Spatial Optimization to Support Mobile Food Market Site Selection: A Case Study in the City of Phoenix

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Arts

Approved November 2022 by the
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ARIZONA STATE UNIVERSITY

December 2022

ABSTRACT

Equity concerning food access has gained a lot of attention in the past decades. This problem can be seen in the dearth of supermarkets offering healthy food at reasonable prices in disadvantaged neighborhoods. Numerous studies show that the disparity in the distribution of food outlets has resulted in disparities in health outcomes. To mitigate the issue, various intervention strategies have been proposed and implemented, including introducing new supermarkets, mobile food markets, community gardens, and city farms in these neighborhoods. Among these strategies, mobile food markets have gained the attention of practitioners and policymakers for their low costs and service flexibility. Challenges remain in identifying the sites for best serving the people in need given limited resources. In this study, a new spatial optimization model is proposed to determine the best locations for mobile food markets in the City of Phoenix. The new model aims to cover the largest number of people with food access challenges while minimizing transportation costs. Compared with the existing mobile market sites, the sites provided by the new model can increase the coverage of low-food access residents with a shorter transportation distance. The new model has also been applied to help expand the service provider of the existing mobile food markets. In addition to mobile food markets, the method provided in this study can be extended to support the planning of other food outlets and food assistance services.

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CHAPTER 1

INTRODUCTION

One of the most significant social issues has been ensuring enough access to nutritious meals. Residents' diet-related health outcomes are negatively associated with access to healthy food. For example, research has shown that a lack of access to food is positively connected with several health outcomes, including obesity, diabetes, heart disease, and cardiovascular illness (Bao et al., 2020; Chrisinger et al., 2016; Elizabeth et al., 2015). Disparities in the availability of healthy food have long been recognized. Low-income and minority neighborhoods typically have fewer full-service markets that sell nutritious, fresh foods like vegetables and fruits than high-income and non-minority neighborhoods. (Falkner et al., 2014; Kuai and Zhao, 2017; Niedzielski, 2021). The early description of the food access equity issue dates back to studies in the1980s and early 1990s, where areas with low-income communities were found to have difficulty accessing fresh food. These areas were called food deserts (Bao et al., 2020; Powell et al., 2007; Tong et al., 2016). In the United States, food deserts have become an important problem. In recent years, the number of people facing the low food access problem has increased. According to the Economic Research Service (ERS) of the USDA (United States Department of Agriculture), about 30.8 million people lived in low food access neighborhoods in 2021 (USDA ATLAS 2021), an increase of 7.3 million people compared to the 2015 statistics (USDA 2015b)

Various approaches have been adopted to help address the low food access problem. For instance, establishing supermarkets and grocery stores in places with limited access to fresh produce has proven to be a key approach. The building of new supermarkets in communities with limited access to fresh food has been encouraged by local and national initiatives including the Healthy Food Financing Initiative (HFFI), the Pennsylvania Fresh Food Financing Initiative (PFFFI), and the "Let's Move" campaign (Kraak et al., 2011). However, establishing a new supermarket in a low-food access area can be challenging considering the difficulty in identifying the space and the cost of establishing the market. As a result, developing a mobile food market system has become an alternative solution to improving healthy food access in low-food access areas. Compared to supermarkets, mobile food markets are less expensive and more flexible in terms of establishing service sites. For example, mobile food markets can provide service in a region by visiting different sites at different periods. However, we are often constrained by limited resources in providing mobile food market services (e.g., staff time, and transportation costs). How to use the limited resources to maximally improve food access in low-food-access neighborhoods remains a challenging question.

This study will develop a new spatial optimization model to support mobile food market service provision. While a few studies have examined identifying the best locations for siting different types of food outlets, very little research has considered specific site selection and route planning involved in mobile food market service provision. The new model takes into account transportation costs as a significant component in choosing the best mobile market service sites while maximizing the overall coverage of low-food access neighborhoods with relatively short travel distances. The model is then applied to the city of Phoenix to support mobile food market service provision. The article is organized as follows. The literature review of pertinent research is provided in the next section, including the benefits of mobile food markets and current models that have been developed to conduct location selection for mobile food markets. The method section introduces the study area and the new spatial optimization model. The model is applied to the city of Phoenix, with results reported in the "Results" section. The "Discussion" section addresses the study's ramifications, points out its limits and suggests further research directions.

CHAPTER 2

BACKGROUND

2.1 Food Access

Food is an essential component of human well-being. Ensuring a stable, equitable food environment has been an important topic in food studies. In the past decades, the food environment has changed dramatically. In particular, the concept of "food desert" was introduced to refer to areas with limited or inequitable access to food outlets that provide fresh, inexpensive, and healthy food. (Beaulac et al., 2009; Cummins and Macintyre 1999; Gallagher 2006; 2007a; Petticrew et al., 2002; Roorda et al., 2010). Neighborhoods with limited access to food draw attention to the presence of social resource distribution disparities in society that span income and race. (Falkner et al., 2014; Kuai and Zhao, 2017; Niedzielski 2021; Smoyer-Tomic et al., 2006; Widener et al., 2013).

In the last few decades, studies have focused on understanding the mechanisms and factors that influence food deserts and then identifying scientific and long-term solutions to mitigating the negative effects (White et al., 2007). However, because the problem of food access is connected to several disciplines, including geography, transportation, and public health, among others, this has led to a wide range of opinions on how to define low food access in early studies, making it also challenging to identify low food access areas. (Paez et al., 2010; Sparks, 2009; Wrigley et al.,2002). In addition, the lack of effective methods to analyze data and visualize results has also led to the lack of in-depth research on food access. With the recent advances in visualization and spatial data analytics, numerous techniques have been employed to research the issue of limited food access, including spatial statistics and geographic information systems (GIS) (Richardson et, al.,2013).

Meanwhile, researchers, government agencies, and non-profit organizations have increasingly paid attention to solving the low food access problem with geographic thinking and methods (Widener et al., 2018). The use of spatial analytic methods and spatial optimization models to identify food distribution sites so that these services can more precisely and effectively reach persons with limited food access is a crucial field of research. In the remainder of this section, we will first review in detail the mechanisms and factors that have influenced the formation of low-food access areas. Additionally, it discusses the detrimental impacts of food deserts on people and society as well as the significance of solving the issue. Then, we review the shortcomings of existing intervention strategies and the advantages of mobile food markets in solving the low food access problem. Finally, we outline the goals of this study's research and show how spatial optimization models can be applied to support the site selection for mobile food markets to help address the low food access problem.

Several studies have looked at the historical causes of limited food access. During the last century's urbanization movement, capital became more concentrated, and grocery sizes steadily became larger with the emergence of supermarkets in urban edge regions. (Westlake, 1993; Wrigley et al.1988). This trend has forced small traditional food stores in urban centers to go out of business when competing with supermarkets (Alwitt and Donley, 1997; Crowe et al., 2018; Diesenhouse, 1993). As these supermarkets offer high quality, diverse products are often located in urban fringe areas, for those who live in the city center, long-distance travel is needed for accessing supermarkets on the edges of the city. This makes it difficult for those who live in the city but do not have enough mobility to buy fresh, high-quality food, such as fruits and vegetables. Gradually, the number of such areas in the city where healthy food is not easily accessible is increasing, and to describe these locations, the notion of "food deserts" has been established. According to studies, people who live in limited food access environments frequently experience negative health effects, which is a problem that is becoming more and more prevalent in the United States. This is partially a result of these people's limited access to nutritious, fresh food. Another issue is that low-food access neighborhoods with an absence of conventional grocery stores or supermarkets tend to have more fast-food restaurants (Hendrickson et al., 2006; Walker, 2010). Poor health outcomes, such as obesity, high blood pressure, cancer, heart disease, and other illnesses, have been linked to little access to healthy food and high exposure to fast-food intake in these neighborhoods. (Adams et al., 2003; Diez 2001; Bao et al., 2020). For instance, Howlett (2015) noted that poor food access leads to higher rates of childhood obesity. In addition to directly causing illness in children, these health issues can even affect their health in adulthood (Howlett et al., 2014; Lopez, 2007; Puhl and Heuer 2009; Roehling 2002; Schafft et al., 2009). Furthermore, lacking food access not only makes people more susceptible to diet-related diseases but also may reduce the effectiveness of treating diseases (Fong et al., 2020).

In addition to the impact on individuals, some scholars have pointed out that some disadvantaged groups are associated with poor food accessibility. Income has a strong correlation with the issue of food access, according to studies. Compared to high-income areas, low-income regions have fewer stores. (Alwitt and Donley 1997; Miller, 1994; Ohri-Vachaspati et al., 2019, Weinberg, 1995). This has led to the fact that most low-food access neighborhoods tend to be low-income communities as well. In addition to the direct difference in the number of supermarkets, according to research by Hendrickson et al. (2006), locations with poor food access had higher food costs and lower-quality, usually inedible, food compared to more affluent ones. Additionally, the variety of food available in stores in underdeveloped regions is lower than in wealthier and easier-to-access places (Hendrickson et al. 2006). Due to the inadequate food environment in these places, residents of communities with restricted food availability must go further to obtain wholesome food. Only residents who own a car or can pay for public transportation are access to affordable fresh food (Guy et al., 2004). Low-income people in low-food access communities are more likely among those who cannot afford a car. For instance, according to Zenk et al. (2005), 28% of residents of the poorest areas lacked a car. The food alternatives available to those who cannot afford the transportation fees to access supermarkets outside of their immediate area are therefore limited (Rose and Richards, 2004).

Meanwhile, minority and other disadvantaged neighborhoods have been found to have poor food access. Larson et al. (2009) concluded that there were disparities in food availability that were connected to racial and ethnic residential segregation after evaluating 54 research that examined neighborhood inequalities in food access in the US. There were differences in the number of supermarkets in the white and black neighborhoods. Block and Kouba's research (2006), compared to Larson's, yielded more conclusive conclusions. They discovered that there were fewer supermarkets and less availability of food in Chicago's predominately black neighborhoods. While this was happening, food in stores in predominately black communities' cost about the same as it did in supermarkets but was of lower quality (Block and Kouba 2006). According to Powell et al. (2007), Black neighborhoods in the US only had 52% as many chain stores as white ones (Powell et al.,2007). Even after accounting for pertinent covariables, such as neighborhood income, these discrepancies persisted. In a related study, Zenk et al. (2005) discovered that in Detroit, residents in the black community need to travel additional 1.1 miles to their closest grocery stores when compared with those in the white community.

2.2 Intervention Strategies

In the past few decades, various strategies have been developed to mitigate food access disparities. One important approach has focused on the introduction of new supermarkets in poor food-access neighborhoods. In addition to helping to increase food access in disadvantaged communities, establishing supermarkets may encourage community economic development by providing employment opportunities, generating tax revenues, and boosting foot traffic to support other shops (Cummins et al., 2014). Several programs have been established to encourage the development of supermarkets in underserved regions, including the Healthy Food Financing Initiative (HFFI), the "Let's Move" program, and the Pennsylvania Fresh Food Financing Initiative (PFFFI) (Kraak et al., 2011). Through these policies, the government provides funding to the private sector to construct and maintain the facilities required for community food supply (Widdus et al., 2001). In certain places, such a method has been successful, with instances in Pittsburgh, Boston, and New York (Pothukuchi, 2000). In conclusion, these strategies can significantly improve low food access difficulties by luring and encouraging stores to areas with low economic standing (Walker et al., 2010).

The effectiveness and efficiency of opening new supermarkets in areas with limited access to food, however, has been questioned in certain research. First, building a supermarket is costly and requires a large space, which might not be feasible in many areas (Roux, 2011; Dubowitz, 2015; Richardson, 2017). Some studies pointed out that the introduction of new supermarkets into food deserts will sometimes have undesirable consequences. For example, the increased competition brought about by a newly introduced supermarket may cause the closure of some local food stores and a decrease in food availability in local stores (Leibtag, 2006; Richardson, 2017), which will lead to a negative impact on the food environment in these communities in the long run. Meanwhile, considering that some minority neighborhoods often rely on local stores or ethnic stores for accessing healthy food (Joassart-Marcelli, 2017), the closure of these markets due to the competition caused by the introduction of new supermarkets can be detrimental to these communities. In some cases, when new supermarkets do not make enough profits, they may close given that most of the low-food access areas are also low-income areas with relatively low purchasing power. As a result, the closure of these intervention supermarkets can lead to a decrease in food accessibility with a condition even worse than before the intervention (Peters, 2017; Isidore, 2017; Flint, et al., 2012; Chrisinger, 2015). Therefore, the blind introduction of supermarkets may not only fail to solve the existing problem but also worsen the food access situation in poor food-access neighborhoods.

In the past few decades, mobile food markets have drawn a lot of interest as a solution to the drawbacks of the supermarket idea. Buses, trucks, or semi-trailers that are outfitted with retailing equipment for refrigeration, cash registers, credit cards, and electronic transfers are the primary vehicles used for mobile markets. Since they can switch locations and operating times to cater to a wider spectrum of potential clients, mobile food markets are more adaptable. The goal of many mobile food markets is to provide low-food-access populations with inexpensive, high-quality, and healthy food. One of the earliest mobile markets, People's Grocery's mobile market in Oakland, California, was founded in 2002 due to a lack of funding for a brick-and-mortar establishment (Community Commons, 2012). In comparison with the supermarket intervention strategy, mobile markets are found to be more cost-effective in a low food-access neighborhood (Zepeda, et al., 2014). Some mobile markets also provide affordable rates and a variety of payment options, including cash, debit/credit cards, and SNAP/EBT. The Twin Cities Mobile Market, for instance, participates in the state-funded and legally mandated Market Bucks program (17.1017 Good Food Access Program: 2016, p. 1017 Minnesota Statutes, 2016), which offers SNAP customers a match (up to $10) for a future purchase of fruit and vegetables, to increase affordability. Some markets provide nutrition education programs and cooking demonstrations and events to help establish the notion of healthier dietary and healthy eating habits (Gary-Webb, 2018).

Existing studies have shown the effectiveness of establishing the mobile food market system in low-food access neighborhoods in helping eliminate spatial barriers to food access, as well as non-spatial barriers through food concessions and promotional activities (Zepeda et al., 2015; Widener et al., 2012). As an example, the study from Gans et al. (2018) studied the nutrition intake of fifteen subsidized housing sites, about 1,597 housing site residents in Providence County, Rhode Island for 12 months. The findings revealed that consumption of fruits and vegetables increased by up to half to one serving per day in regions where mobile food markets were introduced (Gans et al., 2018; Joassart-Marcelli 2017; Zepeda et al., 2015). These outcomes are in line with smaller-scale research on mobile markets, which showed increases in access, purchases, and food consumption after the introduction of mobile food markets (AbuSabha et al., 2011; Gorham et al., 2015; Horning et al., 2020; Hsiao et al., 2018; Leone et al., 2018; Tester, et al., 2012).

2.3 Spatial Optimization Models to Support Mobile Food Market Studies

As most of the mobile food market programs are funded by the local government or non-profit organizations, they often face a budget limit when setting up such markets. As a result, it's critical to provide a low-access population with food while conserving costs by selecting marketplaces and corresponding transportation routes wisely. Currently, many of these markets' sites are determined by ad hoc trial and error approaches. A more scientific method of site selection is necessary in order to increase service effectiveness and reduce operating costs.

Recently, Mendez et al., (2022) conducted a suitability analysis to identify potential areas for the Green Grocer mobile food market (Mendez and Dara,2020). However, this study only determined the areas suitable for mobile food markets but did not give specific routes and the associated market sites for providing the service. For a specific planning objective, the spatial optimization approach has been extensively utilized to specify the ideal spatial arrangement or allocation of entities or resources (Tong and Murray 2012). Spatial optimization has been used to support a range of real-world applications including the telecommunication network design (H. Kim and O'Kelly 2009); bike-sharing station placement (Park, 2017), and emergency facilities siting (Maghfiroh, 2018). Widener et al., (2012) developed a spatial optimization model to support the mobile food market site selection. The model described by Widener et al., (2012) is a variant of the capacitated-median problem.

In Widener et al., (2012), the model aims to identify market sites so that the overall travel distance between residents in need of the service and the closest market available is minimal while considering the capacity of each mobile market. The model provides strategic locations for mobile food markets without considering the actual routing of mobile food markets and the associated service availability (Widener et al., 2012). Considering the relatively small service areas of mobile food markets when compared with supermarkets, residents who live far away from a mobile market site are less likely to be served. Therefore, we use the coverage notion in the new model to ensure suitable service. To identify which sites are the most effective and which sites should be preferred, this study aims to create a new model that maximizes coverage of the potential population. At the same time, this study adopts a practical application perspective by choosing sites and creating several effective routes that can be run to provide a workable solution to the food accessibility problem, unlike prior studies that only highlight the areas where mobile food markets should be deployed and reduce the distance from mobile food markets to geographic units.

To conclude, this project will offer a fresh spatial optimization model to enhance the functioning of the mobile food market system and assist in resolving the problem of restricted access to food. The model will aim to maximize the service coverage of potential customers of the mobile food markets while considering the cost associated with the travel of mobile food markets. We apply the new model to site mobile food markets in the city of Phoenix. The findings will help improve the efficiency and effectiveness of the mobile food markets in the city in order to address the low food access issue in the city and provide recommendations for future service planning. In the study, we also identify the low food access neighborhoods, which provides insights into areas facing healthy food access challenges.

CHAPTER 3

MATERIALS & METHODS

3.1 The Study Area

Phoenix is Arizona's capital and largest city, with a population of 1,633,017. Additionally, it is the most populated state capital in America and the fifth most populous city in the country. According to the USDA, Phoenix contains 43 food deserts with a combined population of 358,946, or 21.9% of the city's total population (USDA Food Access Research Atlas 2019). (Also see Figure 1). Children make up 22% of the population living in a food desert. Not just those who live in food deserts may have had access problems; an extra 866,256 persons, or 53% of Phoenix's total population, may have struggled to find nutritious food (USDA Food Access Research Atlas 2019). In Phoenix, a range of efforts have been made to help eliminate low-food access areas. To boost local citizens' access to fresh, healthful food, these initiatives have concentrated on building community gardens, urban farms, and farmers' markets. To better coordinate future efforts, the 2025 Phoenix Food Action Plan has also been proposed by the city council to develop a resilient food system and promote healthy food for all residents.

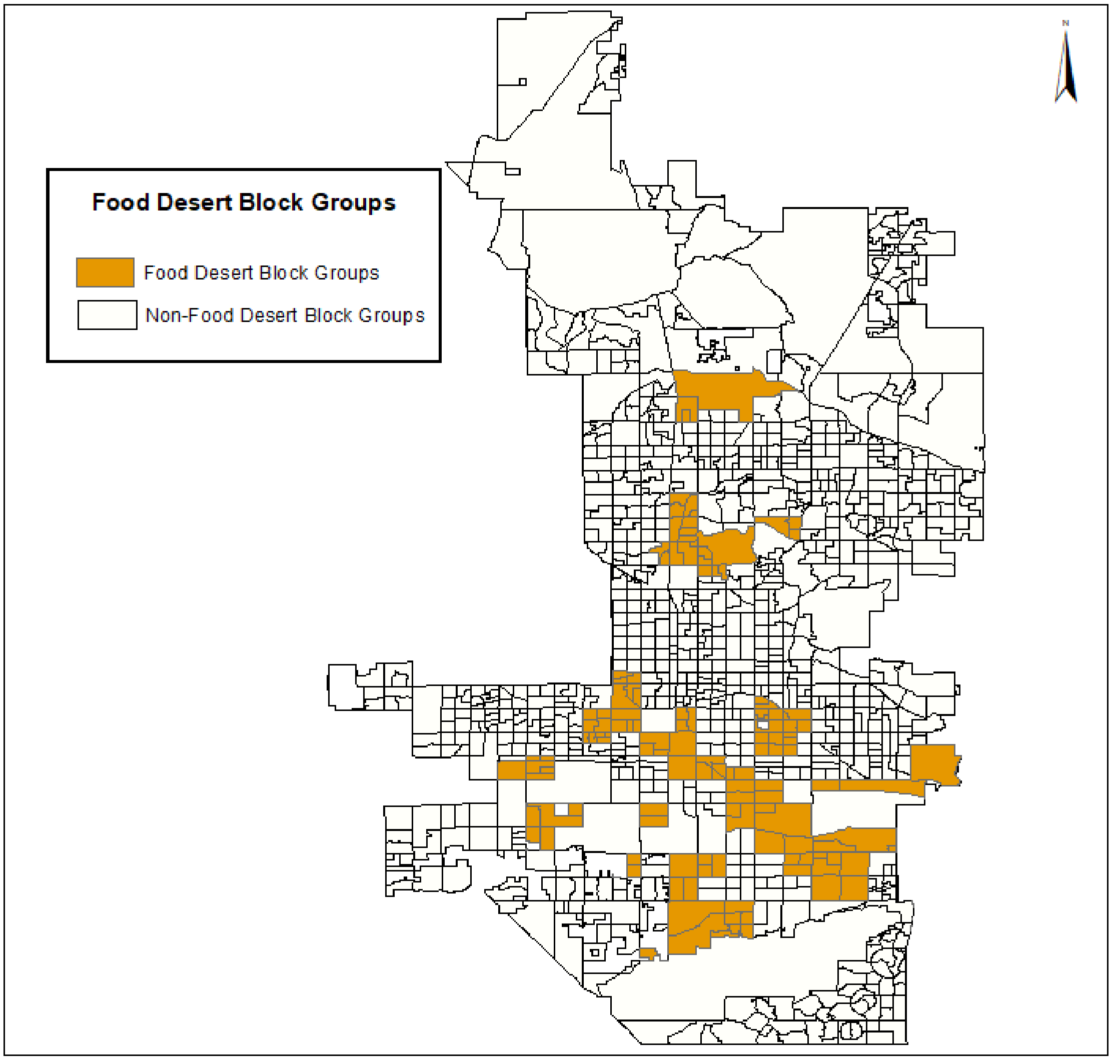

Figure 1. The Distribution of Food Deserts in Phoenix

Among many efforts to improve healthy food access in Phoenix， Farm Express has been a successful model. Farm Express runs a fleet of mobile food markets to provide high-quality, moderately cost food goods in communities with little or no access to nutritious food. Currently Farm Express has two mobile food markets in service. with each market operating from 9:00 am to 4:00 pm and visiting three to four sites a day and three to four days a week. Health clinics, elder centers, housing developments, and other community locations are among the service locations. These service sites have been selected through ad hoc trial and error approaches. This study will focus on developing a systematic modeling approach to identify the set of service sites to maximize the coverage of potential customers while considering the transportation cost of mobile food markets. In doing so, we can improve the efficiency of the service provision as well as better address the food access issue in the region.

3.2 Data

To collect socioeconomic and demographic information at the block group level, utilize the 2019 American Community Survey 5-Year Estimates. This study heavily depends on block group level data because these are the smallest census units with complete socio-demographic information. The social contact patterns that change with the development of street and road networks can be adequately captured using block group-based data (Kuai and Zhao, 2017). In all, 1,633,017 people are living in 1,039 different block groups in the research region. Along with demographic information, household and automobile ownership statistics are also utilized.

The information about food stores was compiled using data from Reference U.S.A. (http://www.referenceusa.com/). Supermarket and grocery store's selection is based on the USDA's definition of the "food store environment." Assuming that grocery stores, supermarkets, specialty food stores, and farmer's markets are considered to be healthy food outlets, the research region contains a total of 425 food shops.

The road network data set was acquired from the census' tiger file.

3.3 Method

3.3.1 Constructing an Inaccessibility Measure

Finding those who need better access to fresh food is the first stage in the study process. These people will serve as the demand for the mobile food markets. In this study, we expand on the idea of food deserts and create a composite score by adding inhabitants' mobility to the USDA's definitional requirements for food deserts. Low income and limited access are the two criteria used by the USDA to identify food deserts. Particularly, the proximity of a supermarket to a neighborhood—1 mile for urban regions and 10 miles for rural areas—is used to determine how accessible it is (USDA 2019). However, simply relying upon the distance of markets from a neighborhood is limited in understanding residents' ability to access food. Many scholars have pointed out that the issue of food access is also related to people's mobility. For instance, having a car and having access to public transit might influence a person's capacity to get food (Caraher et al., 1998; Cummins and Macintyre, 2002; Lee and Lim 2009). Vehicle ownership information has also been incorporated in developing inaccessibility measures to support food service provision planning (Widener et al., 2012). In this study, we incorporate spatial proximity, socioeconomic status, and access to personal vehicle into the identification of neighborhoods for mobile food market service.

The inaccessibility measure index E_k is developed to estimate the level of food inaccessibility in block group k. In particular, E_k calculated as follows:

$$E_k = p_k * v_k * d_k \tag{1}$$

Where:

k – is index of block groups (the entire set is denoted K);

E_k – The inaccessibility measure index for block group k;

p_k – {1,0}, where $p_k = 1$ if block group k is a low-income block group and 0 otherwise;

v_k – The number of households with no access to personal vehicles in block group k;

d_k – The network distance between block group k and the nearest grocery store;

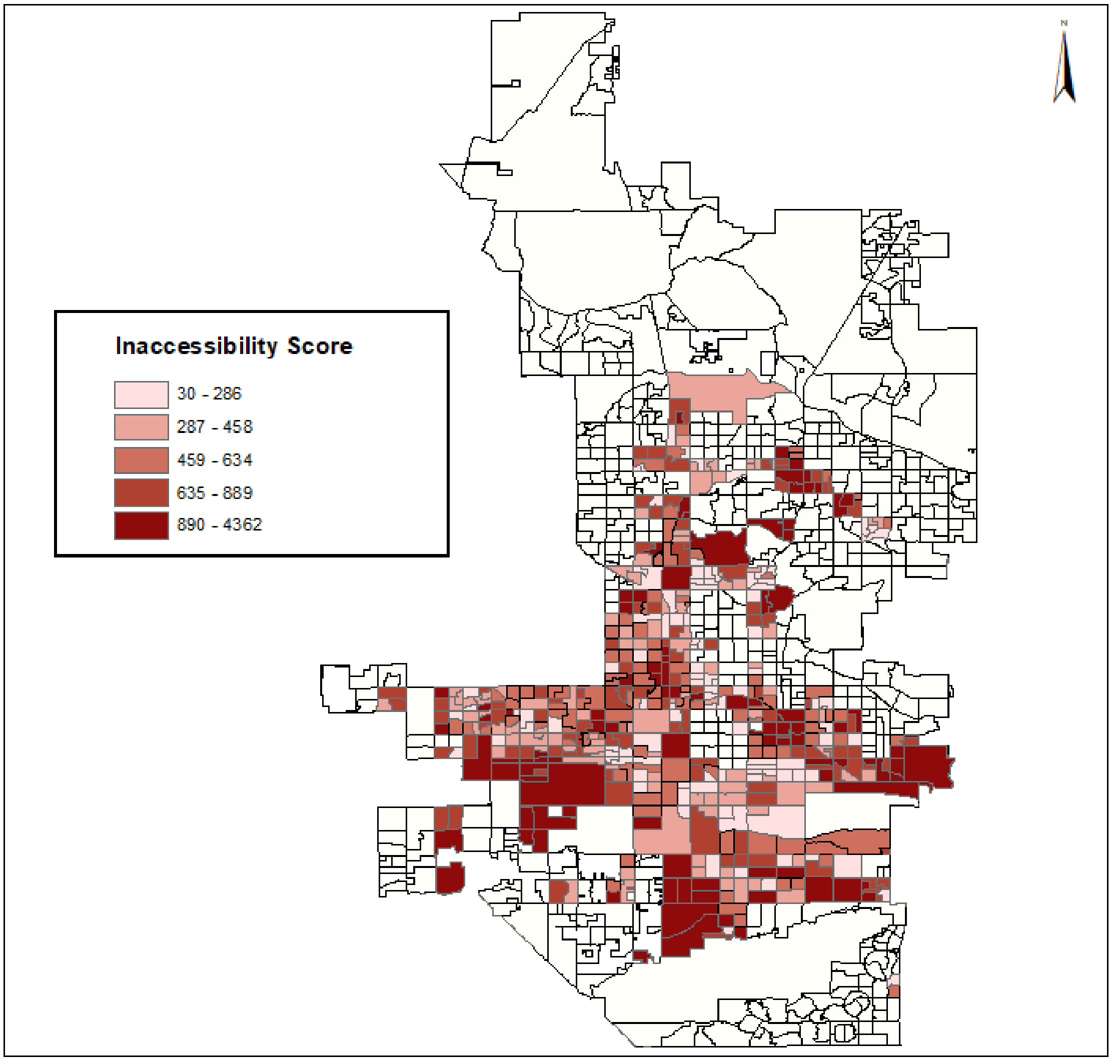

Figure 2. The Distribution of the Food Inaccessibility Score E_k in Phoenix

The distribution of the food inaccessibility levels across Phoenix is depicted in Figure 2. There are a total of 525 low-income block groups in the research region. The change of the color shade represents the change of the inaccessibility value of the block group: the darker color corresponds to areas with more difficulty in obtaining fresh food.

3.3.2 Developing a Spatial Optimization Model

In order to establish the ideal siting strategy for the mobile market network, we develop a novel spatial optimization model. The model especially aims to maximize service coverage while accounting for the whole travel expense of mobile food markets for individuals who need improved access to nutritious food. The mobile food market's path is optimized by the model such that it leaves from the warehouse, travels to neighborhoods where residents with limited access to nutritious food may find them, and then returns to the depot. We construct the new model as follows:

$$Maximize \quad \sum_{k} E_k \, Y_k \qquad (2)$$

Subject to:

$$Y_k \leq \sum_{j \in S_k} X_j \;\; for\ all\ k \in K, \qquad (3)$$

$$\sum_j X_j = t \qquad (4)$$

$$\sum_{j \in T_p} Z_{pj} = 1 \;\; for\ origin\ node\ p, \qquad (5)$$

$$\sum_{j \in T_q} Z_{jq} = 1 \quad for\ destination\ node\ q, \qquad (6)$$

$$\sum_{t \in T_k} Z_{tk} - \sum_{r \in T_k} Z_{kr} = 0\ for\ all\ k \in J\ where\ k \neq p, q, \qquad (7)$$

$$\sum_{i} \sum_{j \in T_i} d_{ij} Z_{ij} \leq D \qquad (8)$$

$$\sum_{i \in V} \sum_{j \in T_i \cap V} Z_{ij} \leq |V| - 1\ for\ all\ V \subset J, 2 \leq |V| \leq n \qquad (9)$$

$$\sum_{i \in T_j} Z_{ij} \geq X_j\ for\ all\ j, \qquad (10)$$

$$X_j = 0, 1\ for\ all\ j \in J, \qquad (11)$$

$$Y_k = 0, 1\ for\ all\ k \in K, \qquad (12)$$

$$Z_{ij} = 0, 1 for\ all\ i \in J, for\ all\ j \in J\ , for\ all\ (i, j) \in A \qquad (13)$$

Where:

k: index of demand nodes (the entire set denoted K);

i,j,r: index of candidate service sites(i.e., mobile food market stop) (the entire sets denoted I and J, R respectively);

s: the coverage range/standard used to determine whether a demand node is covered by a service site or not;

p: the origin node;

q: the destination node;

A: {(i,j)|nodes i and j are connected by an arc that can be traversed from i to j} ;

T_j: the set of nodes that are directly connected to node j;

$S_k = \{j | d_{jk} \leq s\}$ gives the set of facility sites that can provide coverage to demand at k;

E_k: the inaccessibility at block group k;

D: the maximum travel distance of a mobile food market;

V: a subset of all candidate service sites;

$|V|$: the cardinality of set V;

t: the total number of stops;

Y_k : a binary variable determining whether demand k is covered by a market site, Y_k=1 the demand k is covered by a market site, else Y_k=0

d_{ij} : the shortest distance between stops *i* to the stop *j*;

Z_{ij} : a binary variable whither the arc Z_{ij} is selected as the route of mobile food market

$$Z_{ij} \begin{cases} 1, if\ path\ uses\ traverses\ arc\ (i,j) from\ i\ to\ j \\ 0, otherwise \end{cases}$$

X_j : a binary variable determining whether the stop j is selected, if it is X_j=1, else X_j=0

The objective function (2) seeks to maximize the coverage of the sited mobile food markets. Constraints (3) state that for demand *k* to be covered there is at least one stop within the service range. Constraint (4) specifies the total number of stops. Constraint (5) ensures there is a flow out of the origin node. Constraint (6) ensure there is flow into the end node. Constraints (7) ensure flow conservation so that the nodes selected are connected on the route. Constraint (8) specifies the total travel distance of a mobile food market route. Constraints (9) are subtour elimination constraints prohibiting the formation of subtours considering that a subtour consists of $|V|$ vertices will consist of at least $|V|$ arcs. Constraints (10) build the relationship between two decision variables Z_{ij} and X_j, ensure that when a new site is selected there is at least one connected arc that will be selected. Constraints (11)-(13) state that decision variables X_j, Y_k and Z_{ij} are binary.

In total, 198 sites are selected as candidate sites for the mobile markets. These sites are mainly public facilities, including schools, parks, libraries, senior centers, etc. These types of sites were selected through discussion with farm express staff. At the demand sites, a total of 525 block groups were considered, of which 130 were food desert block groups (also see Figure 2).

Based on the farm express service routes in August 2021, each route visits 3-4 stations per day, and had an overall travel distance ranging between 30-50 miles with an average distance of 34.78 miles. In the study, we set D = 40 miles and 30 miles in the model to provide operators with the choice of different operation routes and the associated stations. By setting the upper limit of the running distance shorter than the actual running, model will reduce the total distance of the run. The model is tested with two scenarios: (1) while one examines the maximal coverage that can be achieved when ignoring existing service sites, and (2) the other accounts for the service provided by existing sites to provide the best strategy for future network expansion. The result based on scenario 2 is also compared with the existing sites. CPLEX was used for solving the problem instances. The results were then display in ArcGIS.

CHAPTER 4

RESULTS

The existing routes are showed in Table 1. The blue triangles in the following figures are the depot, which serves the starting and ending points of each route. The black polygons are the existing 32 stations as of August 2021. All our subsequent analyses of the existed and new sites are also based on the existing sites as of August 2021.

	Travel Distance (miles)	Food Desert Population	E_k
Farm Express Route 1	31.3	7,150	21,752
Farm Express Route 2	39.3	6,193	26,844
Farm Express Route 3	41.2	10,523	27,105
Farm Express Route 4	39.5	13,193	25,101
Farm Express Route Average	34.8	8,094	25,974

Table 1. The Details of Existing Routes

Using the food inaccessibility measure E_k, we examined four problem instances/scenarios (also see Table 2). In these problem instances, there are a total of 525 block groups to be considered as demand, and 178 candidate sites that can possibly provide service to these areas. Model results are summarized in Table 3 with the associated routes mapped in Figures 3-6

	Accounting for the existing sites	Travel Distance (miles)	Demand
Scenario 1	No	30	E_k
Scenario 2	No	40	
Scenario 3	Yes	30	
Scenario 4	Yes	40	

Table 2. Scenarios 1 - 4 based on E_k

	Stops	Travel Distance (miles)	E_k
Scenario 1/Route 1	VIRGINIA PARK KID STREET PARK LADMO PARK LITTLE CANYON PARK	23.5	35,834
Scenario 2/Route 2	VIRGINIA PARK KID STREET PARK LITTLE CANYON PARK COUNTRY CLUB OVAL	32.2	39,874
Scenario 3/ Route 3	ROESLEY PARK LITTLE CANYON PARK CAVE CREEK PARK PERRY PARK	29.9	25,361
Scenario 4/ Route 4	SHERMAN PARKWAY ROESLEY PARK LITTLE CANYON PARK PERRY PARK	39.1	27,068

Table 3. Model Solutions Based on Scenarios 1-4

Results based on Scenarios 1 and 2 do ignore existing stations. Model results show that on average E_k has increased 45% with the average route distance decreased by 24%. When comparing between route 1 and 2 with existing routes as shown in Table 1, there is huge space for promotion of efficiency of existing routes planning strategy. The new routes tend to reduce operating expenses by having the shorter travel distances and enhancing the efficiency by covering larger E_k at same time.

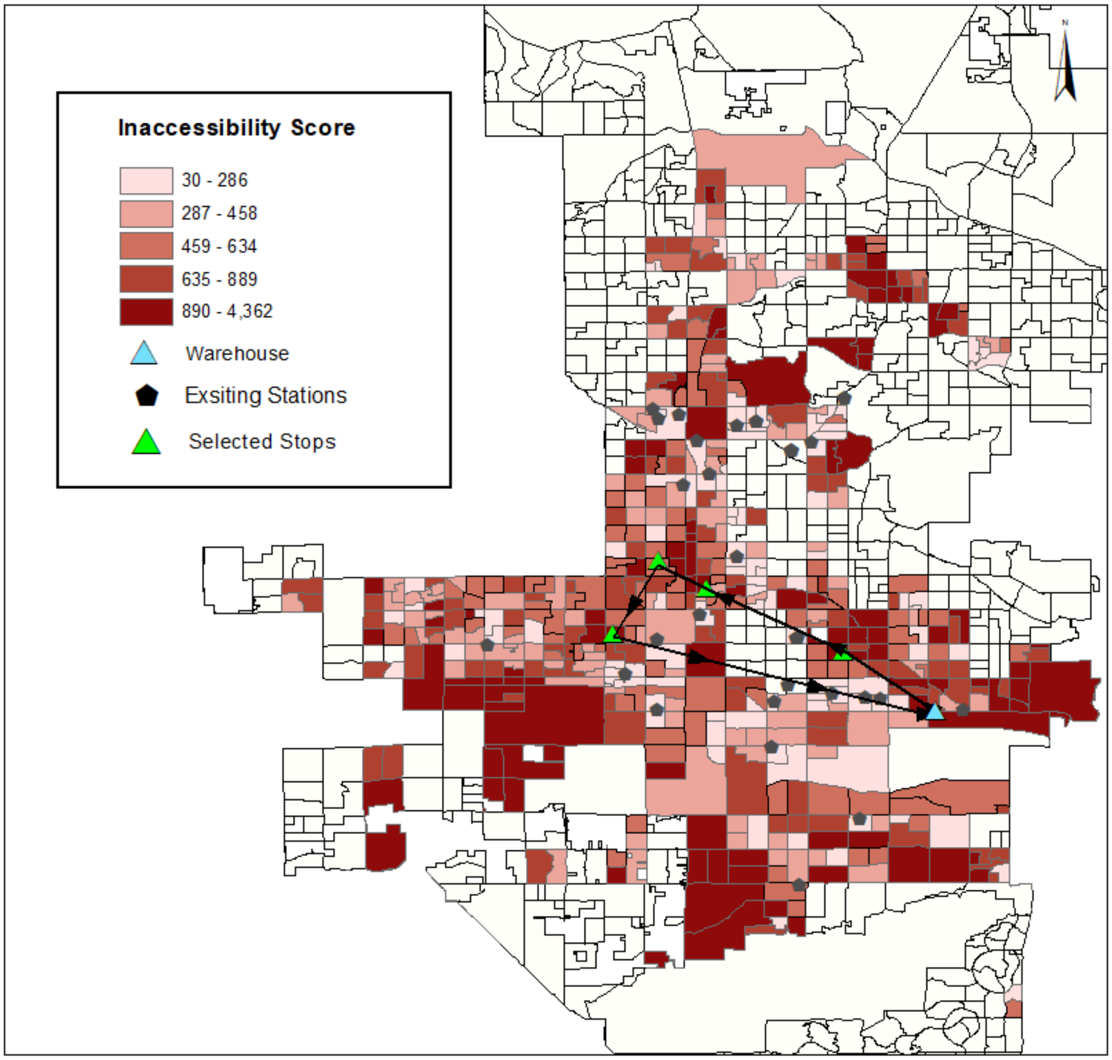

Figure 3. Route 1 Based on Scenario 1

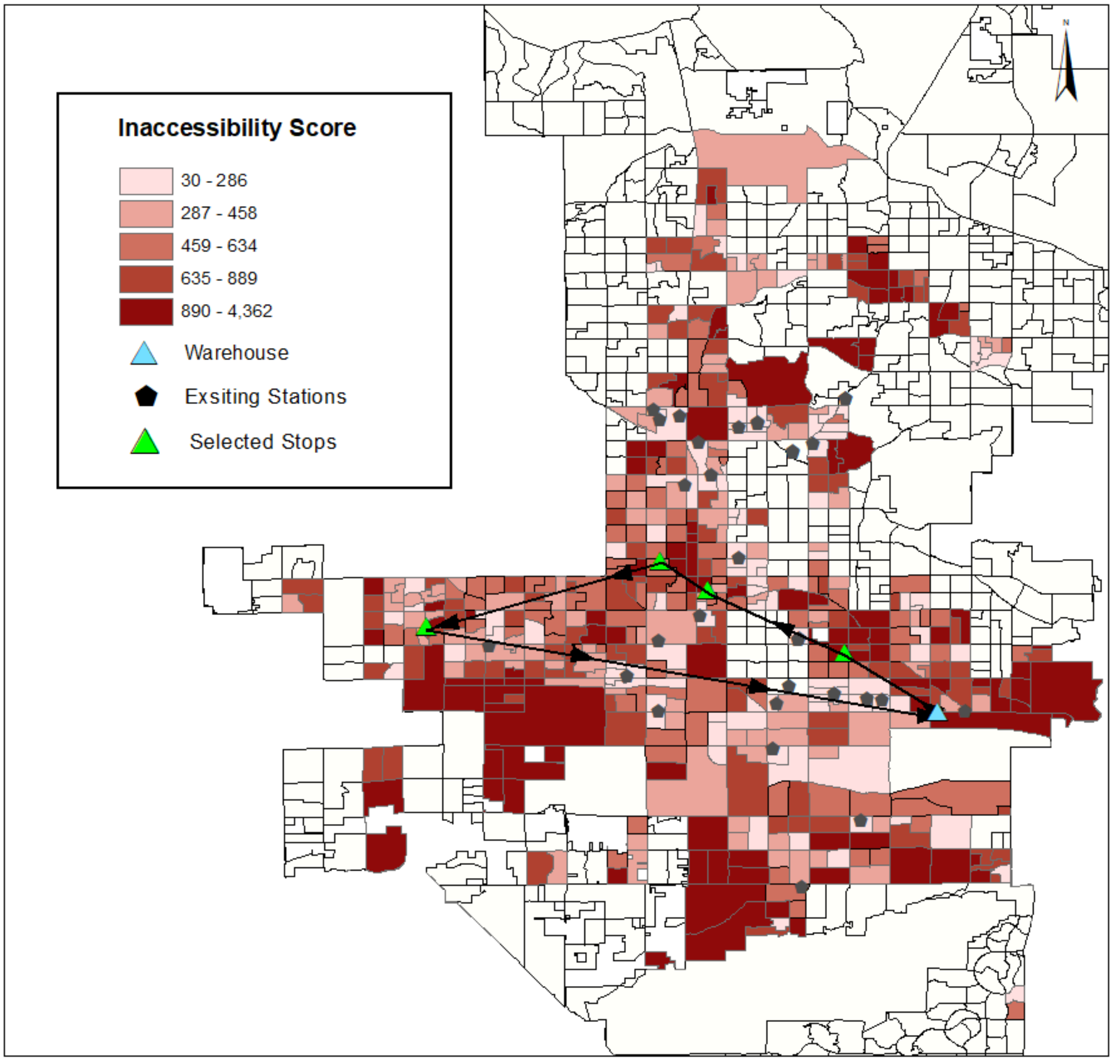

Figure 4. Route 2 Based on Scenario 2

When existing stations are considered (Scenarios 3 and 4 in Figures 5 and 6), the model selected five stations, four of which are not used by existing routes. As shown in Figures 5 and 6 the current sites are strongly concentrated in the city's central and northern areas. The new sites are mostly focused in the region further north and south to fill in the service gaps. We also note that although Scenarios 3 and 4 are meant to fill in the service gaps, their average coverage has been similar to that of the existing four routes (98.4%) with an average travel distance reduction of 8.8%.

As can be seen from Table 3, when distance ranges are the same, comparing the scenarios 1 and 3, and 2 and 4, we note that results (Routes 1 and 2) based on scenarios not considering existing service sites achieves a higher inaccessibility E_k coverage and less travel distance than those based on scenarios considering existing sites. This makes sense as the existing sites cover some neighborhoods effectively and Scenarios 3 and 4 try to cover what's left, which may require a mobile food market to travel longer distance. Furthermore, the site "Little Canyon Park" is present in all four new routes at the same time, indicating that site will be important for new site selection.

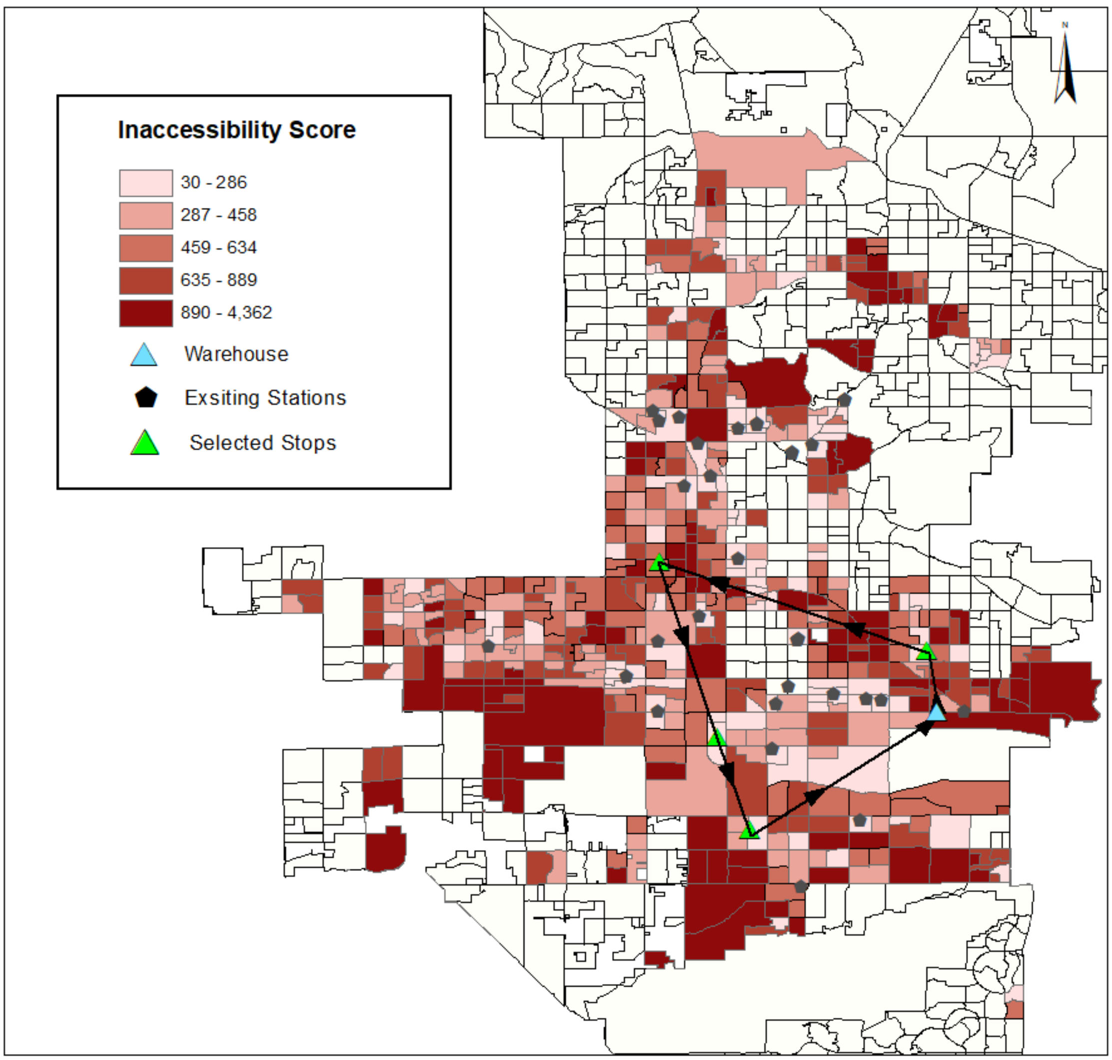

Figure 5. Route 3 Based on Scenario 3

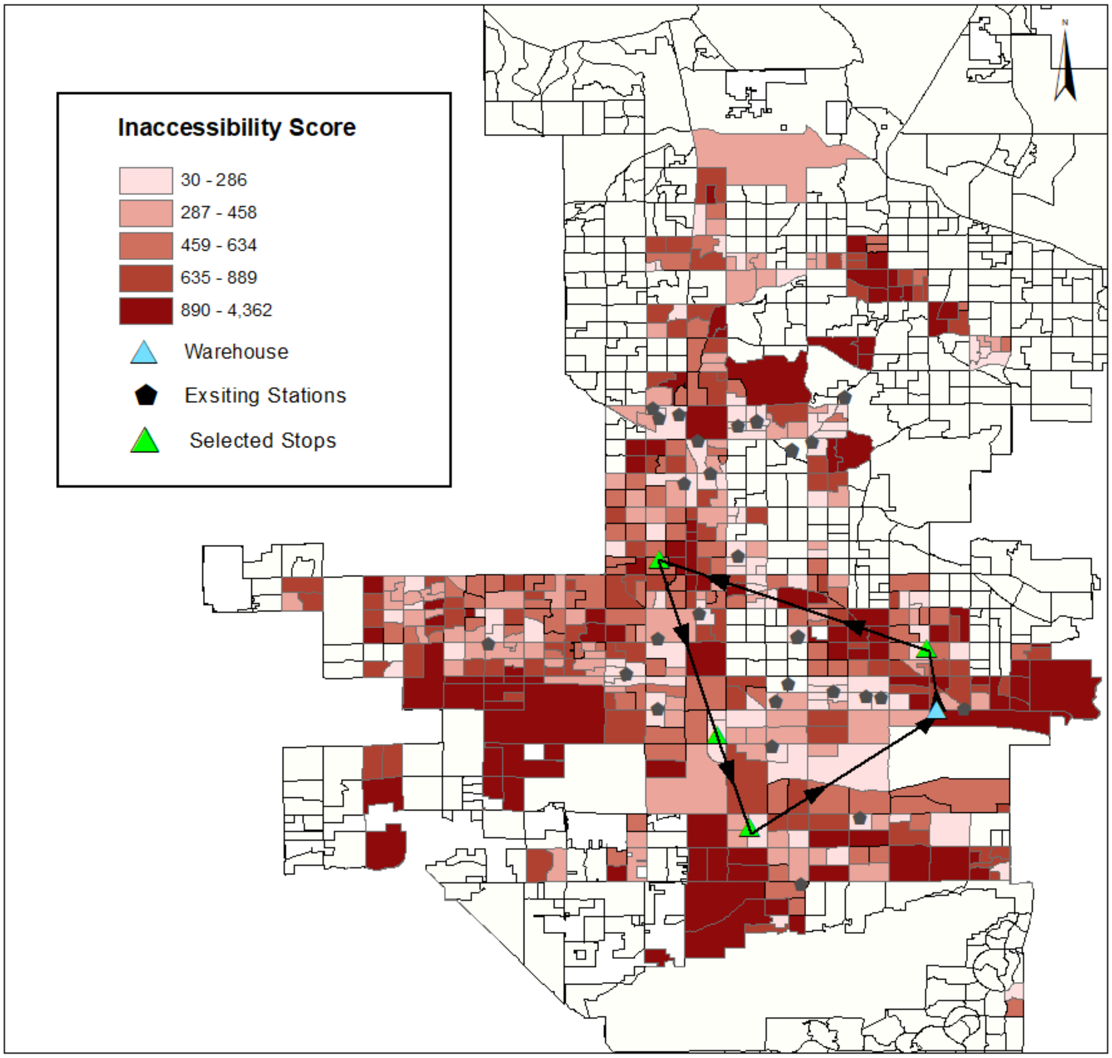

Figure 6. Route 4 Based on Scenario 4

We also examined four additional scenarios where food deserts population was considered as demand (also see Table 4). The four new problem instances give a total of 7 stations. A summary of the model results is provided in Table 5. The routes generated by Scenarios 5 - 8 correspond to Routes 5 - 8 respectively. When ignoring existing service sites, on average Scenarios 5 -8 can cover more about 3.9 times of food desert population when compared with existing routes with a 16% decrease in average travel distance. For Scenarios 7 and 8 that consider existing service sites, model results show that the sites selected by the model can cover additional 88% of food desert population on average when compared with the existing service routes in Table 1. These results suggest that the existing stations give a relatively poor performance in terms of serving food desert population.

	Accounting for the existing sites	Travel Distance (miles)	Demand
scenario 5	No	30	Total Population in Food Desert
scenario 6	No	40	
scenario 7	Yes	30	
scenario 8	Yes	40	

Table 4. Scenarios 5 - 8 Based on Food Deserts

	Stops	Travel Distance (miles)	Food Desert Population	E_k
Scenario 5/ Route 5	VIRGINIA PARK LADMO PARK CIVIC SPACE PARK ROESLEY PARK	27.8	38,352	27,100
Scenario 6/Route 6	CIVIC SPACE PARK VIRGINIA PARK LADMO PARK WINIFRED GREEN PARK	35.8	40,718	27,496
Scenario 7/ Route 7	ROESLEY PARK EL PRADO PARK LADMO PARK VIRGINIA PARK	29.9	23,961	29,647
Scenario 8/Route 8	ROESLEY PARK LADMO PARK SUNRIDGE PARK VIRGINIA PARK	39.1	25,624	34,933

Table 5. Model Solutions Based on Scenarios 5-8

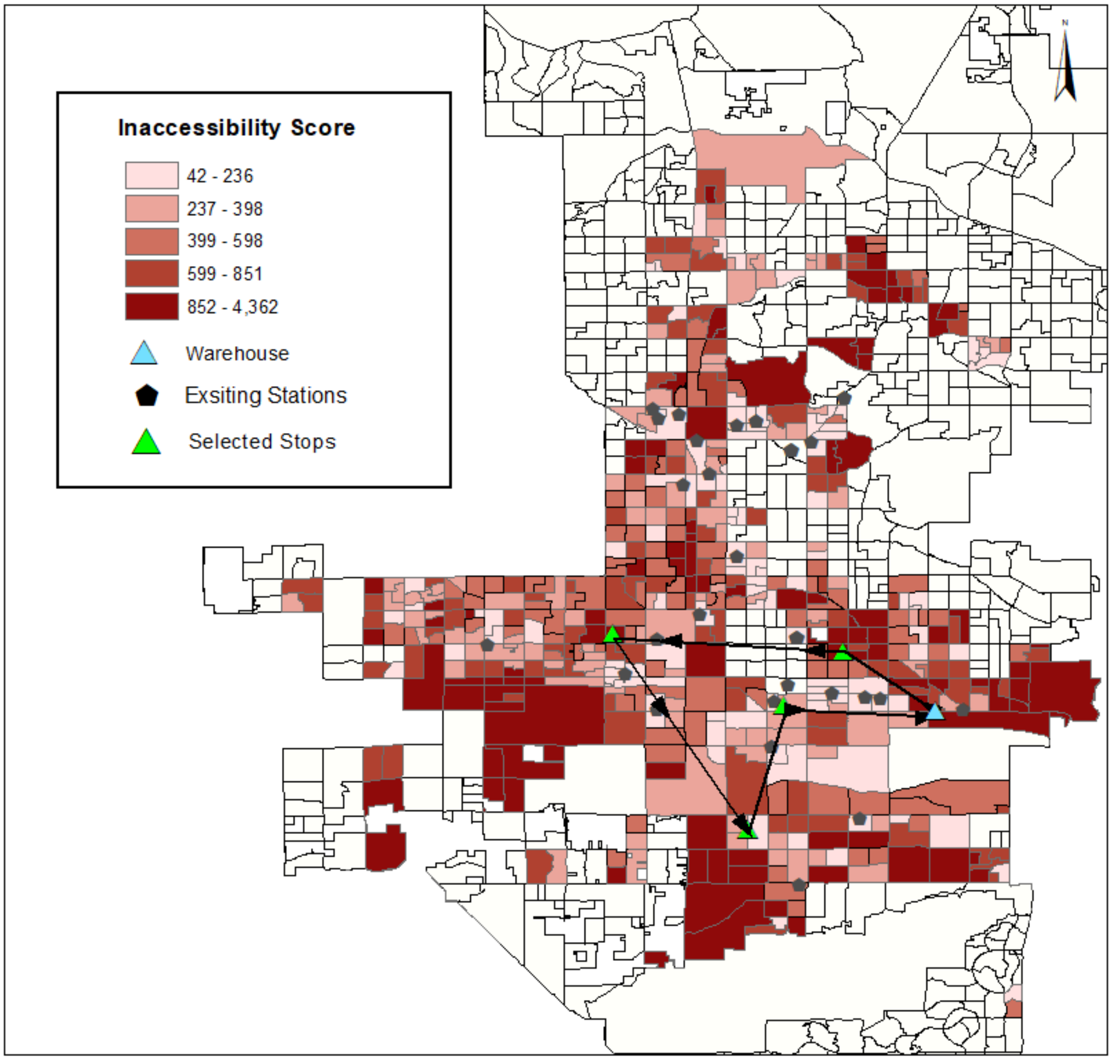

Figure 7. Route 5 Based on Scenario 5

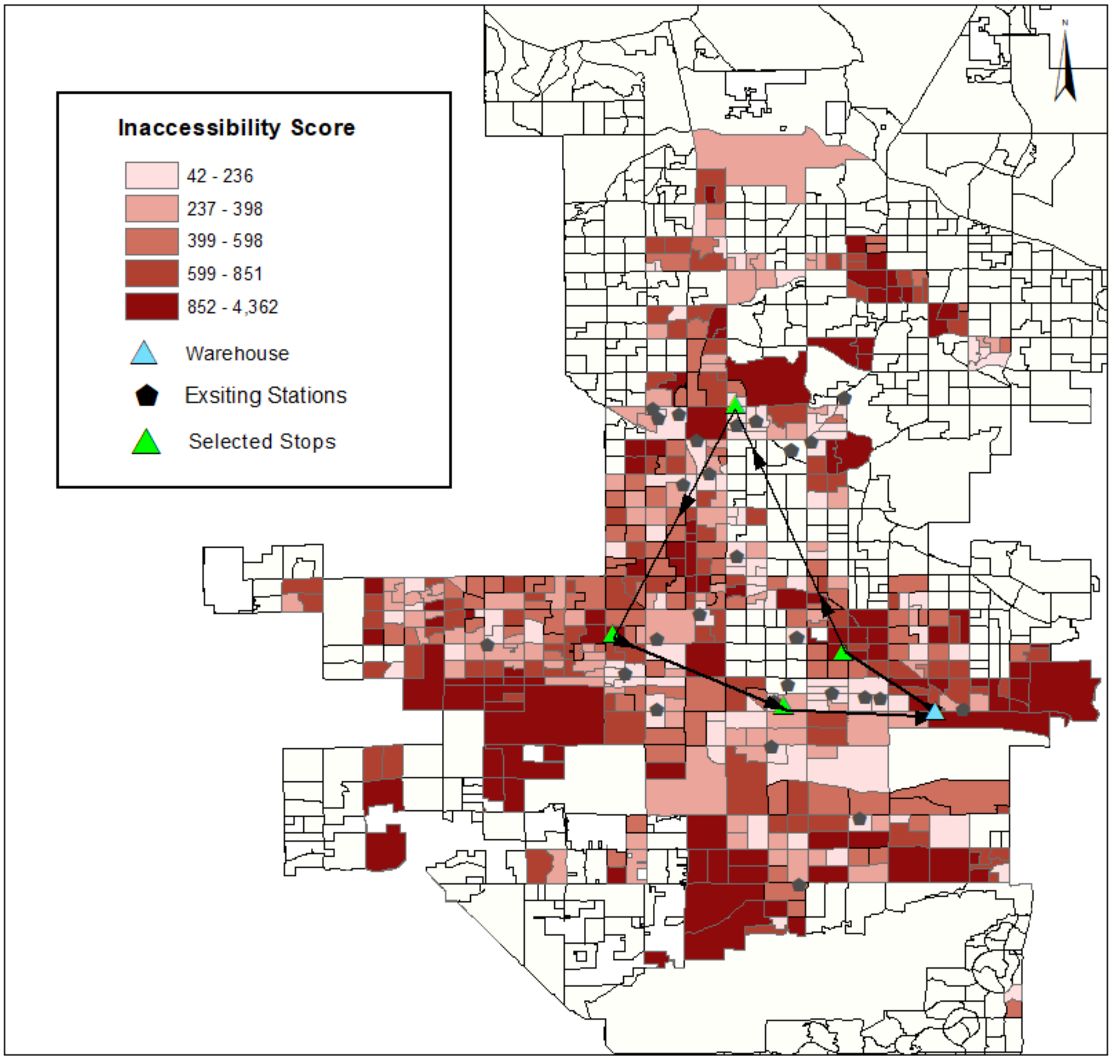

Figure 8. Route 6 Based on Scenario 6

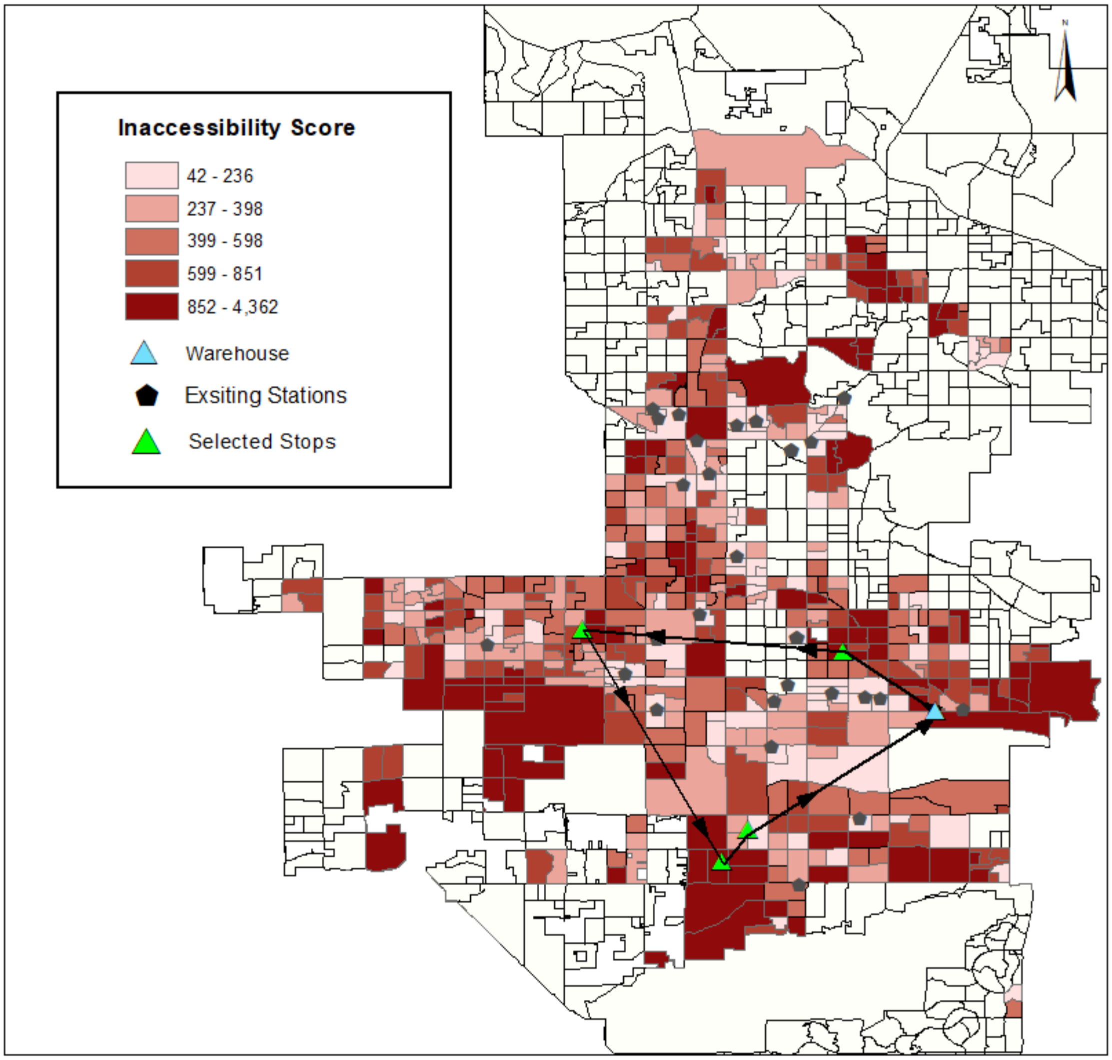

Figure 9. Route 7 Based on Scenario 7

Based on all the model results, it appears that the demand for mobile food markets is higher in the central Phoenix region. Besides, the selection of new sites can be developed in the northern and southern parts of the city. The stops “VIRGINIA PARK”, “ROESLEY PARK”, “LADMO PARK”, “LITTLE CANYON PARK” appeared multiple times in the results, which suggests that these places can serve as effective service sites for new stops and/or routes.

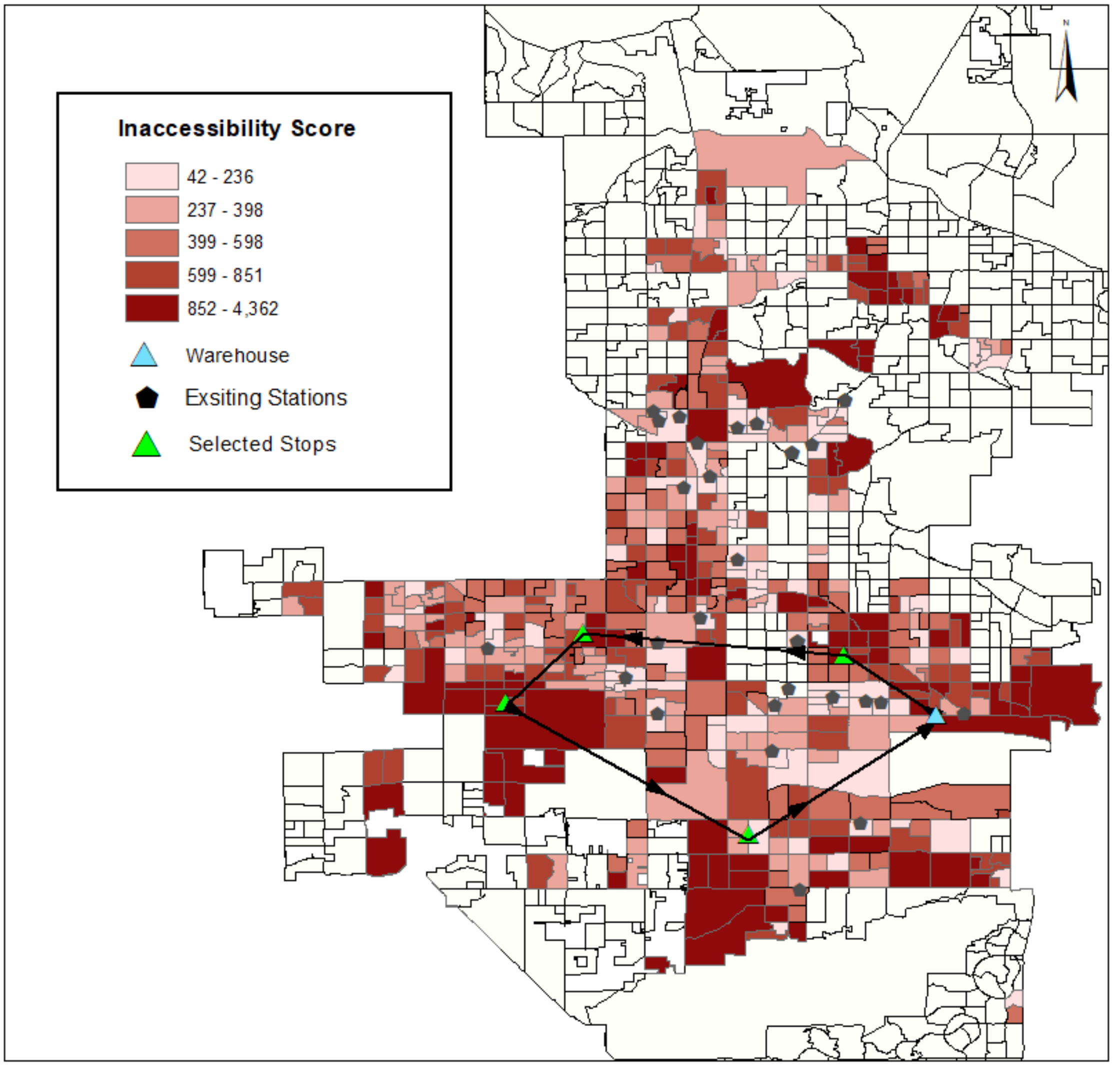

Figure 10. Route 8 Based on Scenario 8

The running time for all the eight (8) problem instances from 6 to 106 seconds. The elimination of subtours ranges from 1 to 21. Despite the model complexity, the relatively small number of stops mobile food markets can make in a day has made the model computationally tractable.

CHAPTER 5

DISCUSSION AND CONCLUSION

By capturing the location of poor and highly immobile populations who have difficulty accessing healthy food, this study proposes a new spatial optimization model to support the planning of mobile food markets. The new model identifies the best sites serving communities with food access challenges while considering transportation costs. The new model was applied to the city of Phoenix to support the efforts in establishing mobile food markets. Model results suggest that sites suggested by the model cover a larger potential population while reducing the total operating distance. This improves efficiency of the mobile food system and reduces operating costs of the program.

There are more aspects of the study that could be improved. As an example, the candidate selection can be further enriched. The existing data only include, libraries, parks and some community centers, and nursing homes. Other public facilities, such as schools and medical facilities, may also be a good choice as candidate sites.

The demand calculation in the model can be further strengthened. In the process of the study, we originally designed a survey to collection information on farm express customers to have a better understanding of the residents who use these markets and their shopping preferences. However, right after we launched the survey, there was the Covid outbreak and all mobile markets stopped their services. We were only able to obtain a few responses, and the sample was not sufficient for users' behavior analysis. In future studies, when information is available on who are more likely to be the mobile food market users, we can incorporate the information into the model to further increase the service effectiveness.

The results of the model in this study only eliminated spatial barriers, as well as a few non-spatial barriers. There are other non-spatial barriers, such as time and other socioeconomic factors, that have not been considered in the model. Taking time as an example, given that Farm Express markets operates during daytime, many residents may be at work. Using their residence information for service provision may not be appropriate. Future studies can consider these additional non-spatial barriers to improve the model performance.

The study has the potential to facilitate governmental and non-governmental agencies planning of food provision and assistance services. In addition to mobile food markets, the method provided in this study can be extended to support the planning of other food outlets, such as farmers' markets, as well as other types of services, such as mobile clinics or medical test sites.

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