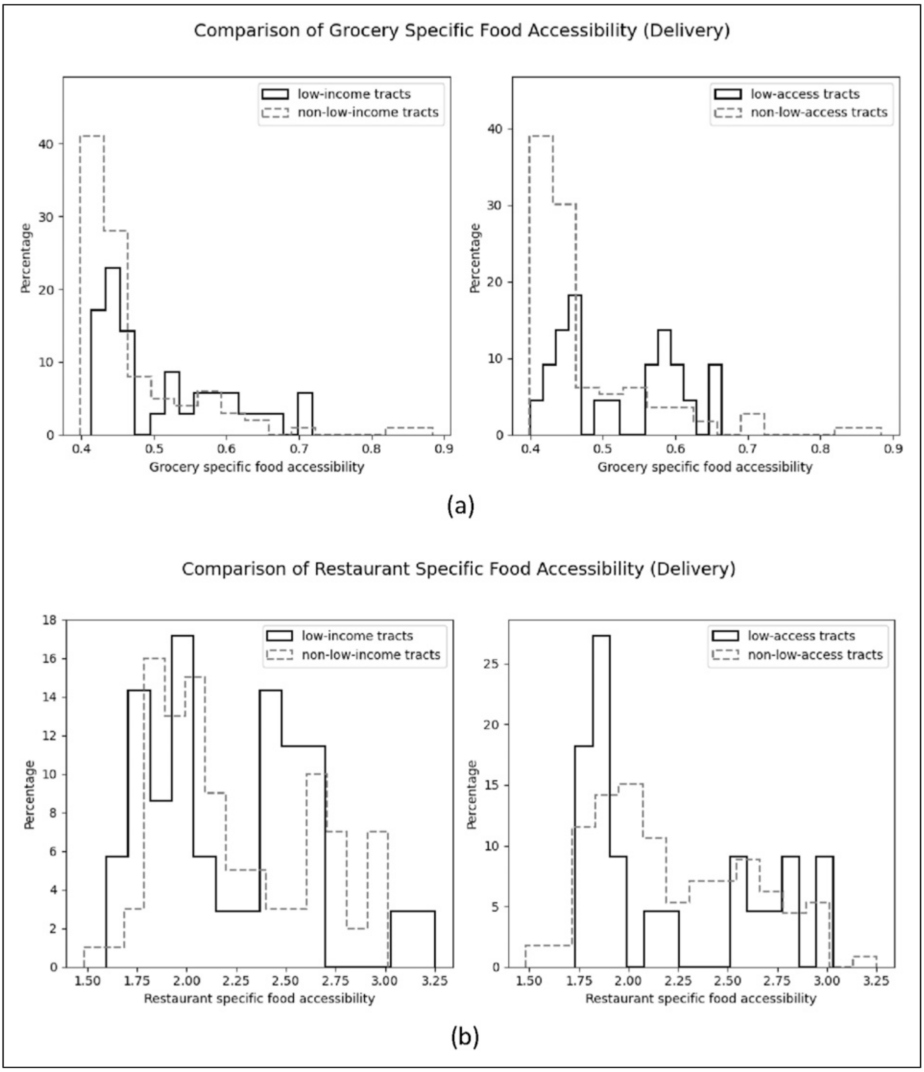

Figure 2. (a) Percentage frequency plot for grocery specific food accessibility via delivery only. (b) Percentage frequency plot for restaurant specific food accessibility via delivery only. Left: low-income versus non-low = income tracts. Right: low-access versus non-low-access tracts.

provide greater benefits to low-income and low-access areas by improving access to fresh produce and promoting a healthier diet.

Similarly, Figure 2(b) compares the restaurant specific food accessibility via delivery for the four types of census tracts. Two observations can be made. First, in general, with delivery option only, both low-income and low-access tracts have higher lower-bound values than their counterparts. Second, the upper-bound value for low-income tracts is larger than the counterpart (non-low-income tracts) while the reverse is true for low-access versus non-low-access tracts. Multi-modal distributions exist for both low-income and non-low-income tracts (the former has three while the latter has two). This phenomenon is less pronounced for low-access and non-low-access tracts. Combing with the observations for Figure 2(a) for grocery store accessibility, the finding is that though delivery services do result in a good number of low-income or low-access tracts to have good accessibility (for both grocery stores and restaurants), there still exist a substantial number that have relatively low levels of accessibility.

Diversity index measures the variety of food options in each census tract, and the heatmaps in Figure 3 revealed an increasing trend of diversity from north to south. As restaurants dominate the study area, increasing diversity could mean more healthy options from grocery stores and fewer cooked options from restaurants. This expands non-restaurant choices for residents, enhancing diversity. Furthermore, with delivery, downtown area has a higher diversity index compared to itself with on-premise service, which further confirms that delivery improves food accessibility diversity when the residents have less food establishments to choose from.

How is the population with low-access to delivered fresh produce supported by SNAP online benefits?

The first three subplots in Figure 4 plot the low-income, low-access, and high-participation tracts, and the dark-colored tracts indicate the tract satisfies the definition. High-participation tracts refer to tracts with participation rate greater than 16% (i.e., the 20% of the population relying the most on SNAP benefit). And the right-most subplot plots the total grocery food accessibility (on-premise and delivery). As expected, the pattern exhibited in the subplot for high-participation matches well with that for the low-income tracts, since SNAP eligibility is based on income alone. Between low-access tracts and high-participation tracts, the patterns seem to have just flipped: though both are in southern Seattle, low-access tracts primarily concentrate on the west side while high-participation ones are on the east side. This means that in Seattle at least, low-income tracts and low-access tracts capture two different populations. The last subplot shows the distribution of accessibility to grocery stores (both on-premise and delivery). Surprisingly, the South side in fact has better accessibility to grocery stores than the north side of the study area.

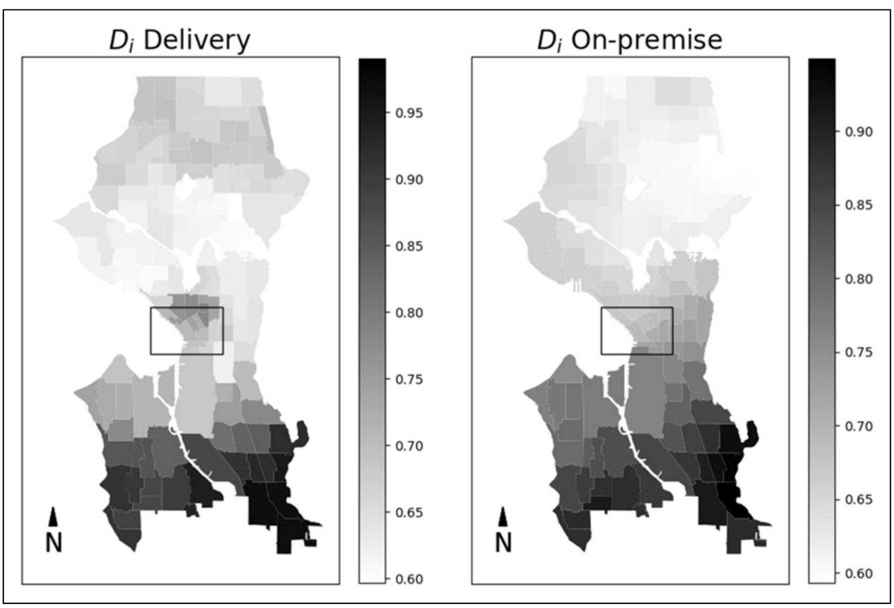

Figure 3. The diversity index, D_i, for delivery (left) and on-premise (right) for each tract in the study area. Darker shaded tracts have more diversified options for food compared to lighter shaded tracts. Downtown Seattle is bounded within the black rectangle.

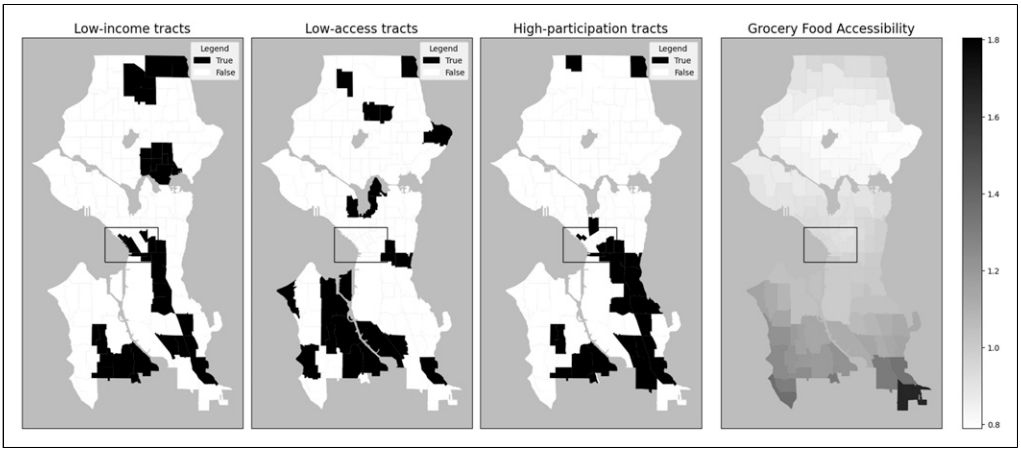

Figure 4. Maps indicating low-income, low-access, and high-participation, and grocery food accessibility (on-premise and delivery combined) tracts in Seattle. Downtown Seattle is bounded within the black rectangle.

The mismatch between those in low-access tracts versus those in high SNAP participation tracts suggest that the SNAP online program, though capturing low-income tracts well, does misses low-access tracts. Additionally, overall, grocery store food accessibility (combining both on-premise and delivery only) fares better for South Seattle than for North Seattle, based on the rightmost plot in Figure 4, suggesting that the SNAP online program may miss pockets in North Seattle. Thus, relying solely on average household income as the criterion for SNAP eligibility may overlook critical factors such as the existing food accessibility landscape, the spatial distribution of establishments, and the competition among residents. In other words, those who actively participating in SNAP might not be the only population segment in great need of the benefit. Furthermore, regions with limited online grocery options, particularly the northern region, receive less SNAP benefit because it has only two tracts with high SNAP participation. Some regions, especially in the northern area, don't have enough online grocery options as shown by the lighter color (and lesser value) of the grocery food accessibility in the rightmost subplot in Figure 4, suggesting that there are likely pockets where SNAP online benefits can be valuable.

Conclusions

Delivery challenges the long-adopted methodologies for calculating food accessibility in that delivery service is less reliant on proximity, is not friendly to closer food choices, and involves competition between supply and demand. This work contributes to the literature by proposing a modified 2SFCA accessibility metric evaluating food accessibility for delivery services that considers the above three features. The proposed methodology is also used to assess the efficacy of SNAP online benefits, considering that the current eligibility criteria rely solely on household income without factoring in food access.

This study raises interesting questions relating to how to improve people's access to fresh food as typically available in grocery stores, especially for the low-income people who are found to spend more at fast-food establishments. Our study shows that in the city of Seattle, the south part where low-income and low-access tracts concentrate, appears to have higher levels of accessibility to fresh food than the north part, due to more availability of grocery stores in the south part than those in the north. This suggests that while adding SNAP online benefits does improve accessibility to fresh food overall for the study area, other policies (in addition to making fresh produce more available) may be needed to increase people's consumption of fresh produce especially for the low-income people. One may point to the fact that while there is already vast availability of on-premise fast-food options (see Figure 1), adding delivering further enhances the accessibility to fast-food significantly, which may not be desirable. As such, one policy discussion is perhaps about how we can reduce accessibility to fast-food while at the same time improving access to fresh produce.

This work relies on annual food inspection data and assuming establishments recorded as operational in these datasets remain open which may not hold true post-pandemic due to significant disruptions in the food industry. This work assumes all food outlets, including restaurants, grocery stores, and fast-food establishments, have adopted delivery services due to the widespread availability of third-party delivery services like Instacart and DoorDash. However, adoption rates may vary across different types of establishments, potentially affecting the observed landscape of food accessibility. The study also does not explore how personal characteristics and preferences (affordability, daily work schedules, mobility, cultural preferences, etc.) affect individuals' choices among available food outlets, thus limited the understanding of food accessibility determinants. Future research endeavors should consider incorporating these individual-level dynamics to provide a more comprehensive and nuanced exploration of the factors influencing food choices and accessibility through delivery.

Acknowledgments

The authors are supported by the National Science Foundation on the project entitled "Re-Engineering for Adaptable Lives and Businesses" (Award no.: 2053373). The authors are also supported by the Center for Teaching Old Models New Tricks (TOMNET), a Tier-1 University Transportation Center sponsored by the US Department of Transportation under grant 69A3551747116, as well as the Center for Understanding Future Travel Behavior and Demand (TBD), a National University Transportation Center sponsored by the US Department of Transportation under grant 69A3552344815 and 69A3552348320.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Division of Civil, Mechanical and Manufacturing Innovation, 2053373, U.S. Department of Transportation; 69A3552344815, U.S. Department of Transportation (TOMNET); 69A3551747116.

ORCID iD

Cynthia Chen https://orcid.org/0000-0002-1110-8610

Data availability statement

The datasets generated during and/or analyzed during the current study are available in the GitHub repository, accessible from this link: https://github.com/UW-THINKlab/delivery_food_access

Supplemental material

Supplemental material for this article is available online.

Notes

1. The numerator is set to 1 because of the assumption on the uniform supply (doctors) available at each physician location.
2. In a general form, other forms of costs such as travel time and monetary cost can also be included.

References

Adamowicz WL and Swait JD (2013) Are food choices really habitual? Integrating habits, variety-seeking, and compensatory choice in a utility-maximizing framework. *American Journal of Agricultural Economics* 95(1): 17–41.

Apparicio P, Abdelmajid M, Riva M, et al. (2008) Comparing alternative approaches to measuring the geographical accessibility of urban health services: distance types and aggregation-error issues. *International Journal of Health Geographics* 7(1): 7.

Beese S, Amram O, Corylus A, et al. (2022) Expansion of grocery delivery and access for Washington SNAP participants during the COVID-19 pandemic. *Preventing Chronic Disease* 19(1): 210412. Available at: https://doi.org/10.5888/pcd19.210412.

Ben-Akiva M and Lerman SR (1979) Disaggregate travel and mobility-choice models and measures of accessibility *Behavioural Travel Modelling*. London: Routledge.

Berg N and Murdoch J (2008) Access to grocery stores in Dallas. In: *International Journal of Behavioural and Healthcare Research*. Geneva: Inderscience Publishers.

Black C, Moon G and Baird J (2014) Dietary inequalities: what is the evidence for the effect of the neighbourhood food environment? *Health & Place* 27: 229–242.

Bonanno A (2012) Food deserts: demand, supply, and economic theory. *Choice* 27(3): 1–4.

Brar K and Minaker LM (2021) Geographic reach and nutritional quality of foods available from mobile online food delivery service applications: novel opportunities for retail food environment surveillance. *BMC Public Health* 21(1): 458.

Caswell JA, Yaktine AL, Food and Nutrition Board, et al. (2013) Committee on examination of the adequacy of food resources and SNAP allotments. In: *Supplemental Nutrition Assistance Program: Examining the Evidence to Define Benefit Adequacy*. Washington, DC: National Academies Press (US). Available at: https://www.ncbi.nlm.nih.gov/books/NBK206919/ (accessed 9 October 2023).

Charreire H, Casey R, Salze P, et al. (2010) Measuring the food environment using geographical information systems: a methodological review. *Public Health Nutrition* 13(11): 1773–1785.

Chen X (2019) Enhancing the two-step floating catchment area model for community food access mapping: case of the supplemental nutrition assistance program. *The Professional Geographer* 71(4): 668–680.

Chen X and Jia P (2019) A comparative analysis of accessibility measures by the two-step floating catchment area (2SFCA) method. *International Journal of Geographical Information Science* 33(9): 1739–1758.

Chen BY, Yuan H, Li Q, et al. (2017) Measuring place-based accessibility under travel time uncertainty. *International Journal of Geographical Information Science* 31(4): 783–804.

Cheng J and Bertolini L (2013) Measuring urban job accessibility with distance decay, competition and diversity. *Journal of Transport Geography* 30: 100–109.

Chung C and Jr SLM (1999) Do the poor pay more for food? An analysis of grocery store availability and food price disparities. *Journal of Consumer Affairs* 33(2): 276–279.

Cicia G, Del Giudice T and Scarpa R (2002) 'Consumers' perception of quality in organic food: a random utility model under preference heterogeneity and choice correlation from rank-orderings. *British Food Journal* 104(3/4/5): 200–213.

Dai D and Wang F (2011) Geographic disparities in accessibility to food stores in southwest Mississippi. *Environment and Planning B: Planning and Design* 38(4): 659–677.

Delamater PL (2013) Spatial accessibility in suboptimally configured health care systems: a modified two-step floating catchment area (M2SFCA) metric. *Health & Place* 24: 30–43.

Desjardins E, Higgins CD and Páez A (2022) Examining equity in accessibility to bike share: a balanced floating catchment area approach. *Transportation Research Part D: Transport and Environment* 102: 103091.

Gordon C, Purciel-Hill M, Ghai NR, et al. (2011) Measuring food deserts in New York City's low-income neighborhoods. *Health & Place* 17(2): 696–700.

Higgs S and Thomas J (2016) Social influences on eating. *Current Opinion in Behavioral Sciences* 9: 1–6.

Jin H and Lu Y (2022) Multi-mode huff-based 2SFCA: examining geographical accessibility to food outlets in austin, Texas. *ISPRS International Journal of Geo-Information* 11(11): 579.

Kaiser ML, Carr JK and Fontanella S (2019) A tale of two food environments: differences in food availability and food shopping behaviors between food insecure and food secure households. *Journal of Hunger & Environmental Nutrition* 14(3): 297–317.

Kerr J, Frank L, Sallis JF, et al. (2012) Predictors of trips to food destinations. *International Journal of Behavioral Nutrition and Physical Activity* 9(1): 58.

Kolak M, Bradley M, Block DR, et al. (2018) Urban foodscape trends: disparities in healthy food access in Chicago, 2007–2014. *Health & Place* 52: 231–239.

Kuai X and Zhao Q (2017) Examining healthy food accessibility and disparity in Baton Rouge, Louisiana. *Annals of GIS* 23(2): 103–116.

Larson NI, Story MT and Nelson MC (2009) Neighborhood environments: disparities in access to healthy foods in the U.S. *American Journal of Preventive Medicine* 36(1): 74–81.

Li L and Wang D (2022) Do neighborhood food environments matter for eating through online-to-offline food delivery services? *Applied Geography* 138: 102620.

Liese AD, Weis KE, Pluto D, et al. (2007) Food store types, availability, and cost of foods in a rural environment. *Journal of the American Dietetic Association* 107(11): 1916–1923.

Lucan SC, Maroko AR, Seitchik JL, et al. (2018) Sources of foods that are ready-to-consume ('Grazing environments') versus requiring additional preparation ('Grocery environments'): implications for food-environment research and community health. *Journal of Community Health* 43(5): 886–895.

Lucan SC, Maroko AR, Patel AN, et al. (2020) Healthful and less-healthful foods and drinks from storefront and non-storefront businesses: implications for 'food deserts', 'food swamps' and food-source disparities. *Public Health Nutrition* 23(8): 1428–1439.

Luo J (2017) Analyzing spatial accessibility to foods in GIS: a case of Springfield, MO In: 2017 25th International Conference on Geoinformatics, Buffalo, NY, USA, 02-04 August 2017, 1–6.

Luo W and Wang F (2003) Measures of spatial accessibility to health care in a GIS environment: synthesis and a case study in the Chicago region. *Environment and Planning B: Planning and Design* 30(6): 865–884.

Martínez LM and Viegas JM (2013) A new approach to modelling distance-decay functions for accessibility assessment in transport studies. *Journal of Transport Geography* 26: 87–96.

Moore LV, Diez Roux AV and Brines S (2008) Comparing perception-based and geographic information system (GIS)-Based characterizations of the local food environment. *Journal of Urban Health* 85(2): 206–216.

Morland K, Wing S and Roux AD (2002) The contextual effect of the local food environment on residents' diets: the atherosclerosis risk in communities study. *American Journal of Public Health* 92(11): 1761–1768.

O'Hara S and Toussaint EC (2021) Food access in crisis: food security and COVID-19. *Ecological Economics* 180: 106859.

Páez A, Mercado RG, Farber S, et al. (2010) Relative accessibility deprivation indicators for urban settings: definitions and application to food deserts in montreal. *Urban Studies* 47(7): 1415–1438.

Paez A, Higgins CD and Vivona SF (2019) Demand and level of service inflation in Floating Catchment Area (FCA) methods. *PLoS One* 14(6): e0218773.

Pereira RHM, Schwanen T and Banister D (2017) Distributive justice and equity in transportation. *Transport Reviews* 37(2): 170–191.

Ploeg MV, Breneman V, Farrigan T, et al. (2009) *Access to Affordable and Nutritious Food: Measuring and Understanding Food Deserts and Their Consequences*. Collingdale, PA: Diane Publishing, 160.

Powell LM, Slater S, Mirtcheva D, et al. (2007) Food store availability and neighborhood characteristics in the United States. *Preventive Medicine* 44(3): 189–195.

Racine EF, Delmelle E, Major E, et al. (2018) Accessibility landscapes of supplemental nutrition assistance program-authorized stores. *Journal of the Academy of Nutrition and Dietetics* 118(5): 836–848.

Riehle H, Grindy B, Lorenzini B, et al. (2021) *2021 State of the restaurant industry.* 1 january. National restaurant association. Available at: https://go.restaurant.org/rs/078-ZLA-461/images/2021-State-of-the-Restaurant-Industry.pdf (accessed 8 March 2024).

Rodrigue J-P, Comtois C and Slack B (2017) *The Geography of Transport Systems*. 4th edition. London: Routledge.

Schlosser E (2012) *Fast Food Nation: The Dark Side of the All-American Meal*. Boston, MA: Houghton Mifflin Harcourt.

Sharkey JR (2009) Measuring potential access to food stores and food-service places in rural areas in the U.S. *American Journal of Preventive Medicine* 36(4, Supplement): S151–S155.

Silva C and Altieri M (2022) Is regional accessibility undermining local accessibility? *Journal of Transport Geography* 101: 103336.

U.S. Department of Agriculture, Food and Nutrition Service (2022) *USDA to Invest in Expanding SNAP Online Shopping | Food and Nutrition Service*. Washington, DC: U.S. Department of Agriculture.

US FOODS (2019) Study reveals how people use food delivery apps. Available at: https://www.usfoods.com/our-services/business-trends/2019-food-delivery-statistics.html (accessed 15 July 2022).

USDA (2022) Usda ers - documentation. Available at: https://www.ers.usda.gov/data-products/food-access-research-atlas/documentation (accessed 12 July 2022).

Wan N, Zou B and Sternberg T (2012) A three-step floating catchment area method for analyzing spatial access to health services. *International Journal of Geographical Information Science* 26(6): 1073–1089.

Weibull JW (1976) An axiomatic approach to the measurement of accessibility. *Regional Science and Urban Economics* 6(4): 357–379.

Widener MJ (2018) Spatial access to food: retiring the food desert metaphor. *Physiology & Behavior* 193(Pt B): 257–260.

Yang Y and Diez-Roux AV (2012) Walking distance by trip purpose and population subgroups. *American Journal of Preventive Medicine* 43(1): 11–19.

Yeh AG-O and Li X (2001) Measurement and Monitoring of Urban Sprawl in a Rapidly Growing Region Using Entropy, *Photogrammetric Engineering & Remote Sensing* 67(1): 83–90.

Grace Jia received the B.S. degree from the University of California at Los Angeles, Los Angeles, CA, USA, in 2019, and the M.S. degree from the University of California at Berkeley, Berkeley, CA, in 2020. She is currently pursuing the Ph.D. degree in transportation engineering with the Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, USA. Her current research interests include promoting food access, adaptation of small and medium-sized businesses in face of disruptions through stochastic optimization, and analyzing travel behavior changes induced by telecommuting.

Ram Pendyala is a professor in and the director of the School of Sustainable Engineering and the Built Environment at Arizona State University. A globally renowned expert in travel behavior, transportation systems modeling, and urban mobility, he has authored over 200 peer-reviewed publications and led numerous high-impact research projects funded by the National Science Foundation, U.S. Department of Transportation, and state and local governments to bridge

academic research and planning practice. Dr. Pendyala has held prominent leadership roles in the Transportation Research Board and the International Association for Travel Behaviour Research.

Cynthia Chen is a professor in the Department of Civil and Environmental Engineering at the University of Washington at the University of Washington (UW), where she directs THINK lab (https://sites.uw.edu/thinklab). She is an internationally renowned researcher in human mobility analysis with small and big data, transportation systems modeling and urban and community resilience. Her research has been supported by many federal agencies including the National Science Foundation, National Institute of Health, US Department of Transportation, and US Department of Energy. She has served many leadership roles including program director at the National Science Foundation, department chair at UW and associate director at both Tier-1 and national University Transportation Centers.