ENHANCING EQUITY IN PUBLIC TRANSPORTATION USING GEOGRAPHIC INFORMATION SYSTEMS AND SPATIAL OPTIMIZATION

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in the Graduate School of the Ohio State University

By
Ho-Seop Cha, M.A.

The Ohio State University
2008

Dissertation Committee:
Professor Alan T. Murray, Advisor
Professor Lawrence Brown
Professor Mei-Po Kwan

Approved by:
Advisor
The Graduate Program in Geography
ABSTRACT

Public transportation is a vital part of urban living. Public transportation agencies receive substantial governmental subsidies due to the significance of their impact on society. For instance, public transportation services help reduce road congestion, oil consumption and air pollution, and they serve people who need to travel throughout urban environments at the same time do not have access to private vehicles. The latter aspect is an important matter of social justice. Therefore, it is necessary to discuss how the issue of equity is addressed in public transportation. It is important to understand why the interest in equity in transport is growing, why public transportation should favor the transport disadvantaged, and why analyses of equity measurement and improvement are needed. Measuring the level of access to public transportation among the transport disadvantaged provides a theoretical basis for analyzing potential improvements in access by adjusting public transportation facility locations. This research will focus on examining what equity issues in transport are present, how they are implemented in current public transportation systems, and their limitations. Another aspect of this research is modeling approaches used in establishing public transportation infrastructure and systems. Using GIS and spatial optimization models, the level of access to public transportation in terms of equity will be evaluated and improvement of the level of access will be attempted by offering
new service stop locations. To this end, the Polygon Intersection with Network Point Set (PINPS) method is developed to locate potential facilities along a continuous road network ensuring complete coverage of polygon demand objects. Using the Maximal Covering Location Problem (MCLP), the optimal locations of potential facilities to cover equity favoring origin- and destination-based demand are identified. This research finally provides a set of optimal service stop locations maximizing coverage of origin- and destination-based demand simultaneously through implementation of a bi-objective model, applied to the City of Hilliard, Ohio. In addition the capabilities of coverage models utilizing PINPS and randomly obtained potential facilities are compared. Also, the use of models that represent polygon-based demand versus those depending on only typical point-represented demand will be discussed.
Dedicated to my parents and wife
First and foremost, I would like to thank my advisor, Dr. Alan T. Murray. He has been consistently supporting me since I met him in 1999 at the Ohio State University. He advised me to explore new ideas when I just started my graduate life as a master’s student and has kept encouraging me to complete my doctoral degree to this moment. As a teacher, researcher, and advisor, his inspiration to my academic career has been fabulous. I would like to give the last special thanks to my advisor for his hiring me as an RA for me to concentrate on this dissertation in the last year of my doctoral program. Dr. Murray started his professional career at the OSU in 1999 when I started my OSU life. Coincidentally, he is now leaving for the Arizona State University when I leave OSU. As a special person in my life, I wish Dr. Murray the best of luck as he continues his career at ASU.

Also, I would like to thank my committee members, Dr. Lawrence Brown and Dr. Mei-po Kwan. Dr. Brown has been of great support since he was a chairperson of this department. His hiring me as an instructor in the department helped me build my teaching experience enormously, and this definitely helped me obtain a professor position. His personal care for me has been greatly appreciated. This did encourage me to keep moving.
whenever I had hard time. Dr. Kwan inspired me to build my knowledge in an academic field. I have gained fruitful ideas and techniques, especially in Geographic Information Systems from her classes. She motivated me to adopt the GIS techniques in my academic research.

This dissertation is my individual work. However, I have received countless pieces of advice and valuable support from my colleagues, Eric Boschmann, Dr. Su-yeul Chung, Dr. Veronica Crossa, Jason Davis, Dr. Alistair Fraser, Hyun Kim, Dr. Kamyoung Kim, Gunhak Lee, and Jeff Olson. I am very grateful to these friends from the bottom of my heart.

The last but not the least, I would like to thank my wife, Sunyun Choi. She has supported me as my shadow. Her personal life has been extremely busy as a mother of two kids, a nursing graduate student, a full time nurse practitioner, and my wife. Nevertheless, I have never seen her act suffered from this hardship. She has always kept troubles to herself and helped me concentrate on my work. I truly think I would not have been able to complete my work without her heartfelt support. Sunyun, my wife, is the winner of this work.
VITA
1999……………….. B.A. The Department of Geography Education, Korea University, Seoul, South Korea

2002……………….. M.A. The Department of Geography, The Ohio State University

2002-2007……….. Teaching Associate, Department of Geography, The Ohio State University

2007-present…….. Research Associate, The Department of Geography, The Ohio State University

PUBLICATION

FIELD OF STUDY
Major Field: Geography
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iv</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>v</td>
</tr>
<tr>
<td>VITA</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xi</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1. Overview</td>
<td>1</td>
</tr>
<tr>
<td>1.2. Problem Statement</td>
<td>3</td>
</tr>
<tr>
<td>1.3. Significance of the research</td>
<td>4</td>
</tr>
<tr>
<td>1.4. Organization of this research</td>
<td>7</td>
</tr>
<tr>
<td>2. LITERATURE REVIEW</td>
<td>10</td>
</tr>
<tr>
<td>2.1. Introduction</td>
<td>10</td>
</tr>
<tr>
<td>2.2. Equity</td>
<td>10</td>
</tr>
<tr>
<td>2.3. Equity in transportation</td>
<td>12</td>
</tr>
<tr>
<td>2.4. Equity implementation</td>
<td>17</td>
</tr>
<tr>
<td>2.5. Access and accessibility</td>
<td>20</td>
</tr>
<tr>
<td>2.6. Optimizing access</td>
<td>25</td>
</tr>
<tr>
<td>2.7. Facility siting on a continuous road network</td>
<td>28</td>
</tr>
<tr>
<td>2.8. Spatial representation</td>
<td>31</td>
</tr>
<tr>
<td>2.9. Summary</td>
<td>32</td>
</tr>
<tr>
<td>3. MODELING ACCESS</td>
<td>36</td>
</tr>
<tr>
<td>3.1. Introduction</td>
<td>36</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 3.1: Notation used in index approach ................................................................. 40
Table 4.1: MCLP result details: PINPS (Polygon-based approach: origin-based)........ 71
Table 4.2: MCLP result details: PINPS (Polygon-based approach: destination-based)... 79
Table 4.3: Solution details for the bi-objective MCLP .................................................. 86
Table 4.4: Comparison of coverage between single- and bi-objective MCLP with full
  weight for either objective ....................................................................................... 91
Table 5.1: MCLP result details: PINPS, 200 meter-spaced, and 100 meter-spaced
  (Polygon-based approach: Origin-based) ............................................................... 103
Table 5.2: MCLP result details: PINPS, 200 meter-spaced, and 100 meter-spaced
  (Polygon-based approach: Destination-based) ....................................................... 107
Table 5.3: MCLP result details: PINPS, 200 meter-spaced, and 100 meter-spaced (Point-
  represented approach: Origin-based) .................................................................... 109
Table 5.4: MCLP result details: PINPS, 200 meter-spaced, and 100 meter-spaced (Point-
  represented approach: Destination-based) ............................................................ 114
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Transport disadvantaged areas</td>
<td>44</td>
</tr>
<tr>
<td>3.2</td>
<td>Coverage of Polygon $ABCD$ by facility $F$</td>
<td>47</td>
</tr>
<tr>
<td>3.3</td>
<td>Identifying covering boundary</td>
<td>49</td>
</tr>
<tr>
<td>3.4</td>
<td>Creating Polygon Intersection with Network Point Set (PINPS)</td>
<td>50</td>
</tr>
<tr>
<td>3.5</td>
<td>Creation of potential facility sites on a continuous road network</td>
<td>53</td>
</tr>
<tr>
<td>3.6</td>
<td>Removing dominated points</td>
<td>54</td>
</tr>
<tr>
<td>3.7</td>
<td>Relationship with the maximum diameter $D$ of the minimum enclosing circles and the covering standard $R$</td>
<td>57</td>
</tr>
<tr>
<td>4.1</td>
<td>Parcels in the study area</td>
<td>62</td>
</tr>
<tr>
<td>4.2</td>
<td>Data transfer to study area (origin-based)</td>
<td>64</td>
</tr>
<tr>
<td>4.3</td>
<td>Data transfer to study area (destination-based)</td>
<td>66</td>
</tr>
<tr>
<td>4.4</td>
<td>Removal of dominated points (origin-based)</td>
<td>68</td>
</tr>
<tr>
<td>4.5</td>
<td>Comparison between actual coverage and complete coverage</td>
<td>69</td>
</tr>
<tr>
<td>4.6</td>
<td>Tradeoff curve by PINPS (Polygon-based approach: origin-based)</td>
<td>72</td>
</tr>
<tr>
<td>4.7</td>
<td>Coverage: Minimum and Maximum within given $p$ values (Polygon-based approach: origin-based)</td>
<td>74</td>
</tr>
<tr>
<td>4.8</td>
<td>Appropriate Coverage (Polygon-based approach: origin-based)</td>
<td>75</td>
</tr>
<tr>
<td>4.9</td>
<td>Removal of dominated points (Polygon-based approach: destination-based)</td>
<td>78</td>
</tr>
<tr>
<td>4.10</td>
<td>Coverage: Minimum and Maximum within given $p$ values (Polygon-based approach: destination-based)</td>
<td>80</td>
</tr>
<tr>
<td>4.11</td>
<td>Desirable Coverage (Polygon-based approach: destination-based)</td>
<td>81</td>
</tr>
<tr>
<td>4.12</td>
<td>Tradeoff curve by PINPS (Polygon-based approach: destination-based)</td>
<td>82</td>
</tr>
<tr>
<td>4.13</td>
<td>Tradeoff curve for bi-objective MCLP</td>
<td>87</td>
</tr>
</tbody>
</table>
Figure 4.14: Coverage configuration by bi-objective MCLP with weights of 0.6 and 0.4
................................................................................................................................. 90
Figure 5.1: MCLP application by demand types and potential facility types................. 96
Figure 5.2: Regularly spaced potential facility points by 100 meters and 200 meters along
the Hilliard road network ........................................................................................................ 97
Figure 5.3: Centroids for origin- and destination-based demand parcels ...................... 99
Figure 5.4: Buffers for evaluation for $N_i$ set ................................................................. 100
Figure 5.5: Tradeoff curves for comparison between PINPS, 200 meter-, and 100 meter-
spaced potential facility points (Polygon-based approach: Origin-based) 101
Figure 5.6: Tradeoff curves for comparison between PINPS, 200 meter-, and 100 meter-
spaced potential facility points (Polygon-based approach: Destination-based) ......................... 106
Figure 5.7: Tradeoff curves for comparison between PINPS, 200 meter-, and 100 meter-
spaced potential facility points (Point-represented approach: Origin-based)
................................................................................................................................. 108
Figure 5.8: Comparison between polygon-based and point-represented approaches..... 113
Figure 5.9: Coverage by objective value, actual coverage, and complete coverage in the
point-represented approach ................................................................................................. 116
Figure 5.10: Covered parcels by objective value, actual coverage, and complete coverage
................................................................................................................................. 117
CHAPTER 1

1. INTRODUCTION

1.1. Overview

Public transportation plays an important role in urban areas, and public transportation organizations have received substantial governmental subsidies (Murray and Davis 2001). There are several reasons for governments to subsidize public transportation service. First, public transportation helps decrease congestion on the road network at peak traffic times by providing alternative choices for travel (Starrs and Perrins 1989) and by providing a higher capacity than personal transport (Gary and Hoel 1992). In addition, public transportation contributes to decreasing energy consumption by serving more people with less fuel, which means that it also helps diminish air pollution by reducing automobile emission (American Public Transportation Association 2007). Finally, a matter of social consideration arises because a fair distribution of costs and benefits, represented by the provision of appropriate transport to the people who need public transportation, is a social good (Hodge 1995). This perhaps is the most important justification for government subsidization of public transportation and will involve more developed discussion later in this dissertation.
The issue of equity arises because of the fact that people who most need public transportation are not often provided sufficient service. The concept of equity is generally associated with the distribution of income, goods or services, which in turn means that equity in public transportation is concerned with the fair distribution of public transportation service (Murray and Davis 2001). Mobility and accessibility are regarded as basic needs for all members of a community, because everyone has a right to suitable mobility and accessibility to their desired destination (Wachs 1979). Of course, mobility and accessibility can be achieved by both personal vehicle and public transportation; however, urban structure does not appear well supported by public transportation. There has been a major shift towards the use of the automobiles as a major form of personal transport in the United States since the 1920s, which has led to decreasing use of public transportation. This was caused not only by the convenience of personal transport, but also by road network-oriented development of urban areas as government policy (Denmark 1998). In addition, suburbanization has contributed to the decline in the prominence of public transportation. Suburbanization disperses service bringing operation difficulties to public transportation providers (Altshuler 1979). Although recent investments in some major urban places have increased the use of public transportation, the beneficiaries are mainly commuters, which are mostly the able-bodied and employed (Denmark 1998). These issues clearly show that all people are not ensured mobility and accessibility. Clearly, some people are excluded from the right of mobility and accessibility.
The group of people who need public transportation services, especially those who do not have access to personal transport, is referred to as the transport disadvantaged (Altshuler 1979). The transport disadvantaged should have adequate service. This involves achieving both social justice and one goal of operations in public transportation. There may be various ways to enhance access of public transportation to the transport disadvantaged, but the most efficient and feasible way is to adjust the location of facilities such as service stop locations or service routes (Wu and Murray, 2005). If adjusted public transportation facility locations provided higher ridership as well as better access, it would contribute to increasing revenues of the public transportation operator and likely decrease the need for governmental subsidy. However, transportation planning is a complicated and involved issue. Without a comprehensive understanding of equity issues in a current transport system, research results may only provide theoretical arguments. Therefore, a clearer and more accurate identification of equity issues in current transport systems and its deficiencies will prove to be of great help in producing practical improvement to access for the transport disadvantaged.

1.2. **Problem Statement**

In order to attain higher levels of equity in public transportation, this research will focus on the following issues. First, this research will examine how equity issues are addressed in current transport planning and operations. In addition, a range of complementary public transit systems already put in place to support the transport disadvantaged in urban and suburban areas will be discussed, including any problems and improvements. This
discussion will also assist in providing a better means to perform analyses regarding equity-incorporated transit service stops. Second, this research will identify optimal locations of public transit service stops using multiple techniques and modeling approaches. This part will include evaluation of origin-based and destination-based public transportation access in terms of equity achievement. This will diagnose the level of equity attainment in public transportation and provide a motive to alter the number of public transportation facility locations such as service stops. This is followed by identification of optimal locations of service stops using a covering problem for each origin-based and destination-based demand. This will include the discretization of a continuous road network to locate potential facilities based on transportation demand being aggregated to polygon objects. Then, a consolidated set of optimized locations of service stops will be provided using multi-objective optimization by maximizing both origin-based and destination-based objectives simultaneously. Finally, spatial representation issues will be discussed. The covering model will be used to analyze various sets of data and approaches including the Polygon Intersection with Network Point Set (PINPS), regularly discretized potential facility sites, and approaches with polygon-based and point-represented demand. Comparison between various data and approaches is also an important part of this section.

1.3. Significance of the research

Many local governments, public transportation providers and non-profit operators are working on improving accessibility for the transport disadvantaged. Such improvements
seem to favor a limited scope of beneficiaries. Also, the above operations do not integrate support for the transport disadvantaged in fixed-route systems. Many strategies have been suggested to improve the performance of public transportation, such as improvement of travel time, number of transfers, transit speed, etc. However, better access should be ensured first, since service quality can only be meaningful when people have access to public transportation. Nevertheless, studies dealing with access-based coverage maximization analysis incorporating equity enhancement have never been carried out.

Therefore, support for all of the transport disadvantaged and integration of equity enhancements into the fixed-route system will be very important. To this end, this research will concentrate on developing the level of access by adjusting the locations of public transportation facilities in a fixed-route system, such as service stops, incorporating the equity problem using GIS and combinations of optimization models. Along these lines, this research first discusses the concept of equity in transportation and the implementation of equity in public transportation.

There are a range of models to discuss regarding locating facilities to cover spatial demand. Mostly, these models are based on predetermined locations of potential facilities. For this reason, how facility locations are selected over continuous space has been an issue since Weber’s (1909) single facility siting problem to minimize transportation costs. Circle Intersection Point Set (CIPS) was developed for the optimization for the coverage of point-based demand by discretizing continuous space to
locate potential facilities. Polygon Intersection Point Set (PIPS) discretizes continuous space for potential facility location based on more general representations of demand including points, lines, and polygons. However, neither of these methods addresses discretization of continuous space along a road network. Since road networks are continuous but line-featured, it is necessary to develop a new method to incorporate network properties into the discretization procedure. As a major contribution of this research in terms of modeling, a new method creating the Polygon Intersection with Network Point Set (PINPS) will be developed. Therefore, this part will discuss the extraction of potential facility sites along a continuous road network derived assuming polygon demand.

With the newly developed PINPS, optimal transit stop locations will be identified using the Maximal Covering Location Problem (MCLP) to provide maximal coverage to a region where both high public transportation demand and deficient access to the public transportation are predominant. This analysis will develop two separate sets of optimal locations for bus stops, origin-based and destination-based. However, in actual planning, one only needs a single set of sites, not multiples. This requires two different sets of optimal stop locations to be integrated into one set. Given this, this section will discuss a bi-objective MCLP for integrating two objectives. This series of analyses is comprehensive and a significant contribution of this research. The PNIPS is a new method, and no other studies have discussed the MCLP approach to identify optimal locations of stop maximizing the level of equity in public transportation, and
consolidation of origin-based and destination-based objectives using a bi-objective optimization method.

In addition, comparison of the MCLP using PINPS and the typical method of regular discretization of potential facility sites will be conducted to observe the advantage of PINPS over the typical method. Using PINPS has another advantage. PINPS allows the analyst to take advantage of polygon demand geometry. Thus, comparison between the new approach using polygon demand and the typical point representation for demand will be carried out to compare the accuracy in both coverage results. These comparative analyses will prove how significantly the use of new method, PINPS, over other typical methods improves the results of models.

1.4. Organization of this research

This dissertation is organized as follows:

**Chapter 1:** This chapter introduces the background and problems addressed by this research, highlighting the significant contributions made by this work. Organization of the chapters is also described here.

**Chapter 2:** Literature related to this research is reviewed. First, concepts of equity in social, geographical and transportation contexts are discussed. Second, how the equity issue is implemented in current transportation system is addressed. Third, access and accessibility are examined to apply them in a modeling approach. This concerns not only
theoretical discussion but also the methodological issues, involving the discretization of continuous space to locate potential facilities and spatial representation.

**Chapter 3:** This chapter mainly discusses PINPS, which is a method to discretize a continuous road network to extract potential facilities ensuring complete coverage for polygon-based demand. As a significant contribution of this research, complete details with respect to PINPS are included. The beginning of this chapter also includes data preparation procedures and research area development.

**Chapter 4:** This chapter implements insights from the previous chapters to plan a public transportation system. Optimal public transportation stop locations are identified using PINPS and the MCLP to provide maximal coverage to the areas with high public transport demand and poor access to public transportation. Two sets of stop locations will be created by this analysis, which are based on origin-based demand and destination-based demand. For the real planning purposes, these two different sets will be consolidated into one set of stop locations simultaneously maximizing both origin-based and destination-based objectives using a bi-objective optimization model.

**Chapter 5:** PINPS has been developed to discretize continuous road networks to locate potential facilities ensuring complete coverage for polygon-based demand. Discretized point sets provided by PINPS are superior to typical randomly distributed potential facility sets in terms of efficiently covering polygon-based demand. Coverage comparison between PINPS and typical potential facility sets will show how efficiently PINPS improves coverage. In addition, coverage comparison between polygon-based demand by PINPS and point-represented demand will be presented. This also shows the
improvement by PINPS regarding coverage for polygon-based demand over that for point-represented demand.

**Chapter 6:** Conclusions drawn from this research are made here. Suggestions for future study enhancing redundancy removal and developing new multi-objective models are also made.
CHAPTER 2

2. LITERATURE REVIEW

2.1. Introduction

This chapter will review literature over all fields of this research. First, the concept of equity will be addressed in a social context. This will be broken down into geographical context, and further into the context of equity in transportation systems. Meanwhile several notions characterizing the transport disadvantaged are reviewed. Second, equity implementation in current transit systems is discussed. This focuses on how transit agencies incorporate equity issues into the current operations regarding examining whether or not all necessary beneficiaries are properly served. In this case equity in planning aims for access-oriented improvement, and it is integrated into a fixed-route system. Third, concepts of access and accessibility will be discussed. This involves identifying suitable concepts for the model used in this research. This is followed by the review of models for optimizing access. Then, technical issues for the optimization modeling will be discussed, such as discretization of continuous space to locate potential facilities and spatial representation issues.

2.2. Equity

Equity, fairness, and justice have been broadly discussed in a large literature, especially
in the discipline of philosophy, political science, and law (Barry 1990). Hay (1995) identified eight key concepts: procedural fairness, expectations, formal equality, substantive equality, equal choice, desert, right, and need. Hay (1995) concludes that the individual concepts of equity, fairness, and justice do not directly correspond to any of the above eight key ideas, which implies that the concepts of equity, fairness, and justice are analogous. Murray and Davis (2001) also discussed that the terms, equity, fairness, and justice can be interchangeably used as synonyms. In general, the concept of equity in a social context concerns the distribution of income, goods, or services (Murray and Davis 2001).

In a geographical context, the concept of equity has been also widely and continually referenced in the literature such as Geography and Social Justice (Smith 1994), Unfairly Structured Cities (Badcock 1984), and Social justice and the city (Harvey 1973). A case study by Smith (1994) presents the eight key ideas of equity described above interpreted in a geographical context as all groups or individuals benefiting from a certain form of equity, or suffering from inequity, are residing in geographical locations. In a more specific scale, equity deals with the distribution of services in urban systems. Harvey (1973) and Badcock (1984) discussed this distributive mechanism in cities and analyzed how unfair or poorly distributed spatial concentrations of wealth and employment opportunities are.
2.3. *Equity in transportation*

Public transportation is an important social service in urban areas. Due to its significance, public transportation has been supported by government subsidies (Murray and Davis 2001). Over $34.5 billion was invested in unprofitable public transportation systems in the United States in 2004 (The Public Purpose 2007). At the local level, Columbus Ohio received a $57 million operating subsidy in 2006, which is approximately 76% of COTA’s total operating expenses (Ohio Department of Transportation 2007).

There are many reasons why public transportation should be supported by the public. First, public transportation decreases road congestion at peak traffic times because it provides an alternative choice to personal transport (Starrrs and Perrins 1989), allowing for a higher person per vehicle capacity than provided by car (Gary and Hoel 1992). Second, the use of public transportation decreases energy consumption by serving more people with less fuel. This has two advantages: it saves fossil fuel, which is a limited non-renewable resource, and it also decreases air pollution caused by fuel combustion. Reduced air pollution is accomplished through lower automobile emissions (American Public Transportation Association 2007). The fourth reason public transportation should be supported is a matter of social justice. The provision of appropriate transport for people who, for whatever reason, need public transportation must not be overlooked (Hodge 1995). This will be the main topic of this research.
In transportation, the notion of equity primarily concerns a discussion of the fairness of distribution of cost and benefits associated with transportation in urban areas (Hodge, 1995). A study of rural transport issues in New South Wales, Australia reported that equity in transport is occasionally regarded as equal access and affordability as a more specific concept (Denmark 1998). Hay and Trinder (1996) found that the idea of equity is being increasingly used by academics and transport-related groups to evaluate social and distributional issues in transport policy. For instance, they identified that most transport policy administrators conceive equity in transport to be equal treatment within a reference group, such as equal access to transport facilities supported by local taxation or minimum requirements to fulfill certain common objectives like extended service of subsidized transport to rural areas.

Improvements in transportation help to enhance mobility and prosperity in urban areas. This enhancement in mobility and prosperity, however, does not necessarily occur in such a way that the benefits are evenly distributed. Rather, they yield both winners and losers; those who are main beneficiaries, and those who are disadvantaged by development (Hodge 1995). This unequal distribution of benefits has raised an equity issue in transport. Hodge explains this concept of equity using dichotomous concepts, financial equity and beneficial equity. The former is concerned with those who finance public investment in transportation, and the latter is related to who receives the benefit from the investment in transportation.
Urban transportation investment is financed by several sources including taxes, tolls, and fares. Taxes are the largest money source, however. Those taxes involve gas tax, Motor Vehicle Excise Tax (MVET), sales tax, property tax, and income tax. Capital funds, which are spent to construct the initial transport system, are mostly supported by the federal and state governments, which draw funds from gas taxes and income taxes. Operational funds are used for everyday costs and additional capital expenses, and are typically supported by gas taxes, sales taxes and MVET, but they are substantially covered by sales tax. Since both funds are seriously dependent upon taxes, the issue of financial equity arises in terms of whether or not the amount of taxes collected from people is fair. When taxes are regressive, that is they are assessed in relative amounts to income, poor people pay relatively more taxes. When taxes are progressive, or assessed in absolute amounts, wealthy people pay more.

Beneficial equity is further classified into two subdivisions, fiscal equity and service equity. Fiscal equity concerns the monetary focus of subsidies, while service equity deals with the quality of transport service. In the fiscal equity issue, the focus is on whether the distribution of benefits is locally even. Fiscal equity includes two perspectives, operating subsidy and capital subsidy. Operating subsidy involves the fact that there are two groups of people: those who pay more than the real cost due to high load factors, shorter trips or peak travel time and those who pay less than real cost as a result of lower load factor, longer trip or off-peak travel (Corvero et al. 1980, Pucher 1981). Consequently, it can be said that those who pay less than average costs are subsidized by those who pay a larger
proportion of their real costs. Another concern of operating subsidy is the amount of tax support. Hodge (1988) found that the spatial distribution of beneficiaries of operating subsidies by both the fare system and tax support are not even in urban areas. Capital subsidy is also situated in a similar circumstance. When new transport infrastructure is designed, and especially if it is funded by local sales taxes, residents are more sensitive to whether or not they directly benefit. If the tax payers do not benefit, the equity issue arises again.

Service equity involves spontaneous inequity and systematic inequity. MacGregor (1981) assessed transit service quality by comparing travel times in different places and found that the quality of services favor central urban places. This, however, is not surprising since this is a reflection of typical urban characteristics. That is, those central urban places have better service, and better service generates more users, who in turn facilitate the demand for better service. Systematic inequity is mainly concerned with service provision favoring minority groups, low-income people and the transport disadvantaged. Several issues are involved here, such as service quality, air pollution and mobility. The most important issue is mobility. Society believes that minimal mobility should be guaranteed to all urban residents. In more detail, National Roads and Motorists Association (NARA) Public Affairs Group (1995) (quoted in Denmark 1998) stipulated that reduced mobility to the transport disadvantaged results in reduced access to essential services, such as employment, shopping, leisure, or medical services. This in turn potentially causes unemployment, personal and family stress, ill-health and personal
Wachs (1979) discussed that mobility is a key aspect of anyone’s life style and particularly stressed that mobility is essential to the elderly since it is critical to their physical, social, and psychological life.

Cha and Murray (2001) characterized the transport disadvantaged as the young, the old, low income earners, those with no vehicle and the disabled. Similar notions have been discussed regarding a need of public transportation. Falcocchio and Cantilli (1974) suggested that the handicapped and the poor are groups of transportation disadvantaged. Taebel and Cornhels (1977) described the transport disadvantaged using the term *outsiders* and identified them as the poor, the elderly, the handicapped, and minority groups. Morgan (1992) simply discussed that the transport disadvantaged are those who have mobility and accessibility problems. Morris (1981) stated that there are groups of people who need public transportation. They are those who are too young or old to drive, the disabled, home workers, low income earners, unemployed youths, and migrants. Starrs and Perrins (1989) noted that the people with the greatest need for public transportation are the elderly, the young, those who cannot drive a vehicle, the disabled, low-income earners, women and those of an ethnic background.

Hodge (1995), in discussing service equity, argued that public investment in transportation infrastructure ought to favor the transport disadvantaged. Trinder et al. (1991) similarly argued that equity should be related to need when it is examined in transportation. Therefore, public transportation should meet the demand of people who
need travel assistance (Cha and Murray 2001). Detailed equity issues in transportation have been discussed above. They mostly deal with distribution in regard to costs and benefits. They are all individually important issues, but the most important point is the matter of mobility discussed in service equity since everybody has a right to have minimal mobility, and this mobility is critical for well-being in their lives.

2.4. Equity implementation

Some work has been done to improve accessibility for the transport disadvantaged, even though it does not favor all types of the transport disadvantaged. The most visible practices are paratransit, such as dial-a-ride systems in the U.S.A. and community transport in the U.K. and Australia (Denmark 1998). Paratransit generally includes car and van pools, Jitney-type operations, and dial-a-ride services (Vuchic 1981 and Meyer and Gomez-Ibanez 1981). Car and van pools commonly serve commuters, while the other two services are aimed at the transport disadvantaged. The notion of paratransit comes from Demand Responsive Transport (DRT). DRT is an alternative to traditional public transportation systems designed to enhance equity in urban transport systems by serving the disabled, the elderly and the poor or provide community luxury by serving children and providing commuters with connections to and from fixed route transport. Community transport lends support to those who cannot easily use conventional transport due to their special needs, such as wheelchair dependency or other mobility difficulties.
The Americans with Disabilities Act (ADA) requires every public transportation agency to provide additional paratransit services (Bailey 2004). It also requires that all fixed-route buses purchased after July 1990 be accessible to passengers in wheelchairs (Central Ohio Transit Authority 2007c). However, unlike the disabled, access to public transportation for older people without disabilities is not legally mandated (Bailey 2004). In order to compensate for those flaws and to enhance access for the transport disadvantaged, a range of complementary services have been implemented. Throughout the nation, over 5200 public and private non-profit transit agencies are providing demand responsive transport services. The Metropolitan Transit Authority (MTA) in Des Moines, Iowa has offered an On-Call service to support elderly residents living around suburban Johnston. The elderly, when they need the service, can call the On-Call service bus drivers directly. Another similar On-Call service in Urbandale provides the elderly with connection services to and from park-and-ride lots as well as express bus services during rush hours. Charlotte Transit (North Carolina) provides subsidized vouchers for local taxi services for elderly residents who neither live close to public transportation routes nor are eligible for transportation assistance offered by human service programs. Valley Metro System in Phoenix, Arizona, has purchased low-floor buses for seniors’ easy access and these buses currently account for 80% of its fleet (American Public Transportation Association 2005). COTA in Columbus, Ohio, equipped all fixed-route buses with appropriate devices to assist those dependent upon wheelchairs and other mobility devices. It also operates paratransit programs called ‘Will Call Program’, ‘Main Stream’ and ‘Sedan Voucher’ to serve those who are not functionally capable of using fixed-route
buses (Central Ohio Transit Authority 2006, 2007a, 2007c). Other minor system enhancements have been suggested such as kneeling features, lift devices and low floors for buses, low platforms, better sidewalks and resting places (American Public Transportation Association 2007).

As discussed above, many programs have been implemented to enhance services for the transport disadvantaged. Unfortunately, current implementation is mostly limited to serve the disabled and the elderly. There are other transport disadvantaged people excluded from existing programs: who are the young, the poor and people with no personal vehicle. Another concern is that system enhancements such as kneeling features and lift devices do not directly relate to access improvement, which is the main focus of this research. The other problem of current programs is that paratransit and community transport are not integrated services into fixed-routes but separate complementary services. The Americans with Disabilities Act (ADA) stipulates “fixed-route bus service shall be the primary means of public transportation for everyone, including people with disabilities.” Vuchic (1981) also argued that paratransit should be integrated in the urban transport system. These arguments suggest that it is worthwhile to study the integration of equity issues into fixed-route systems to enhance the level of service favoring the transport disadvantaged.
2.5. *Access and accessibility*

Measuring accessibility and developing methodologies to achieve accessibility is important since it can help facilitate better transportation planning, land use planning, building designs, access to employment opportunities and other facilities benefiting various social groups (Church and Marston 2003, Kwan et al. 2003). There have been various kinds of classical accessibility measures, and they have been applied to analyze social problems for a long time now.

Topological measures focus on the presence and number of links rather than measuring actual distances between network nodes (Pirie 1979). Distance measures are approaches to measure accessibility of one place to another. ‘Relative accessibility’ is the simplest way to measure accessibility of one place. The basic idea is that accessibility is highest when points are close together. Distance, time or cost work for separation measures. ‘Integral accessibility’ measures accessibility of one place to all other places, which is an integration of all relative accessibilities from a given point to all other points (Ingram, 1971). Hansen (1959) introduced Gravity measures and discussed that the key idea is the number of opportunities at one particular node, known as a destination, is discounted by the distance of the node from some reference point, known as an origin. The discounted number of opportunities is a measure of the relative accessibility of opportunities at the destination. Cumulative-opportunity measures depict the accessibility of various opportunities based on the number that can be reached from the origin of interest within specified travel distance or times. One big difference between the Gravity measure and
this measure is that the Cumulative-opportunity measure does not reflect decay as
distance increases (Pirie 1979). Hägerstrand (1970) was the first to propose Space-time
accessibility. The concept behind this measure is the idea of a time geographic
framework. It shows that time cannot be separated from space when activity participation
and accessibility are examined. A space-time prism consists of a set of isochrones, lines
of equal travel time, based on travel from a given location. The allowable travel velocity
determines the spacing of the isochrones and the volume of the space time prism. With
two different travels anchor at two fixed locations, they delineate a time budget for
discretionary travel. The space-time prism provides remarkable insights into accessibility.
It is useful for transportation system analysis and travel decision making when
incorporated into GIS.

From a transportation perspective, a more sophisticated measurement approach is desired
since transportation systems exist to increase participation in activities associated with
time and space (Miller and Shaw 2001). Handy (1997) discussed that accessibility results
from the spatial distribution of potential destinations, the ease of reaching each
destination, and the magnitude, quality, and character of the activities found here. He also
argued that less travel cost, such as less time and money, more destination choices, and a
variety of travel choices are key factors for greater accessibility. Therefore, both land use
and the nature of the transport system determine the accessibility. While most definitions
of accessibility discussed above deal with ease of connection between two different
locations, such as origin and destinations, Murray et al. (1998) suggested that access be
differently defined. Access is an opportunity to use a transport system in terms of a person’s proximity to service and cost. In other words, access is determined by the distance or the barriers from the user to service locations, such as bus stops. That is to say, a longer distance to service locations will discourage users to use those services. However, access and accessibility are interdependent and both are important for a successful public transportation system. Murray and Davis (2001) presented three major factors relating to access, one of which contributes to being transport disadvantaged. One factor is constraints on locational choice, such as cost of housing and proximity to family or employment. Another factor is dispersed services that arise from the location of employment, education, shopping, and recreation. The last factor is inadequate transportation, which means poor or no access either to public or to personal transportation. All three factors concern access issues, but the third, inadequate transportation, relates especially to issues of access to public transportation. Transport disadvantage reflects the link between where people live, work and need to travel to/from and public transportation. It is clear that assessing and enhancing the level of access for the transport disadvantaged is vital. Few studies involve access and accessibility analysis to enhance the level of equity in public transportation. Ensuring greater mobility for the transport disadvantaged directly addresses the access problem identifying whether or not they have suitable proximity to transport service locations.

While classical location models have been used for measuring accessibility to services for a long time, coverage and location-allocation models have continuously evolved in
research. There are many location models, but these two methods have been more widely used and developed (Kwan et al. 2002). *P*-median problem is probably the most commonly applied location-allocation model. This model assumes that users will travel to their closest facility or center to minimize travel cost. The model is referred to as the location-allocation model because it suggests both the optimal locations of facilities and the allocation of customers to facilities at the same time. Coverage models, on the other hand, involve each of the models discussed above and will be further discussed in greater detail in the following sections.

The level of access of a geographical area can be described in terms of the coverage by public transportation to the population. Murray and Davis (2001) discussed an approach for determining access coverage that compares the shortest distance from the closest stop in a residential area to a distance-based access standard. Studies have evaluated the level of access based on equity attainment and on general context. They stipulated a suitable access standard of 400 meters from residential areas to transportation stops (Demetsky and Lin 1982, Levinson 1992, Federal Transit Administration 1996, Ammons 2001, Murray 2001, Cha and Murray 2001, Murray and Davis 2001). COTA (1999) also requires that transportation stops should be located so that the distance from any residence to the nearest transportation stop does not exceed one quarter mile (400 meters), based on the notion that people prefer to walk at most a quarter mile to reach a transportation stop. If an area or residence is within a distance from the nearest
transportation stop that is considered acceptable, then the area or residence has adequate public transportation access coverage (Cha and Murray 2001).

Sanchez (1999) showed how to measure the level of access to bus route networks using an employment index in Portland and Atlanta. This measurement was further developed as transport planning agencies applied it to measuring public transportation coverage in a practical field (Larwin 1999). Even though these studies discussed the measure of access in public transportation, they did not include the equity issue. Litman (2002, 2007) tried to thoroughly address equity issues in transportation. They focused on overviews of transport equity from various perspectives, evaluation of equity impacts, incorporation of equity analysis into transportation planning, and financial issues. However, their discussion was qualitative and did not include evaluation of access coverage or its improvement. Murray and Davis (2001) measured public transportation access coverage of southeast Queensland, Australia as a part of an evaluation of equity levels. They effectively measured the level of equity and clearly presented how it was calculated, but this study was limited to the accessibility of origin-based demand, which did not include the measurement as to how conveniently the transport disadvantaged can reach their desired destination. Cha and Murray (2001) also measured the level of equity in public transportation using access of bus stop locations to the transport disadvantaged in Columbus, Ohio. Their study successfully included destination-based demand. Hodge (1995) created mobility/accessibility categories such as employment, shopping, medical, social service, education and downtown, using various forms of equity guidelines.
Murray et al. (1998) also discussed business activity, education, employment and recreational opportunities as activities that an urban population needs to access. These categories were utilized to establish data for destination-based demand measurement.

2.6. **Optimizing access**

The Location Set Covering Problem (LSCP) was first detailed in Toregas et al. (1971). This problem was developed to identify the minimum number of facilities and their locations where each demand unit is satisfied by being located within a prespecified distance or time away from a facility (Church and Gerrard 2003). The Location Set Covering Problem has been applied to many to resolve real world problems. Toregas et al. (1971) developed this model for locating emergency facilities. Gleason (1975) applied the LSCP to analyze the locations of bus stops. Murray (2001) applied the LSCP to public transportation to measure the degree of redundancy and inefficiency of the location of public transportation stops in Brisbane while maintaining equal access coverage. There have been other modeling studies using more mathematical approaches to achieve better access to public transportation. Wirasinghe et al. (1981) tried to determine optimal spacing of bus stops along a local bus route. Furth et al. (2000) developed a model to evaluate the impact of changing bus stop spacing on a bus route in order to make the best stop location decisions.

Other studies involve improving public transportation access associated with service effectiveness or cost effectiveness. Measuring the degree of redundancy and inefficiency
of the public transportation stops is an instance of improving public transportation access related to service effectiveness (Murray 2001). Minimizing the redundancy is one means to offer better service to users. Time is another factor that affects users’ choice in terms of service effectiveness. Total travel time while the public transportation is running also influences users’ willingness to travel with public transportation (Levinson 1983). Cost of public transportation is an issue that involves users’ choice. Furth and Rahbee (2000) identified different types of costs that determine riders’ willingness to travel with public transportation. People believe that reduced cost promotes passengers to choose public transportation. Saka (2001) identified that fewer stops resulted in faster travel speeds and this, in turn, decreases operational costs of the public transportation.

The Maximal Covering Location Problem (MCLP) was first introduced by Church and ReVelle (1974). This model identifies optimal locations of a fixed number of facilities in order to satisfy as much demand as possible within a desired service distance or time (Church and ReVelle 1974). This problem is useful to obtain an optimal given number of public transportation stops that maximizes access coverage to service stops within the prescribed distance standard. Current and ReVelle (1985) developed a multi-objective formulation by combining the maximal covering problem and the shortest path problem. Wu and Murray (2005) identified the tradeoff between public transit service quality and access coverage by expanding this model to multiple route systems, called Multiple Route Maximal Covering/Shortest Path Problem (MRMCSP).
An adjustment of public transportation routes is another way to enhance users’ access to the public transportation service. However, few studies have argued public transportation routes contribute to access problems (Ramires and Seneviratne 1996). Ramirez and Seneviratne (1996) developed two methods for improving public transportation routes using socioeconomic and demographic data. Their models either decreased travel distance or significantly increased route coverage. The result of significantly increased route coverage was achieved at the expense of increased travel time, which implies that conflicting objectives, such as travel time versus route coverage, makes network design difficult.

Dantzig et al. (1954) introduced a Traveling Salesman Problem (TSP) to identify the minimum cost of visiting a set of cities one time from an origin city back to the city of origin. This model is useful to define shortest path or least cost only if the route is limited to loop travel and the condition of one visit at a time. In reality, however, it is not necessary for a salesman to visit every city on the route. It is sufficient for several cities to be near a stop on the route as a group (Current and Schilling 1989). Current and Schilling (1989) presented a Covering Salesman Problem (CSP). This model is an extension of a Traveling Salesman Problem. It improves upon the unrealistic assumption that the salesman must visit each city on the network: that is, the model identifies the shortest or least cost tour of given cities such that every city is within some preselected covering distance standard of a city that is located on the city. They suggested many potential applications of the CSP, such as designing a collection/delivery route for a
bimodal distribution system and routing health care delivery teams in developing countries where the route does not need to visit all villages on condition that a stop within a certain maximum distance of all villages is included in the route.

Current et al. (1984) developed a Shortest Covering Path Problem (SCPP). This model is a synthesis of the Location Set Covering Problem and the Shortest Path Problem. While the Location Set Covering Problem focuses on seeking an optimal facility set, the Shortest Covering Path Problem further develops optimization of the network connecting the chosen facility set. Therefore, the Shortest Covering Path Problem defines the shortest or least costly route from a given starting point to a given destination point, connecting all demand nodes on the path. If any demand nodes are located on the route or if a demand node is located within a preselected maximum distance from a node on the route, then the node is considered to have enough coverage.

Previous sections discussed various sorts of modeling methods for improving transport facilities, such as service stop locations and route arrangement. However, they are not oriented to develop the level of equity. This research will apply and develop models to enhance the level of access to serve the transport disadvantaged better.

2.7. Facility siting on a continuous road network

Models are developed to identify either the optimized number of facilities and their locations or shortest or least costly route. These models are, however, based on
prespecified locations of potential facilities. An issue of facility placement arises in that selecting facility location in continuous space is a challenging problem. In this research, how public transportation stop locations can be placed along a continuous road network will be discussed. Many studies have involved bus stop placements or designs (Wirasinghe and Ghoneim 1981, Demetsky and Lin 1982, Federal Transit Administration 1996, Furth and Rahbee 2000, Saka 2001) but methodologies developing stop placements along a continuous road network maximizing the coverage of demand for mass transit have not been discussed.

Facility placement in continuous space has been a major concern since Weber’s (1909) single siting problem in pursuit of minimal total transportation costs. This simple but leading work has been followed by various spatial optimization problems locating facilities in continuous space to maximize or minimize spatial planning objectives. Due to the fact that siting facilities in continuous space involves consideration of an infinite number of facilities, it has been occasionally challenged by computational difficulties (Murray and Tong 2007). However, those shortcomings have been overcome by academic and technological advances, and accordingly more studies regarding siting facilities in continuous space have been presented.

Matisziw and Murray (2007) developed a method to site a single facility in continuous space to maximize coverage of a region by using medial axes of polygon units to identify potential facility locations. The continuous space $p$-center problem using Voronoi
diagrams is another example of siting facilities in continuous space (Suzuki and Drezner 1996, Suzuki and Okabe 1995, Wei et al. 2006). An approach for identifying a finite set of covering point locations by discretizing continuous space has been developed by Church (1984) and Mehrez and Stulman (1982). It is noticeable that this point set inevitably includes the optimal points to appropriately cover corresponding demand points since the point set was derived from the demand. Church (1984) defined this approach as Circle Intersection Point Set (CIPS) since this point set discretizing continuous space intends to optimize the coverage of point-based service demand. Unlike the feature of CIPS based on point-based demand (Church 1984), Murray and Tong (2007) developed PIPS to identify locations which can cover areal extents of demand. While CIPS is an abstraction of point-based demand, PIPS include more general representations of demand, such as point, lines, and polygons.

Using the idea of CIPS, Church (1984) and Mehrez and Stulman (1984) developed the Planar Maximal Covering (PMC) location problem. PMC is an application of the MCLP on the plane, that is, two-dimensioned continuous space. Mehrez and Stulman (1984) addressed that siting fire stations or radar stations are possible applications for the MCLP in the public sector. Murray et al. (2007) applied this method to placing emergency warning siren stations in a continuous region. There have been a range of studies developing methods for discretization of demand on a continuous surface and applications to planning fields. However, none has been discussed regarding network incorporation into the discretization such as road network in a transport system.
2.8. **Spatial representation**

Spatial representation has been a major concern in geographical analysis. To analyze geographical access, a point- or zone-based framework can be adopted. For example, entities such as neighborhoods, towns or cities can be represented using points, and a continuous space such as Census tracts or Census block groups can be represented using a zone (Murray and O’Kelly 2002). In facility location research, while a service facility can be located only in a finite number of locations when it is analyzed in a point-base framework, a service facility can be located anywhere in the region when it is analyzed in a zone-based framework (Miller 1996). Typically in location modeling analysis, however, space itself, locations of facility, and regional demand have been represented as discrete points (Bennett and Mirakhor 1973, Miller 1996, Mirchandani and Francis 1990, ReVelle 1991, Church 1999, Murray and O’Kelly 2002, Murray and Tong 2007). Herein, Openshaw and Taylor (1981) and Current and Schilling (1990) noted that inaccuracy of the results may occur when representation of space is utilized.

Understanding the Modifiable Area Unit Problem (MAUP) is useful because frame-dependence was observed in spatial optimization (Murray 2005), which suggests that the solution of spatial models may be subject to choice of scale or definition of units. MAUP is a form of ecological fallacy associated with the aggregation of data into areal units for geographical analysis (Openshaw 1984). The MAUP observes the problem of changing the shape (i.e. the aggregation problem) or size (i.e. scale problem) of the geographical
units containing the data can change the location model results. Significantly different analytical results can be derived when data is gathered and reported at different resolutions or units of aggregation.

As mentioned before, Miller (1996) also notes that point-based representation can cause computational error because representing complex vector objects, such as lines and polygons, with points is too simplistic given current advanced GIS technology. Murray and O’Kelly (2002) specified that the error caused by point-based representation in coverage-based location modeling could result in over-estimation of the actual coverage measured. In order to overcome this problem, Murray and Tong (2007) proposed a method, PIPS, to site facility locations in continuous space to serve not only point-based demand but also line- and polygon-based demand. This method substantially reduced the necessities for reducing zone-based demand into points by utilizing the zone-based demand as it is in coverage modeling. PIPS is generally applicable to continuous planar space. However, it is not specifically applicable to continuous linear space, such as public transportation route.

2.9. **Summary**

The literature has discussed equity in social context and generally concerns the distribution of income, goods, or services. The concept of equity in a geographical context is similar to that in the social context, but more focuses on distribution in geographical locations, especially in urban systems. Equity in transportation is commonly
associated with the provision of appropriate transport for people who need public 
transportation. Hodge (1995) detailed the concept of equity in transportation using 
financial equity and beneficial equity. Beneficial equity is further divided into two 
concepts, fiscal equity and service equity. Service equity is again classified into 
spontaneous inequity and systematic inequity. This systematic inequity is associated with  
service provision favoring minority groups, low-income people, and the transport 
disadvantaged. Many studies characterized the transport disadvantaged using various 
notions and the following five notions are most common: the young, the old, the disabled, 
low income people, people with no personal vehicles.

More and more transit agencies try to improve accessibility to favor the transport 
disadvantaged. Paratransit is one of widely used system as a part of DRT. There are other 
types of services to support DRT, such as On-Call service, Will Call program, Main 
Stream, and vouchers for taxi services. Other system enhancements are also implemented 
including kneeling buses, lift devices, low floor buses, and low platforms. However, all 
of these implementations do not necessarily favor all types of the transport disadvantaged, 
do not directly improve access to the transport disadvantaged, and are not operable in 
fixed-route systems.

Access and accessibility are essential concepts in discussing transportation issues. Most 
definitions of accessibility are associated with ease of connection between two remote 
places. In contrast to this, access is differently defined as an opportunity to use a transport
system depending upon users’ proximity to service and cost. Given this, the level of access of a public transportation can be evaluated by distance-based coverage by stop location to population. A distance from service stop to origin or destination of 400 meters is considered provide adequate access.

There are many methods developed to maximize access. LSCP identifies the least number of facilities and their locations while demand area is covered by prescribed distance or time. MCLP was developed to seek optimal locations of a given number of facilities maximizing coverage of demand within a prespecified effective service distance or time. Other models, such as TSP, CSP, and SCPP were proposed to enhance access in locational problems. All applications of the models above have not addressed equity issues in public transportation.

Analysis in geographical access has raised important issues. One aspect in the models discussed above is that these models are based on prespecified locations of potential facilities. CIPS and PIPS were developed to locate potential facilities over continuous space. CIPS is developed to maximize the coverage of point-based service demand and PIPS extends the types of demand for coverage to polygon including points and lines as well. However, both methods seek discretization of continuous planar space, not a continuous network, such as a road network. There is another issue in spatial representation concerning the geographical analysis. A point- or zone-based framework can be utilized in analysis of geographical access. As previously discussed, since
representing complex vector objects (such as lines and polygons) with points is too simplistic given current advanced GIS technology, computational error can be caused by point-based representation. Such computational error could result in over-estimation of the actual coverage measured in coverage-based location modeling.
CHAPTER 3

3. MODELING ACCESS

3.1. Introduction

This chapter presents a methodology for modeling access to enhance equity in a transit system. We begin with data preparation and processing issues. Following this, model development is detailed. Next, a Polygon Intersection with Network Point Set (PINPS) will be developed. Collectively, this chapter enables access to be modeled in order to address issues of equity in transit planning.

3.2. Planning context and data

The city of Columbus in Franklin County, Ohio is currently experiencing enormous growth and is now the fifteenth largest city in the United States (U.S. Census Bureau 2007). The Mid-Ohio Regional Planning Commission (MORPC) has projected that central Ohio will experience a 35% increase in population and a 48% increase in employment by 2030 (Central Ohio Transit Authority 2007b). This growth has caused traffic problems and raised a number of transport issues. Public transportation, which is managed by COTA, has played an important role in trying to solve these problems. COTA has been trying to improve transport accessibility and to expedite mobility by
serving residents and employers through self-diagnosis such as COTA’s Planning and Development Guidelines For Public Transit (COTA 1999). Like most large urban public transportation systems, COTA is dependent on substantial governmental subsidies. The status and amount of these subsidies are important because COTA plans to extend its services in various ways. This research intends to develop ways in which COTA can feasibly expand services while achieving goals of providing access to the transport disadvantaged and equity to the residents of central Ohio.

This research requires collecting various types of data including public transportation related data, socio-economic data, demographic data and land use data. Since this research involves public transportation facilities, basic data associated with public transportation are required, which are Franklin county road network data, COTA bus stop location data, COTA bus route data.

In order to identify the origin-based transport disadvantaged, socioeconomic data and demographic data are required. Many studies have defined the category of the transport disadvantaged and they are summarized in Falcocchio and Cantilli (1974), Taebel and Cornhels (1977), Morris (1981), Starrs and Perrins (1989), Morgan (1992), Murray and Davis (2001), and Cha and Murray (2001) as comprising the following groups:

**Young:** people aged under 14 years

**Old:** people aged 65 and over

**Low household income:** below $15,000 per year
Household with no vehicle

Disabled people

Data was extracted from the 2000 Census. There are three levels of statistical boundaries that are considered: Census tracts, Census block groups, and Census blocks. Census tracts are too crude to perform the intended analysis in sufficient detail, while Census blocks do not have the needed information associated with the above five indicators. Census block groups are the smallest geographical unit satisfying the availability of all five indicators listed above.

When five indicators were applied to need with origin-based demand, ages 14 and 65 were used as breakpoints for “young” and “old” respectively. Age 14 is derived from the fact that people are allowed to drive legally when 16 years old in Ohio (Ohio Bureau of Motor Vehicles 2007). The cohort broken by age 16, however, was not available, so the closest age value was alternatively selected. For age 65, choosing this age is relatively obvious, since this is a starting year of people’s Social Security (U.S. Social Security Administration 2007). There is no doubt that this is a clear watershed for people’s age. The US Census Bureau established the poverty threshold for the year 2000 to be $17,050 for a four-person household. (U.S. Department of Health and Human Services 2007). The 2000 Census data household category of “income less than $15,000” is closest to the standard discussed above. For the disabled people, data was based on work disability aged 16 and higher in 2000 (Centers for Disease Control and Prevention, 1993).
For the evaluation of destination-based demand, land use data characterizing attractive destinations are necessary. Several indicators can be used, such as employment, shopping, medical, social service, education, downtown, and recreational opportunities (Hodge 1995, Murray et al. 1998, Cha and Murray 2001). These variables appear to be alike in many ways, so five common and essential indicators are extracted: employment, shopping, amenity facilities, educational institutions, and public service facilities.

Employment data is taken from Franklin County business information (source: Center for Urban and Regional Analysis (CURA) at the Ohio State University). Data for the other four indicators is taken from Franklin County land use data (source: CURA). The business information contains 41,552 names of businesses, their addresses, selected Census characteristics, geocoded spatial coordinates, and other information. The land use data consist of parcels coded for land use by the Ohio Board of Tax Appeals. Geocoding this data produced 12,992 useable parcels. Geocoded coordinates were used to relate both business and land use data to Census block groups. Among the five indicators, employment is unique. Employment places may include all other categories. For instance, even though a location is classified as a shopping center in terms of land use, and thereby a destination for shoppers, it can also fall under the employment category because it is a work place for shopping center employees. In fact, all four of the other indicators are likely to overlap with employment. In the destination-based approach to public transportation planning there are differences in attractiveness. For example, some types of shopping attract more customers due to higher quality, lower price, and better
shopping environment. Such distinctions among levels of attractiveness affect the level of demand for a given destination. However, including this effect in this research is not possible, as the appropriate data is unavailable. Consequently, only the number of facilities of each indicator in a Census block group will characterize the level of need in destination-based demand.

The five factors of the transport disadvantaged were used to assess the level of need for origin-based analysis. The greater the prevalence of these characteristics in an area, the higher the level of need for public transportation is likely to be. For the destination-based analysis, they utilized the five common indicators to determine areas which these people will likely demand to be served. Like origin-based analysis, the more an area has of activities with such characteristics, the higher the level of destination attractiveness.

The following notation introduces the index approach that was used in the analysis by Cha and Murray (2001) to identify the level of need for public transportation.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i$</td>
<td>Index of geographic areas</td>
<td>Each Census block group</td>
</tr>
<tr>
<td>$j$</td>
<td>Index of indicators</td>
<td>Each of ‘age under 14’, ‘age over 65’, ‘income below $1,500, etc</td>
</tr>
<tr>
<td>$R_{ij}$</td>
<td>Derived value of indicator $j$ in geographic area $i$</td>
<td>·</td>
</tr>
<tr>
<td>$\Phi_i$</td>
<td>Integrated measure of relative need</td>
<td>·</td>
</tr>
</tbody>
</table>

Table 3.1: Notation used in index approach
Once each demographic indicator is indexed by their values respectively, then all potential need for public transportation can be integrated using the following function:

\[ \Phi_i = f(R_{i1}, R_{i2}, \ldots) \]

10 intervals were created for the index purpose, with values from 1 to 10 consecutively. Thus, the derived value of each indicator in \( R_{ij} \) in each geographic area will be an integer from 1 to 10. In this context, the highest value will be 10, characterizing ‘Most Needy’, and the lowest value will be 1 depicting ‘Least Needy’.

It is challenging to choose an appropriate mathematical function for integration of values derived from indicators. Even interpretation of a simple summation is not necessarily straightforward. The previous research utilized both summation and multiplication in order to explore how analysis results may differ in application. However, this study only adopts the result by summation since this result is necessary for the base data purpose only. This result, as already performed research, only provides criteria for the areas of transport disadvantaged with high demand and poor access to the current public transportation.

The level of access of a geographical area can be described in terms of coverage by public transportation stations. Murray and Davis (2001) and Cha and Murray (2001) discussed an approach for determining access coverage that compares the shortest distance from the closest stop in a residential area to a distance-based access standard. As
a large literature suggested, 400 meters is used for the distance standard. Therefore, if an area or residence is at a distance from the nearest transportation stop that is within the 400 meter access standard, then the area or residence has adequate public transportation access coverage. In the assessment of suitable access, an assumption of uniform distribution is necessary for dealing with residential populations in Census block groups. The areal proportion of Census block groups covered gives the percentage of the population suitably served.

The percentage from 0 to 100 needs to be divided into 10 classes with a classification scheme as was done for indexing of need. These 10 classes are indexed 1 to 10. The highest percentage value will be allocated to 1 representing ‘best served unit by public transit stop’ and the lowest percentage value will be assigned to 10 referring to ‘worst served unit by public transit stop’. These indexes, denoted as $\Psi_i$, indicate the level of access. In this context, the highest value will be assigned to 10 characterizing ‘Most Needy’ and the lowest value will be allocated to 1 depicting ‘Least Needy’.

The next step is to identify the transport disadvantaged areas by integrating the levels of need and of access. Cha and Murray (2001) developed an integration approach using thresholds. This approach specifies a threshold for need in order to characterize areas as needy or not needy. This is done using the following notation:

$$\alpha = \text{threshold for need}$$
$$\beta = \text{threshold for access}$$
Given need for service $\Phi_i$ and level of service $\Psi_i$, equity may be evaluated as follows:

$\Phi_i \geq \alpha$, then the area has a high level of need

$\Psi_i \geq \beta$, then the area has a low level of access

Choosing the threshold is arbitrary whether or not this choice is defendable. They consider using the mean and median, measures of central tendency to select thresholds (McGrew et al. 1993). Their research adopted the mean and the median values as thresholds for integrating need and access. Again, this study chooses only a set by mean as a threshold.

As a result, shown in Figure 3.1, Cha and Murray (2001) identified areas of the transport disadvantaged featured with high demand for current public transportation but with poor access to it in Franklin County, Ohio based on both origin-based demand and destination-based demand. This identification of the transport disadvantaged areas is very important because the goal of the following analysis is to maximize coverage by new stop locations for the transport disadvantaged population.
3.3. Model Formulation

One of the goals of this research is to identify optimal transit stop locations to provide maximal coverage to the areas with high public transportation demand but with poor current access to the public transportation. To this end, the MCLP of Church and ReVelle (1974) makes sense because the model identifies optimal locations of a fixed number of facilities in order to satisfy as much demand as possible within a prespecified service standard. The model formulation is as follows:

Maximize \[ \sum_i a_i Y_i \]  
Subject to \[ \sum_{j \in N_i} X_j - Y_i \geq 0 \quad \forall i \]  

\[ (3.1) \]
\[ (3.2) \]
\[ \sum_j X_j = p \]  \hspace{1cm} (3.3)

\[ X_j \in \{0,1\} \quad \forall j \]  \hspace{1cm} (3.4)

\[ Y_i \in \{0,1\} \quad \forall i \]

Where

\( i \) = index of demand parcels;

\( j \) = index of potential facility locations;

\( a_i \) = area for demand parcel \( i \);

\( N_i = \{ \text{set of potential facilities } j \text{ capable of covering demand parcel } i \} \)

\[ = \{ j | d_{ij} \leq R \} \]

\( p \) = number of facilities to site;

\( d_{ij} \) = shortest distance from demand parcel \( i \) to potential facility \( j \);

\( R \) = the distance that could be traveled to suitably cover demand parcel;

\[ Y_i = \begin{cases} 
1, & \text{if demand } i \text{ is suitably covered} \\
0, & \text{otherwise} 
\end{cases} \]

\[ X_j = \begin{cases} 
1, & \text{if a potential facility } j \text{ located} \\
0, & \text{otherwise.} 
\end{cases} \]

The objective (3.1) is to maximize the total demand covered within the prescribed service distance; in our case this is 400 meters. Constraint (3.2) tracks with service areas provided suitable coverage. Constraint (3.3) specifies \( p \) transport stops to be located. Constraint (3.4) imposes integer requirements on decision variables.
3.4. **Representing potential stops**

In order to overcome the limitation of needing to prespecify potential facility locations to implement the MCLP, Church (1994) and Murray and Tong (2007) suggested planar versions of the MCLP, called Planar Maximal Covering Problem (PMC) and the Extended Planar Maximal Covering Location Problem-Euclidean (EPMCE) respectively. Both approaches relax the requirement of discrete facility locations by allowing facilities to be located anywhere in continuous space. While the PMC maximizes coverage for point-based demand, the EPMCE maximizes coverage for various types of demand objects; that is, not only points but also lines and polygons. The EPMCE is very useful for providing unbiased and complete coverage for demand objects (points, lines, or polygons), eliminating the need for a single point representation that possibly misleads the actual coverage assessment. This is especially true, when areas consist of zone-based demand, such as Census geography units (e.g., tracts, block groups, or blocks).

Before proceeding, it is necessary to examine how continuous space is discretized based on point, line and polygon demand objects. Murray and Tong (2007) first proved coverage properties of points, lines and polygons. This research is carried out based on Census geography units or parcels. The coverage properties of polygons will be primarily discussed.
Figure 3.2: Coverage of Polygon $ABCD$ by facility $F$

Figure 3.2 shows coverage of polygon $ABCD$ covered by facility $F$ within service radius $R$ based on Euclidean distance. The polygon coverage property stipulates that if each end point of line segment in given polygon $ABCD$ is covered by facility $F$ within service radius $R$, any point on the boundary or inside the polygon is also covered by facility $F$. The proof of this property is as follows: If each vertex of polygon $ABCD$ is covered by facility $F$ within prescribed service standard $R$, any line segments formed by a pair of vertices from the polygon $ABCD$ are also covered by facility $F$ by the property of line segment coverage\(^1\). This discussion, therefore, proves that the boundary of polygon $ABCD$, a set of line segments, is covered by facility $F$ within service standard $R$.

\(^1\) The property of line segment coverage is defined as: If any two points are both covered by a given facility within the prespecified service standard, any additional points on segments formed by the two points are also covered by the facility (For further details of proof of property of line segments, see Murray and Tong 2007).
Next, the coverage inside polygon needs to be discussed. Point $M$ is located inside polygon $ABCD$ in Figure 3.2. Consider a line passing thorough $M$ in any direction. This line will intersect any two or more line segments of the polygon boundary. In the example from Figure 3.2, there are two intersection points, $\theta_1$ and $\theta_2$. Based on the discussion of line coverage above, both $\theta_1$ and $\theta_2$ are covered by facility $F$ since they are on the boundary of the polygon. In addition, according to property of line segment coverage, point $M$ is also covered by facility $F$ since $M$ is located on line segment $\overline{\theta_1 \theta_2}$. Thus, the above two discussions prove that if each end point of a line segment in given polygon $ABCD$ is covered by facility $F$ within service radius $R$, any point on the boundary or inside the polygon is also covered by facility $F$.

Polygon coverage by a facility within the suitable service standard can be defined. This extends to the identification of the area for which placement of facility provides the desired coverage of given demand. This area is called the ‘covering boundary’ in this research. How to derive this area will be discussed next.
Figure 3.3: Identifying covering boundary

Part (a) in Figure 3.3 shows a polygon representing a spatial extent of demand. In order to create the covering boundary for this polygon, all circles of radius $R$, which is the prescribed service standard, are centered on each vertex and are drawn in Figure 3.3 (b). This is followed by finding the overlapping areas of all circles in Figure 3.3 (c). Since the hatched area in Figure 3.3 (c) shows the overlapping area by all four circles, a facility located anywhere in this space is ensured to cover all four vertices, $ABCD$. By the
property of polygon coverage discussed earlier, it is clear that polygon $ABCD$ is completely covered by the hatched area. Thus, any point on or inside the covering boundary completely covers the polygon $ABCD$ with prespecified service distance $R$.

**Figure 3.4:** Creating Polygon Intersection with Network Point Set (PINPS)

Once covering boundaries are discovered, identifying the intersection point set on the road network is necessary. In Figure 3.4, any point as facility in or on $K_{ABCD}$ can serve demand polygon $ABCD$. Likewise, placing any facilities in or on $K_{EFGH}$ serves demand polygon $EFGH$. In terms of efficiency of maximizing coverage, the overlapping covering boundary shown as the hatched area in Figure 3.4 is very important and is called the
‘critical location’\(^2\). A facility placed in an overlapping covering boundary provides coverage for multiple demand areas. Therefore, PIPS by Murray and Tong (2007) was developed as a set of intersection points of overlapping covering boundaries to locate potential facilities over continuous planar space.

This research, however, utilizes a road network. Potential transit facilities are located strictly along a continuous road network. The idea of discretization of continuous space from PIPS is selectively adopted because a road network is also one kind of continuous space even though it is linear-featured, not planar-featured. This research uniquely develops a method to discretize a continuous linear feature. In this research, the linear feature is a road network. There are four intersection points, \(\gamma_1, \gamma_2, \gamma_3,\) and \(\gamma_4\) created by the covering boundaries and road network. Facilities placed on \(\gamma_1\) and \(\gamma_2\) provide coverage to both polygons \(ABCD\) and \(EFGH\) because the facilities are sited in this critical location. Unlike \(\gamma_1\) and \(\gamma_2\), facilities located on \(\gamma_3\) and \(\gamma_4\) only cover their corresponding polygons, that is, \(\gamma_3\) covers polygon \(ABCD\) and \(\gamma_4\) covers polygon \(EFGH\). Thus, facilities sited on intersection points with overlapping areas have advantages over the facilities placed on intersection points with unoverlapped covering boundaries. This implies that selecting those points within overlapping areas is more efficient assuming that all demand polygons have overlapping areas. In the real world, however, in areas

\(^2\)The critical locations are the overlapping covering boundaries of the CIPS (Church 1994) and PIPS (Murray and Tong 2007). It is known that these critical locations contain optimal solutions to the planar maximal covering location problem with Euclidean travel distances (PMCE) (Church 1994) and the Extended planar maximal covering location problem with Euclidean travel distances (EPMCE) (Murray and Tong 2007).
such as Census geography units, there might exist demand zones that are not close enough to create overlapping covering boundaries. In this case, only points intersecting with mutually exclusive covering boundaries will be available. If those points are not included in the potential facility locations, it is possible that those remotely located zones do not have any locations that can cover their demand. For this reason, such locations, $\gamma_3$ and $\gamma_4$, should be included in the model as potential facility sites. On the other hand, some facility points on the unoverlapping covering boundaries might be unnecessary to consider as potential facilities. Those redundant points will be removed due to the nature of the MCLP. A set of points shown in Figure 3.4 is called Polygon Intersection with Network Point Set (PINPS) in this research. This set of points was created by the method to locate potential facilities along a continuous road network. Also, these points provide complete coverage to polygon-based demand when used as potential facilities. The development of this set of points via this method is a core contribution of this research.

In order to create potential facility sites on a continuous road network, the following approach is developed. As shown in the flowchart in Figure 3.5, the first step is identification of demand polygon in the research area. Second, polygon vertices are to be extracted. Third, circles for each demand polygon vertex are drawn and overlay to find covering boundaries. Fourth, intersection points of road network with covering boundaries are extracted. Last, redundant points might be removed thereafter for computational efficiency. Demand polygons in this research are land parcels. Further details regarding the parcel data will be discussed later. The second thorough last steps
are manipulated by standard and customized GIS functions. The second, third, and fourth steps are central processes of PINPS and the last step is optional, but this research carries out redundancy removal because this removal brings an enormous reduction of data volume for potential facility before MCLP is carried out.

Figure 3.5: Creation of potential facility sites on a continuous road network
Due to the fact that all intersecting points of covering boundaries with road network are included in the total set of potential facility locations, there are some redundant points. As shown in Figure 3.6 there are many intersecting points, but they have different coverage levels. Assuming that the number of coverage intersections with the road network corresponds to the level of coverage, point \( a \) has a level of 1. Point \( b \) has 2, point \( c \) 2, point \( d \) 2, and so forth. All points and their levels are searched by each polygon, which results in:

- **K1**: point \( a \) (level: 1), point \( b \) (level: 2), **point \( c \) (level: 2)**
- **K2**: point \( b \) (level: 2), point \( c \) (level: 2), point \( d \) (level: 2), **point \( e \) (level: 2)**
- **K3**: point \( d \) (level: 2), point \( e \) (level: 2), point \( f \) (level: 2), **point \( g \) (level: 2)**
- **K4**: point \( f \) (level: 2), **point \( g \) (level: 2)**, point \( h \) (level: 1)
- **K5**: point \( i \) (level: 1), **point \( j \) (level: 1)**
Polygon $K1$ includes three intersection points of $a$, $b$, and $c$. Point $b$ and $c$ both have a level of 2, so either point $b$ or $c$ can be selected. Since point $b$ and $c$ have the same covering levels and they produce no difference whichever is selected, the last one based on data ID number is chosen. Thus, in this instance in Figure 3.6 point $c$ in polygon $K1$, point $e$ in $K2$, point $g$ in $K3$, point $g$ in $K4$, and point $j$ in $K5$ are selected. Using this algorithm reduced 60% of total potential facilities by removing dominated points in terms of coverage level. Although dominated points were removed, there are still redundant points that can possibly be removed. Intuitively, another point set can be selected. One point from $b$ or $c$ can be selected from polygon $K1$ and $K2$. Another point from $f$ or $g$ can be chosen from $K3$ and $K4$. The last point from $i$ or $j$ can be selected from $K5$. In this case, all three potential facility locations can cover all demand provided in the covering boundaries. This intuitive method seems simple in the example, but it appears that developing a consistent algorithm for complicated real data is challenging. However, the given algorithm above already removed redundant points in the example. Further, it turned out that this algorithm removed enough redundant points for GIS and optimization software to easily handle potential facility data in this research.

In terms of the usable size of individual zone-based demand area, it is limited by the prescribed coverage standard $R$. Thus, one assumption is required in regard to the relationship between individual zone-based demand object and coverage standard $R$. The assumption follows that the size of demand objects is notably smaller than the prespecified coverage standard $R$. In more detail, the maximum diameter $D$ of the
minimum enclosing circle\textsuperscript{3} for a demand object should be equal to or smaller than twice the coverage standard $R$.

Murray and Tong (2007) similarly discussed the limitation of the maximum diameter $D$ of minimum enclosing circles. They argued that the maximum diameter $D$ of minimum enclosing circles is required to be equal to or smaller than the covering standard $R$. This is because we must find the overlapping areas between multiple covering boundaries, (the critical locations), to extract intersection point sets from the critical locations. These areas represent potential optimal locations. If the critical locations do not exist, intersection point sets in continuous space cannot be derived. This condition requires that the covering standard $R$ should be greater than the maximum diameter $D$ of the minimum enclosing circles as noted by Murray and Tong (2007).

This research, however, focuses on the intersection of road network with covering boundary. The requirement of only using critical locations as potential facilities is relaxed since any intersection points of the road network with the covering boundary are valid to be used as potential facilities, although intersection points of road network with critical locations have higher covering levels.

\textsuperscript{3} Minimum enclosing circle is the smallest circle that completely contains a set of points or formally, this circle is characterized with the smallest radius such that all points in the planar surface are contained either inside the circle or on its boundary (Wei et al. 2006, Xu et al. 2003).
Figure 3.7: Relationship with the maximum diameter $D$ of the minimum enclosing circles and the covering standard $R$
As shown in Figure 3.7 (a), when the maximum diameter $D$ is greater than twice $R$, no covering boundaries can be created. In this case it is suggested that the demand object needs to be partitioned or a covering standard $R$ might need to be increased. In Figure 3.7 (b) there are hatched overlapping areas serving as covering boundaries due to the condition of $D$ being less than half the size of $R$. If this requirement is not properly met in real data in the research area, zone-based demand objects need to be partitioned into smaller objects to meet this coverage area to minimum enclosing circle ratio, because the prespecified covering standard cannot be altered by nature of the research.

3.5. Summary

This chapter provided explanations for research preparation and model development. For research preparation, data collection was done to create both origin-based and destination-based demand for public transportation. This data set was processed and incorporated into the research area to develop base maps for both origin- and destination-based demand. Five demographic features were selected to build origin-based need: young, old, low household income, household with no vehicle, and disabled people. Another five features, employment, shopping, amenity facilities, educational institution, and public service facilities, were used for destination-based need. The level of access was evaluated for the current public transit system. All these analyses were integrated into the research area and produced the transport disadvantaged areas that are characterized as high level of need with a low level of access for both origin- and destination-based demand.
The other part of this chapter detailed the MCLP and development of the PINPS. The PINPS is based on CIPS (Church 1994) and PIPS (Murray and Tong 2007), but is applicable for the discretization of potential facilities along a continuous road network. The PIPS accepts all points, lines, and polygons as demand objects, but this assumes that potential facilities can be placed anywhere in a continuous plane. This is a powerful tool in terms of discretization in a collection of infinitive potential facilities, but more consideration is necessary when the continuous space is limited to line objects. The PINPS is developed to overcome this limit and, therefore, is more suitable when potential facilities are restricted to a network.
CHAPTER 4

4. ACCESS APPLICATION FOR ACHIEVING EQUITY

4.1. Introduction

This chapter identifies optimal transit stop locations to provide maximal coverage to areas with high public transportation demand but poor current access to public transportation using PINPS and the MCLP. An important contribution of this research is the improvement in implementing the MCLP using PINPS. The focus is an origin-based and destination-based access. Solution details and coverage patterns will be discussed for both approaches. Another part of this chapter is a bi-objective MCLP in order to reconcile these two separate objectives.

4.2. Data

In order to identify the optimal locations of public transportation stops maximizing zone-based demand, the MCLP was applied using PINPS. As discussed earlier in regard to the assumption that the size of demand objects is notably smaller than the prespecified coverage standard, the smallest zone-based demand objects should be explored. The data collected to characterize both origin- and destination-based needs are only available down to the Census block group for the area to be studied in this research. Unfortunately,
the diameter of maximum enclosing circles of an individual Census block group is far bigger than twice the prescribed covering standard, 400 meters. Therefore, discovering appropriate demand object units with suitable size is important. In order to satisfy this property of size between demand object and covering standard, the most suitable zone-based demand object is the parcel. However, the data that is required for this research is only available at Census block group level. Thus we need to transfer the data available at the level of the Census block group to parcels assuming an even distribution of demand in a given Census block group. That is, a demand characteristic of a Census block group is identical for all parcels in the block group.

Microdata\(^4\) from the Census can be obtained and one can develop his/her own data down to the Census block. It is true that Census block data is more detailed and smaller than Census block groups, but the size of the minimum enclosing circles for an individual Census block is generally still bigger than 800 meters. Thus, we need to find smaller demand unit objects, which possibly are parcels. Another discouraging factor in using Census blocks is that customizing user oriented data using microdata is labor and time intensive for the research area, because this task will involve tables from crude responses to Census questionnaires. Even if the customization was carried out, the information, again, should be transferred down to parcel data as we do for the Census block group due to the fact that this information is only available down to Census block. Therefore, using parcel data with data transferred from Census block groups is the most efficient way to

\(^4\) Microdata is detailed information available at the U.S. Census Bureau allowing users to build their own customized data set of most population and housing subjects (U.S. Census Bureau 2001).
represent this level of mass transit demand, both origin- and destination-based. However, there are still parcels bigger than 800 meters, which will be partitioned into the appropriate size. In all, information for each parcel was transferred from corresponding Census block group data assuming all obtained characteristics of the Census block group are evenly distributed over the entire block group. Even though different parcels might have different data values in one common Census block group, each parcel is considered to have an identical data value represented by the Census block group where they are located.

Figure 4.1: Parcels in the study area
The study area was limited to the City of Hilliard, Ohio. As shown in Figure 4.2, this city has many Census block groups identified as being transport disadvantaged. This fact encourages the use of this area in the research because the goal of the model is to maximize coverage for such areas meeting such demographic criteria. In addition, figure 4.1 shows that there are 363,838 parcels in Franklin County, and in terms of data handling efficiency and capacity of software and hardware, it is recommended to limit the research area to a part of Franklin County with a more reasonable data size. The City of Hilliard, Ohio has 9,646 parcels on the base map, and this is a number of parcels that is feasible for this analysis. This city also has an appropriate distribution of both origin- and destination-based characteristics.

Another needed data layer for transit access planning is the street network, which represents the public transit infrastructure and we will locate facilities on this continuous network. These potential facilities are characterized as bus stop, so streets that the bus fleet can be driven along are considered. Based on communication with COTA technical staff (Manczak 2007), there are no regulations stipulating road characteristics that indicate the suitability for carrying bus traffic. Thus, GIS analysis was carried out to filter roads to find the most suitable roads for bus operation. The street data used was originally created by ESRI and classified as freeway, highway, ramps and local roads. From these four classes, freeway, highway, and ramps were excluded, with local roads used as primary data set. Freeways, highways and ramps are excluded because bus stops cannot be located there. Residential streets could be controversial for inclusion. Some bus stops
are actually placed inside residential neighborhoods. Those properties can be coded in the data set, so whenever updates or new policies from public transportation operators are made, the data set is readily adjusted to include the new features by the standard functions of commercial GIS software.

**Figure 4.2:** Data transfer to study area (origin-based)

Figure 4.2 shows the parcel data that will be used for this analysis. All parcels shown are classified as transport disadvantaged with both high demands by the specified feature and low access to the public transportation stops. Originally, the demographic information used was available only down to Census block group data but was transferred into each parcel assuming demand of all individual parcels follows that of the Census block group.
where they fall into. There are more parcels than there are block groups, but only 6,277 parcels categorized as residential areas were included.

Figure 4.3 is a map of the transport disadvantaged areas with destination-based demand. Processing with respect to data allocation to parcels is basically the same as done for origin-based demand. Based on employment data and landuse data, the parcels are classified using characteristics of employment, shopping, amenity facilities, educational institutions, and public service facilities. One notable feature of the destination-based parcel set is that there are many parcels which have a maximum diameter of the minimum enclosing circles are greater than twice the covering standard. In this case, they are partitioned to meet the assumption between demand object size and the covering service standard.
4.3. **Origin access**

The analysis was performed on a personal desktop computer with Pentium Xeon 3.0 GHz processor and 2GB of Ram. ArcGIS 9.2 was used for data preparation and spatial analysis. The PINPS approach was carried out using ArcObjects and is primarily structured in Visual Basic Application. The MCLP was formulated using PINPS as potential facility sites and a CPLEX readable text file was created by ArcGIS 9.2. CPLEX 10.1 imports this text file and solves the MCLP. The results are exported to ArcGIS 9.2 and MS Office Excel 2003 for further analysis and visualization.

Once the research areas with the road network and parcel data are ready, the continuous road network will be discretized to derive potential bus stop locations according to the

---

**Figure 4.3:** Data transfer to study area (destination-based)
PINPS approach. Figure 4.2 shows zone-based spatial demand objects in need of coverage. This set of parcels is characterized as the transport disadvantaged areas with high needs of public transportation as defined by the aforementioned demographic information. In addition to this high level of need, the access to public transportation of these areas is limited by insufficient provision of bus stops and routes. As discussed previously, the information for the parcels was transferred from Census block groups where those socio-economic and demographic data were available. This is followed by extraction of demand polygon vertices to create covering boundaries. Identification of covering boundaries is then carried out. Finally, intersection points between covering boundary and road network will be derived and will serve as potential bus stop locations. All these spatial data manipulations and analyses are carried out in ArcGIS with customization by Visual Basic Application programming.

Figure 4.4 (a) shows discretized points along the Hilliard road network. They total 62,172 potential bus stops. There are two ways to handle this huge dataset. One is to use this dataset without any further processing, and proceed to applying the MCLP. Unfortunately, this creates computational problems, so it is necessary to remove redundant potential facility locations. Hence, the other way to handle this data set is removing dominated potential facilities before MCLP application. Figure 4.4 (b) shows all dominating points after redundant potential facility points were removed. After removal, only 914 points are available. This step reduced the original set by 98.5%.
Figure 4.4: Removal of dominated points (origin-based)
Figure 4.5: Comparison between actual coverage and complete coverage

Complete coverage only includes completely covered polygon demand of parcels. The areas of actual coverage in Figure 4.5 (a) are measured by further GIS processing by clipping. The areas of complete coverage are directly obtained by objective values of MCLP results. This direct gain is enabled by the use of covering boundary in the constraint (3), \( \sum_{j \in N_i} X_j - Y_i \geq 0 \ \forall i \), from the formula. When

\[ N_i = \{ \text{set of potential facilities } j \text{ capable of covering demand parcel } i \} = \{ j | d_{ij} \leq R \} \]

is evaluated, the covering capability of a facility location is defined based on its covering boundary. Thus, only potential facilities completely inside of the covering boundary are defined as set of \( N_i \). This ensures that the objective parcels of MCLP are all completely covered parcels. This is a polygon-based approach.
As discussed earlier that point-representation would cause over-estimation of the actual coverage, it is important to compare coverage provided by MCLP with PINPS by a polygon-based approach with actual coverage. As shown in Figure 4.6, for all $p$ value ranges, actual coverage is consistently higher than complete coverage. This is not surprising in that complete coverage only includes parcels completely contained inside the service coverage radius and actual coverage includes a measure of parcels partially covered as well as completely covered parcels. Thus, each coverage does not cause any errors between each other. They provide two different types of exact coverage.

The MCLP was evaluated with given potential facility sites across the origin-based demand parcels using polygon-based approach varying $p$ from 2 to 50 to evaluate the tradeoff in number of stops to the amount of demand served. Coverage and calculation details are listed in Table 4.1. The table shows that new bus stop coverage ranges from 9.59% in the case of $p=2$ to 94.37% in the case of $p=50$ (by objective value\(^5\)) and 10.42% in the case of $p=2$ to 95.32% in the case of $p=50$ (actual coverage by spatial process\(^6\)) (see Figure 4.7). Solution time was seconds for the given computer specification and at most 11.17s when the $p$ value was 12. According to iterations, branches and solution times given by CPLEX, it does not appear that the MCLP was difficult to solve.

---

\(^5\) This is an objective value given by the MCLP objective (3.1).
\(^6\) Actual coverage is obtained by clipping and calculating areas of all demand parcels contained inside service coverage.
<table>
<thead>
<tr>
<th>$p$</th>
<th>Complete Coverage (%)</th>
<th>Actual Coverage (%)</th>
<th>Branches</th>
<th>Iterations</th>
<th>Solution Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>9.59</td>
<td>10.42</td>
<td>0</td>
<td>6812</td>
<td>1.22</td>
</tr>
<tr>
<td>4</td>
<td>18.59</td>
<td>20.31</td>
<td>0</td>
<td>7786</td>
<td>1.70</td>
</tr>
<tr>
<td>6</td>
<td>26.99</td>
<td>29.19</td>
<td>0</td>
<td>7839</td>
<td>1.78</td>
</tr>
<tr>
<td>8</td>
<td>34.29</td>
<td>36.82</td>
<td>0</td>
<td>7854</td>
<td>1.91</td>
</tr>
<tr>
<td>10</td>
<td>40.62</td>
<td>43.49</td>
<td>0</td>
<td>8022</td>
<td>2.09</td>
</tr>
<tr>
<td>12</td>
<td>46.68</td>
<td>49.62</td>
<td>1</td>
<td>8531</td>
<td>11.17</td>
</tr>
<tr>
<td>14</td>
<td>52.48</td>
<td>55.85</td>
<td>0</td>
<td>8655</td>
<td>2.53</td>
</tr>
<tr>
<td>16</td>
<td>57.58</td>
<td>61.01</td>
<td>0</td>
<td>8211</td>
<td>2.38</td>
</tr>
<tr>
<td>18</td>
<td>62.50</td>
<td>65.66</td>
<td>0</td>
<td>7883</td>
<td>2.39</td>
</tr>
<tr>
<td>20</td>
<td>66.82</td>
<td>70.25</td>
<td>0</td>
<td>7201</td>
<td>2.14</td>
</tr>
<tr>
<td>22</td>
<td>70.70</td>
<td>73.73</td>
<td>0</td>
<td>7389</td>
<td>2.33</td>
</tr>
<tr>
<td>24</td>
<td>74.32</td>
<td>77.37</td>
<td>0</td>
<td>5952</td>
<td>1.87</td>
</tr>
<tr>
<td>26</td>
<td>77.50</td>
<td>80.62</td>
<td>0</td>
<td>5466</td>
<td>1.89</td>
</tr>
<tr>
<td>28</td>
<td>80.19</td>
<td>83.05</td>
<td>0</td>
<td>4703</td>
<td>1.63</td>
</tr>
<tr>
<td>30</td>
<td>82.29</td>
<td>84.97</td>
<td>0</td>
<td>4621</td>
<td>1.66</td>
</tr>
<tr>
<td>32</td>
<td>84.29</td>
<td>86.70</td>
<td>0</td>
<td>4209</td>
<td>1.53</td>
</tr>
<tr>
<td>34</td>
<td>85.99</td>
<td>88.23</td>
<td>0</td>
<td>3771</td>
<td>1.36</td>
</tr>
<tr>
<td>36</td>
<td>87.53</td>
<td>89.62</td>
<td>0</td>
<td>3570</td>
<td>1.47</td>
</tr>
<tr>
<td>38</td>
<td>88.89</td>
<td>90.73</td>
<td>0</td>
<td>3348</td>
<td>1.36</td>
</tr>
<tr>
<td>40</td>
<td>90.09</td>
<td>91.90</td>
<td>0</td>
<td>3009</td>
<td>1.50</td>
</tr>
<tr>
<td>42</td>
<td>91.10</td>
<td>92.73</td>
<td>0</td>
<td>3064</td>
<td>1.78</td>
</tr>
<tr>
<td>44</td>
<td>92.05</td>
<td>93.55</td>
<td>1</td>
<td>2693</td>
<td>2.61</td>
</tr>
<tr>
<td>46</td>
<td>92.87</td>
<td>94.19</td>
<td>0</td>
<td>2584</td>
<td>4.75</td>
</tr>
<tr>
<td>48</td>
<td>93.65</td>
<td>94.78</td>
<td>0</td>
<td>2297</td>
<td>2.94</td>
</tr>
<tr>
<td>50</td>
<td>94.37</td>
<td>95.32</td>
<td>0</td>
<td>1879</td>
<td>2.86</td>
</tr>
</tbody>
</table>

**Table 4.1:** MCLP result details: PINPS (Polygon-based approach: origin-based)
Figure 4.6: Tradeoff curve by PINPS (Polygon-based approach: origin-based)

Figure 4.6 shows the tradeoff curve demonstrating how the amount of demand coverage changes with an increasing number of potential facilities. In general, the curve shows that the percentage of coverage is increasing with a decreasing rate, forming a convex curve. Even though the increasing rate decreases, the total coverage is still increasing up to 70% to 80%, requiring some 25 facilities (transit stops). After a $p$ value of 25, the increase rates decreases significantly, so the total coverage does not substantially increase. This means that adding another 25 potential facilities only increases total coverage by 20%, which is less than two-thirds of the total increase with the first 25 facilities. This clearly shows that most convex-shaped MCLP tradeoff results consider that coverage of 70% to
80% is efficient given demand and limited conditions, such as planning budget (Grubesic and Murray 2002). The MCLP results show that in the case of \( p=22 \), the coverage levels are 70.70% (by objective value) and 73.73% (actual coverage by spatial process) and in the case of \( p=26 \), the coverage levels are 77.50% (by objective value) and 80.62% (actual coverage by spatial process). These results are shown in Figure 4.8.

One miscellaneous finding depicted in Figure 4.6 is that the tradeoff curve does not seem to reach 100% with increasing \( p \) values. When the study area is closely observed, this finding is not surprising because the southwestern part of Hilliard has poor coverage by the current road network in Figure 4.7 (b). This is due to fact that no road network is present around the parcels. It does not appear that the mass transit coverage there will be improved, even though the MCLP is evaluated with an increasing \( p \) value, because there are no potential facilities around the uncovered parcels in Figure 4.4 (a) and (b). This can be explained in two ways. One is data error, which means some parts of the road network data are missing. This instance can be easily fixed with updated data. The other case is that some demand areas are actually too far away in terms of service coverage. If this is the case, this will raise another issue of the justification of suitable access standard of 400 meters. Otherwise, this demand area will be permanently excluded from bus service coverage. However, some field work by the author found that this absence of roads is an error in the data layer.
Figure 4.7: Coverage: Minimum and Maximum within given $p$ values (Polygon-based approach: origin-based)
(a) Actual coverage of 73.73% with $p=22$

(b) Actual coverage of 80.62% with $p=26$

Figure 4.8: Appropriate Coverage (Polygon-based approach: origin-based)
4.4. Destination access

This section examines destination-based access. Destination-based demand parcels are featured with employment, shopping, amenity facility, educational institutions, and public service facilities. All other methodological details are exactly the same for origin-based demand. Figure 4.9 (a) shows discretized points along the Hilliard road network using PINPS approach previously developed. There are 4,468 potential bus stops. It was discussed that there are two ways to handle this data set for the MCLP: with or without dominated point removal or removal of dominated points before MCLP. The origin-based approach utilized dominated point removal before MCLP application. Likewise, the destination-based approach takes advantage of dominated point removal before MCLP for better computational efficiency. After removal, only 163 points are available (Figure 4.9 (b)). This removal reduced the original set by 96.4%.

The MCLP was then applied using the 163 potential bus stop locations serving the destination-based demand parcels varying $p$ from 2 to 50. Except for the demand areas, all other analytical methods are same as the origin-based analysis. Coverage and calculation details are depicted in Table 4.2. The table shows that new bus stop coverage varies from 8.00% (by objective value) and 9.51% (actual coverage by spatial process) in the case of $p=2$ and 84.83% (by objective value) and 92.68% (actual coverage by spatial process) in the case of $p=50$ (see Figure 4.10). Solution time was less than a second in the given computing environment. Based on the relatively small numbers of iterations, branches and solution times, the solution of the MCLP appears to be easy.
The tradeoff curve in Figure 4.12 shows the coverage increase pattern. This does not
differ much from that of the origin-based approach. Adding the first 25 service stops
increases the coverage up to 60% to 70% of total demand, but an additional 25 stops only
increases coverage to roughly 20% of the total demand. Assuming that we pursue 70% to
80% coverage levels, a value of $p$ of 28 to 36 provides the coverage in Figure 4.4. In the
case of $p=28$, the coverage levels are 65.71% (by objective value) and 75.92% (actual
coverage). In the case of $p=36$, the coverage levels are 74.81% (by objective value) and
85.27% (actual coverage).

One finding between origin-based and destination-based access is that the difference
between coverage by objective and actual coverage for origin-based access and between
coverage by objective and actual coverage in destination-based access differs noticeably.
The gap between the two curves in Figure 4.12 for destination-based access is greater
than the gap in Figure 4.6 for origin-based access. This is easy to understand intuitively,
because the individual sizes of origin-based demand parcels are much smaller than those
of destination-based. Total areas of covered portions of intersecting parcels with the
boundary of service coverage are less when intersecting individual parcels are smaller.
Therefore, these small sized origin-based parcels contribute to the reduction of the total
areas of clipped parcels by the border of service coverage. This implies that when the
PINP approach is applied, the smaller the demand objects are, the smaller the differences
between objective values and actual coverage levels are.
Figure 4.9: Removal of dominated points (Polygon-based approach: destination-based)
<table>
<thead>
<tr>
<th>$p$</th>
<th>Complete Coverage (%)</th>
<th>Actual Coverage (%)</th>
<th>Branches</th>
<th>Iterations</th>
<th>Solution Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8.00</td>
<td>9.51</td>
<td>0</td>
<td>483</td>
<td>0.03</td>
</tr>
<tr>
<td>4</td>
<td>15.06</td>
<td>19.11</td>
<td>0</td>
<td>484</td>
<td>0.03</td>
</tr>
<tr>
<td>6</td>
<td>21.22</td>
<td>27.34</td>
<td>0</td>
<td>481</td>
<td>0.02</td>
</tr>
<tr>
<td>8</td>
<td>27.10</td>
<td>33.62</td>
<td>0</td>
<td>483</td>
<td>0.01</td>
</tr>
<tr>
<td>10</td>
<td>32.54</td>
<td>38.82</td>
<td>0</td>
<td>470</td>
<td>0.06</td>
</tr>
<tr>
<td>12</td>
<td>37.28</td>
<td>44.26</td>
<td>0</td>
<td>452</td>
<td>0.01</td>
</tr>
<tr>
<td>14</td>
<td>41.83</td>
<td>49.20</td>
<td>0</td>
<td>467</td>
<td>0.02</td>
</tr>
<tr>
<td>16</td>
<td>46.16</td>
<td>54.10</td>
<td>0</td>
<td>455</td>
<td>0.03</td>
</tr>
<tr>
<td>18</td>
<td>50.26</td>
<td>58.63</td>
<td>0</td>
<td>439</td>
<td>0.03</td>
</tr>
<tr>
<td>20</td>
<td>53.98</td>
<td>63.61</td>
<td>0</td>
<td>399</td>
<td>0.02</td>
</tr>
<tr>
<td>22</td>
<td>57.24</td>
<td>67.35</td>
<td>0</td>
<td>387</td>
<td>0.03</td>
</tr>
<tr>
<td>24</td>
<td>60.17</td>
<td>69.90</td>
<td>0</td>
<td>377</td>
<td>0.03</td>
</tr>
<tr>
<td>26</td>
<td>63.00</td>
<td>72.12</td>
<td>0</td>
<td>364</td>
<td>0.03</td>
</tr>
<tr>
<td>28</td>
<td>65.71</td>
<td>75.92</td>
<td>0</td>
<td>361</td>
<td>0.02</td>
</tr>
<tr>
<td>30</td>
<td>68.37</td>
<td>78.57</td>
<td>0</td>
<td>348</td>
<td>0.02</td>
</tr>
<tr>
<td>32</td>
<td>70.83</td>
<td>81.20</td>
<td>0</td>
<td>296</td>
<td>0.03</td>
</tr>
<tr>
<td>34</td>
<td>72.93</td>
<td>84.03</td>
<td>0</td>
<td>267</td>
<td>0.02</td>
</tr>
<tr>
<td>36</td>
<td>74.81</td>
<td>85.27</td>
<td>0</td>
<td>264</td>
<td>0.03</td>
</tr>
<tr>
<td>38</td>
<td>76.60</td>
<td>86.47</td>
<td>0</td>
<td>256</td>
<td>0.03</td>
</tr>
<tr>
<td>40</td>
<td>78.37</td>
<td>87.17</td>
<td>0</td>
<td>220</td>
<td>0.02</td>
</tr>
<tr>
<td>42</td>
<td>79.92</td>
<td>89.28</td>
<td>0</td>
<td>217</td>
<td>0.02</td>
</tr>
<tr>
<td>44</td>
<td>81.30</td>
<td>90.15</td>
<td>0</td>
<td>197</td>
<td>0.05</td>
</tr>
<tr>
<td>46</td>
<td>82.56</td>
<td>91.23</td>
<td>0</td>
<td>164</td>
<td>0.02</td>
</tr>
<tr>
<td>48</td>
<td>83.75</td>
<td>91.93</td>
<td>0</td>
<td>164</td>
<td>0.02</td>
</tr>
<tr>
<td>50</td>
<td>84.83</td>
<td>92.68</td>
<td>0</td>
<td>129</td>
<td>0.02</td>
</tr>
</tbody>
</table>

**Table 4.2:** MCLP result details: PINPS (Polygon-based approach: destination-based)
(a) Actual minimum coverage of 9.51% with $p=2$

(b) Actual maximum coverage of 92.68% with $p=50$

**Figure 4.10:** Coverage: Minimum and Maximum within given $p$ values (Polygon-based approach: destination-based)
Figure 4.11: Desirable Coverage (Polygon-based approach: destination-based)
Multi-objective methods are associated with decision-making problems where several conflicting objectives exist. Likewise, in optimization, there are many problems involved in the simultaneous optimization of multiple and frequently competing objectives in the real world (Fonseca and Fleming 1993, Zitzler and Thiele 1998, Cohon 2003). In this case, it is rarely possible that there is a single optimal solution. Rather, a combination of multiple objectives generally provides the framework for decision making. These multiple objectives lead to tradeoffs. This is called the Pareto-optimal solution set, which consists of a set of optimal points rather than a single optimal point. That is to say, the set
of solutions include partial solutions from each objective and provide optimal solutions by combining the best individual partial solutions for objectives for the given instances. Given this, developing a multi-objective MCLP in order to obtain one consolidated stop location set based on two different objectives, which are origin-based access and destination-based access, will give us a set of options to locate bus stops to serve the transportation disadvantaged.

There are several methods to develop a tradeoff curve\(^7\), but among them, two approaches, the constraint method and the weighting method, are the simplest and most popular (ReVelle 1993, Farhan and Murray 2008). In the constraint method, one of the objectives remains as the objective function and the other objective works as a constraint to the main objective function by setting it equal to some predetermined value. The weighting method obtains the tradeoff curve by varying non-negative weights on each objective summing to 1, and the weighted objectives are combined into one objective to be maximized together. A disadvantage of the weighting method is that there might be missing non-inferior points in the gaps over the tradeoff curve between points defined by set of weights varying 0 to 1. Unlike the weighting method, the constraint method could find such possible missing non-inferior points. However, this requires intensive computational burden. Thus, the weighting method is more popular and is a reasonable approach even though it has the risk of missing non-inferior points in the weighting gaps. Decision makers are usually interested in the general pattern of tradeoff curve, not in

---

\(^7\) Tradeoff curve is used as a synonym of the Pareto curve (solution), non-inferior curve (solution), or non-dominated curve (solution) (Cohon 2003).
specific gap points (ReVelle 1993). Thus, this model will be formulated using the weighting method.

4.5.1. Problem formulation

Maximize

\[ Z = W \sum_i a_i O_i + (1-W) \sum_m a_m D_m \]  \hspace{1cm} (4.1)

Subject to

\[ \sum_{j \in N_i} x_j - O_i \geq 0 \hspace{1cm} \forall i \]  \hspace{1cm} (4.2)

\[ \sum_{j \in N_m} x_j - D_m \geq 0 \hspace{1cm} \forall m \]  \hspace{1cm} (4.3)

\[ \sum_j x_j = p \]  \hspace{1cm} (4.4)

\[ x_j = \{0,1\} \hspace{1cm} \forall j \]  \hspace{1cm} (4.5)

\[ O_i = \{0,1\} \hspace{1cm} \forall i \]

\[ D_m = \{0,1\} \hspace{1cm} \forall m \]

Where

\[ i = \text{index of origin demand parcels}; \]
\[ m = \text{index of destination demand parcels}; \]
\[ j = \text{index of potential facility locations}; \]
\[ a_i = \text{area for origin demand parcel } i; \]
\[ a_m = \text{area for destination demand parcel } m; \]
\[ N_i = \{j | d_{ij} \leq R \}; \]
\[ N_m = \{j | d_{mj} \leq R \}; \]
\[ d_{ij} = \text{shortest distance from origin demand parcel } i \text{ to potential facility } j; \]
\[ d_{mj} = \text{shortest distance from origin demand parcel } m \text{ to potential facility } j; \]
\[ p = \text{number of facilities to site}; \]
\[ R = \text{the distance that could be traveled to suitably cover demand parcel: } 400 \text{m}; \]
The objective (4.1) maximizes coverage for both origin- and destination-based demand simultaneously with varying weights within the given service standard, 400 meters. Constraints (4.2) and (4.3) account for suitable coverage of origin-based demand and destination-based demand respectively. Constraint (4.4) entails the number of facilities to be located. Integer requirements are specified in constraints (4.5).

4.5.2. Application and results

This part of the research is an extension of the previous section, so all computation environments were the same as specified in the past chapter. Among several data sets developed during this research, PINPS with polygon-based approach for both origin- and destination-based objectives was used to formulate the bi-objective MCLP. Thus, there are two sets of potential facility locations. One is a set created by the PINPS approach using origin-based demand and the other is a set created by PINPS approach using destination-based demand. Likewise, two different sets of parcels are used for representing demand. One is origin-based parcels and the other is destination-based parcels. The PINPS created by origin-based demand with origin-based parcels are used
for the objective for origin-based access. PINPS created by destination-based demand with destination-based parcels are used for the objective for destination-based access.

<table>
<thead>
<tr>
<th>Weight for Origin-based</th>
<th>Weight for Destination-based</th>
<th>Complete coverage of parcels by PINPS: Origin-based (%)</th>
<th>Complete coverage of parcels by PINPS: Destination-based (%)</th>
<th>Branches</th>
<th>Iterations</th>
<th>Solution Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>87.85</td>
<td>21.82</td>
<td>0</td>
<td>3678</td>
<td>1.64</td>
</tr>
<tr>
<td>0.9</td>
<td>0.1</td>
<td>87.52</td>
<td>29.28</td>
<td>1</td>
<td>4887</td>
<td>4.98</td>
</tr>
<tr>
<td>0.8</td>
<td>0.2</td>
<td>86.41</td>
<td>34.44</td>
<td>0</td>
<td>5053</td>
<td>5.52</td>
</tr>
<tr>
<td>0.7</td>
<td>0.3</td>
<td>82.20</td>
<td>47.73</td>
<td>0</td>
<td>5057</td>
<td>1.80</td>
</tr>
<tr>
<td>0.6</td>
<td>0.4</td>
<td>78.39</td>
<td>54.97</td>
<td>0</td>
<td>5681</td>
<td>1.81</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>74.30</td>
<td>58.92</td>
<td>0</td>
<td>6247</td>
<td>2.06</td>
</tr>
<tr>
<td>0.4</td>
<td>0.6</td>
<td>68.19</td>
<td>64.71</td>
<td>0</td>
<td>5847</td>
<td>1.72</td>
</tr>
<tr>
<td>0.3</td>
<td>0.7</td>
<td>57.63</td>
<td>71.91</td>
<td>0</td>
<td>6649</td>
<td>1.58</td>
</tr>
<tr>
<td>0.2</td>
<td>0.8</td>
<td>42.98</td>
<td>75.69</td>
<td>0</td>
<td>5969</td>
<td>1.00</td>
</tr>
<tr>
<td>0.1</td>
<td>0.9</td>
<td>35.20</td>
<td>77.70</td>
<td>0</td>
<td>6268</td>
<td>1.26</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>28.00</td>
<td>78.17</td>
<td>0</td>
<td>365</td>
<td>0.16</td>
</tr>
</tbody>
</table>

**Table 4.3**: Solution details for the bi-objective MCLP
The bi-objective MCLP utilized a polygon-based representation of demand to assess coverage, the PINPS method to identify potential bus stop locations, and a $p$ value of 36. This means that we are trying to cover as many parcels, weighted by origin and destination demand as possible, while only siting 36 bus stops. Choice of $p$ value is dependent upon decision-makers’ strategy, that is generally budget limitation, but ensuring coverage from 70% to 80% would be reasonable if any limitation is not
specifies. For this reason $p = 36$ was selected, for which the coverage of parcels with origin-based demand was 74.81% and for destination parcels was 87.53%.

Table 4.3 shows solution details. In terms of computation complexity, solution time and number of iterations and branches have similar patterns to those of solution details when each objective is evaluated by single MCLP separately. That is to say that it was not difficult to solve this new bi-objective MCLP. As seen in Figure 4.13, the combination of both origin-based and destination-based coverage varies along the Pareto curve. When $w=1$, the formulation is merely same as the single objective MCLP in favor of origin-based approach. When $w=0$, it is the same as the single objective MCLP maximizing destination-based mass transit demand. This tradeoff curve shows that when $w=0.6$, this combined objective maximizes origin coverage by covering 78.39% of demand while also covering 54.97% of destination demand. When $w=0.4$, this bi-objective model locates the 36 stops in a manner that most evenly covers both origin and destination demand parcels by 68.19% and 64.71% respectively. These are theoretical statistical findings. The most suitable combination of coverage would be based on specific planning goals.

In Figure 4.14, two maps show the coverage results of $w=0.6$ and $w=0.4$. Based on the different weights, the model with $w=0.6$ favors origin-based demand more and $w=0.4$ favors destination-based demand more. The coverage inside the blue rectangles is exclusive for the model with $w=0.6$ and the coverage zones are mostly covering origin-
based parcels. The coverage inside red-hatched rectangles is exclusive in the model with \( w=0.4 \) and the coverage zones are concentrated around destination-based parcels.
Figure 4.14: Coverage configuration by bi-objective MCLP with weights of 0.6 and 0.4
There is an interesting finding in this section. When $w=1$, the total coverage should be the same as complete coverage provided for origin-based access with $p=36$ in Table 4.1. Likewise, when $w=0$, the total coverage is the same as that of destination-based access with $p=36$ in Table 4.2. However, Table 4.4 shows that coverage levels for the bi-objective MCLP models are better than single-objective MCLPs respectively.

<table>
<thead>
<tr>
<th></th>
<th>Origin-based</th>
<th>Destination-based</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-objective MCLP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bi-objective MCLP with $w=1$</td>
<td>87.53 %</td>
<td>87.85 %</td>
</tr>
<tr>
<td>Single-objective MCLP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bi-objective MCLP with $w=0$</td>
<td>74.81 %</td>
<td>78.17 %</td>
</tr>
</tbody>
</table>

Table 4.4: Comparison of coverage between single- and bi-objective MCLP with full weight for either objective

This improvement was caused by the use of different potential facilities. If this bi-objective MCLP had used different demand fields but the same potential facilities, the values in Table 4.4 should have been the same in pairs by origin-based and by destination-based. However, this analysis utilized two different potential facility sets; one is derived from origin-based PINPS and the other is destination-based PINPS. When two single objectives are evaluated in bi-objective MCLP simultaneously, the two potential facility sets are used together, which means any of the combined potential facility locations can provide coverage to either origin-based demand or destination-based
demand. Therefore, most coverage was gained from its original potential facility locations, but the additional coverage was born from some potential facility locations that chosen from the other set of potential facility. This turns out to be an additional contribution of bi-objective MCLP when different sets of potential facility are used.

4.6. Summary

In this chapter, the details of application of the MCLP using PINPS for both origin-based and destination-based access have been discussed. Most of all, due to the nature of PINPS in regard to the relationship between the size of demand objects and diameter of service coverage, the demand objects in a research area should be small enough. This encouraged the use of parcel data where demographic data were transferred down. Using parcels increases the computation burden due to the high number of spatial objects, so city of Hilliard was chosen to reduce total number of parcels in the research area instead of utilizing the whole of Franklin County.

For both the origin-based and destination-based access, the PINPS approach was first derived from the road network. PINPS produced a good amount of potential facilities. Redundancy removal was carried out to see how effectively it removes the dominated potential facilities. This removal process reduced the number of potential facilities substantially by 98.5%. This was followed by MCLP application using potential facility points using PINPS varying $p$ from 2 to 50. The tradeoff curve shows that like other MCLP results, the increasing rate of coverage decreased quickly after reaching 70% to
80% of total coverage. This implies that coverage of 70% to 80% is the reasonable choice for the economics of planning purposes. This application produced two sets of results for both origin-based and destination-based access, which are coverage assessed by objective values by resulting from the MCLP formulation and actual coverage. Coverage by objective values only includes parcels completely covered by the given service coverage standard. Actual coverage is obtained by further spatial process by clipping parcels with the border of service coverage. Another finding is that the gap between coverage by objective value and actual coverage depends on sizes of individual parcels in the study area.

Using the bi-objective MCLP, the coverage for both origin-based and destination-based access were maximized simultaneously. Along the Pareto curve, the combination of maximal coverage for each varies by assigned weights. This method is useful when multiple objectives are required to be maximized simultaneously to create a set of solutions, integrating all multiple objectives in a planning application. Another finding of bi-objective approach is that additional coverage can be achieved when different potential facilities are used for individual objectives, because they offer more potential facilities and their difference can compromise each other when combined for bi-objective MCLP.
CHAPTER 5

5. COMPARATIVE ANALYSIS

5.1. Introduction

There are a number of ways to locate facility sites over continuous space. Placing potential facility sites as a regular grid pattern over the area of analysis is one way. Positioning potential service stops of public transportation randomly along a continuous road network is an extension of this method. A method for discretizing a continuous road network to find good potential transit stops has been discussed in the past chapter, and these discretized points were derived from polygon-based demand to ensure complete coverage for the individual demand object. According to relevant literature, however, zone-based demand is often represented as points in order to reduce analysis complexity at the expense of the precision of the results. Given this, this chapter will discuss both placing potential facility sites evenly along a network and representing zone-based demand objects with points. This will examine how the developed approach, PINPS, improves existing methods utilizing point representation.
5.2. **MCLP using PINPS**

In the previous chapter, the covering boundary and PINPS were derived. PINPS was used for creating potential facility locations and the covering boundary was used to extract PINPS from road network. However, it cannot be overlooked that the covering boundary was also used when \( N_i = \{\text{set of potential facilities } j \text{ capable of covering demand parcel } i\} \) was evaluated. This enabled all selected parcels to be completely covered by a facility’s maximum service radius. In order to assess the performance of this new method of deriving potential transit stops, points will be randomly but evenly placed along the network. These resulting points will be used to formulate and solve the MCLP for the Hilliard area. This will give us a comparison between the traditional method of locating facilities, and the new proposed method of exploiting the covering boundary of polygon demand objects. Another issue to be examined is the adequacy of representing polygon demand with points. In this case, land parcels will be represented by points and the \( N_i \) set will be evaluated based on circular buffers created from points using ArcGIS. This buffering method will substitute for the use of the covering boundary in the polygon-based parcel analysis. This will also include comparison between potential facility sites developed by PINPS and by the randomly (but evenly) selected potential facilities. This relationship is summarized in the following table.
The first combination with polygon-based parcel demand and PINPS was discussed in the previous chapter. As shown in Figure 5.1, all six combinations are evaluated to compare the levels of coverage and computation complexities.

This analysis requires a new potential facility data set, where potential facilities are randomly but regularly spaced. Since gaps of distributed facilities are expected to affect both coverage levels and computation complexities, two instances, 200 meter-spaced and 100 meter-spaced point sets, were developed. The 200 meter-spaced point set includes 3,531 total points and the 100 meter-spaced point set includes 4,813 points (Figure 5.2). Both point sets will be applied to origin-based and destination-based approaches.

Compared to the number of potential facilities created by PINPS, 914 for origin-based and 163 for destination-based access after dominated points removed, these approaches
involve far more potential facilities. This is expected to influence computation complexity later.

![Figure 5.2: Regularly spaced potential facility points by 100 meters and 200 meters along the Hilliard road network](image)

(a) 200 meter spacing  
(b) 100 meter spacing

**Figure 5.2:** Regularly spaced potential facility points by 100 meters and 200 meters along the Hilliard road network

While the number of potential stops adds to the computational complexity, and thus likely increasing the time necessary to solve the MCLP, this will not influence the coverage level. Accordingly, the road network range is limited rectangularly to include all necessary demand parcels by visual inspection.

In contrast to the use of the covering boundary in the previous chapter, new demand data will be created by adopting a point representation. Using centroids for point
representation of zone-based demand is a very popular method in geographical analyses (ReVelle 1991, Miller 1996, Grubesic and Murray 2002, Murray and Wu 2003, Murray 2005, Matisziw et al. 2006, Jia et al. 2007, Farhan and Murray 2008). This research will also utilize centroids for point representation (Figure 5.3) in order to compare representational methods. Since it is assumed that the entire parcel is covered when its centroid is covered by service coverage, circular buffers of individual centroids for parcels utilized to evaluate $N$, set in Figure 5.4. This is a point-represented approach.
Figure 5.3: Centroids for origin- and destination-based demand parcels
Figure 5.4: Buffers for evaluation for $N_t$ set
5.2.1. *Application and results*

Computational environments are the same as the previous analyses as a personal desktop computer with a Pentium Xeon 3.0 GHz processor and 2GB Ram, ArcGIS 9.2, ArcObjects with Visual Basic Application., CPLEX 10.1, and MS Office Excel 2003 were utilized for analysis.

![Tradeoff curves for comparison between PINPS, 200 meter-, and 100 meter-spaced potential facility points (Polygon-based approach: Origin-based)](image)

**Figure 5.5:** Tradeoff curves for comparison between PINPS, 200 meter-, and 100 meter-spaced potential facility points (Polygon-based approach: Origin-based)

This part discusses the comparison between PINPS, 200 meter-, and 100 meter-spaced potential facility locations based on the polygon-based demand using origin-based access.
Figure 5.5 shows that maximizing coverage of demand by \( p \) facilities is similar for PINPS, 100 meter spacing, and 200 meter spacing of potential facilities. Therefore, the comparison will focus on the coverage level and computation complexity. As shown in the tradeoff curve in the figure, coverage by PINPS is better in most ranges than the other two approaches using regularly spaced potential facilities. It is not surprising that coverage by 100 meter-spaced potential facilities is higher than 200 meter spacing, due to the density of points located along the road network providing better chances to cover given demand. However, when coverage reached around 90% with \( p \) value of 42, the coverage by 100 meter-spaced potential bus stops becomes better than others. This will be discussed later.
<table>
<thead>
<tr>
<th>( p )</th>
<th>PINPS</th>
<th>200 meter-spaced</th>
<th>100 meter-spaced</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Complete Coverage (%)</td>
<td>Branches</td>
<td>Iterations</td>
</tr>
<tr>
<td>2</td>
<td>9.59</td>
<td>0</td>
<td>6812</td>
</tr>
<tr>
<td>4</td>
<td>18.59</td>
<td>0</td>
<td>7786</td>
</tr>
<tr>
<td>6</td>
<td>26.99</td>
<td>0</td>
<td>7839</td>
</tr>
<tr>
<td>8</td>
<td>34.29</td>
<td>0</td>
<td>7854</td>
</tr>
<tr>
<td>10</td>
<td>40.62</td>
<td>0</td>
<td>8022</td>
</tr>
<tr>
<td>12</td>
<td>46.68</td>
<td>1</td>
<td>8531</td>
</tr>
<tr>
<td>14</td>
<td>52.48</td>
<td>0</td>
<td>8655</td>
</tr>
<tr>
<td>16</td>
<td>57.58</td>
<td>0</td>
<td>8211</td>
</tr>
<tr>
<td>18</td>
<td>62.50</td>
<td>0</td>
<td>7883</td>
</tr>
<tr>
<td>20</td>
<td>66.82</td>
<td>0</td>
<td>7201</td>
</tr>
<tr>
<td>22</td>
<td>70.70</td>
<td>0</td>
<td>7389</td>
</tr>
<tr>
<td>24</td>
<td>74.32</td>
<td>0</td>
<td>5952</td>
</tr>
<tr>
<td>26</td>
<td>77.50</td>
<td>0</td>
<td>5466</td>
</tr>
<tr>
<td>28</td>
<td>80.19</td>
<td>0</td>
<td>4703</td>
</tr>
<tr>
<td>30</td>
<td>82.29</td>
<td>0</td>
<td>4621</td>
</tr>
<tr>
<td>32</td>
<td>84.29</td>
<td>0</td>
<td>4209</td>
</tr>
<tr>
<td>34</td>
<td>85.99</td>
<td>0</td>
<td>3771</td>
</tr>
<tr>
<td>36</td>
<td>87.53</td>
<td>0</td>
<td>3570</td>
</tr>
<tr>
<td>38</td>
<td>88.89</td>
<td>0</td>
<td>3348</td>
</tr>
<tr>
<td>40</td>
<td>90.09</td>
<td>0</td>
<td>3009</td>
</tr>
<tr>
<td>42</td>
<td>91.10</td>
<td>0</td>
<td>3064</td>
</tr>
<tr>
<td>44</td>
<td>92.05</td>
<td>1</td>
<td>2693</td>
</tr>
<tr>
<td>46</td>
<td>92.87</td>
<td>0</td>
<td>2584</td>
</tr>
<tr>
<td>48</td>
<td>93.65</td>
<td>0</td>
<td>2297</td>
</tr>
<tr>
<td>50</td>
<td>94.37</td>
<td>0</td>
<td>1879</td>
</tr>
</tbody>
</table>

Table 5.1: MCLP result details: PINPS, 200 meter-spaced, and 100 meter-spaced (Polygon-based approach: Origin-based)
In terms of complexity, the most important comparison is solution time. Due to the reasonable data size and well equipped computation environments, most solution times were in seconds, or at the longest about forty seconds. However, in relative perspectives, there are notable differences between the three given approaches. When the 200 meter spacing was used, the average solution time was increased by 78.6% compared to using PINPS. When 100 meter-spaced potential facilities were used, which is definitely twice as densely distributed than 200 meter-spaced data, the solution time was almost double 200 meter-spaced time. In Table 5.1, based on the fact that formulating the MCLP by PINPS has the lowest average of branches and iterations when solved with CPLEX, this approach is the most efficiently solved. In all, assessing modeling approaches using average demand coverage, solution time, branches and iterations, the PINPS method provides better coverage with less computation complexity.

PINPS was derived from the covering boundary of individual parcels, so it can be generally expected that the MCLP with potential facilities from PNIPS would generate the best coverage when the $N_i$ set is evaluated by the covering boundary. It is true through this research and will be shown in the following analysis. Nonetheless, in some portion of a tradeoff curve an unexpected coverage result was shown. As mentioned earlier, after a $p$ value of 42, the coverage of demand for public transportation by potential facilities at a 100 meter spacing became higher than the coverage provided by PINPS. This can be interpreted as follows: first, 100 meter-spaced points are very densely distributed and this data set provides more number of potential facility locations, which means more
opportunities to cover demand. Therefore, better coverage might be possible with a
greater number of potential facilities. However, solution time is roughly three times that
of using the PINPS approach. Branches and iterations have similar pattern, which means
this additional coverage was gained at the expense of computation complexity. If the
analyst places more weight on coverage, the model using PINPS with polygon-based
approach will lose solution efficiency. If, in contrast, the analyst wants to keep reasonable
computational efficiency, then such additional coverage needs to be disregarded. This
greater demand coverage only appears when coverage reached about 90% or higher. It is
already discussed that most coverage maximization models pursue coverage of 70% to
80% due to economic efficiency. Thus, the better coverage gained in the range of over
90% or higher does not mean much in terms of real planning purposes. In all, it is
concluded that this unexpected better coverage does not much benefit the method with
100 meter-spaced potential facilities over PINPS in a normal planning operation, based
on efficiency context.

This part discusses the comparison between PINPS, 200 meter-, and 100 meter-spaced
potential facility locations based on the polygon-based demand using destination-based
access. The set of destination-based approaches do not show much difference from
origin-based models. As seen in Table 5.2, in all fields, which are coverage, branches,
iterations, and solution times, results by PINPS have better solutions. Just as observed
with the origin-based approach, results with 100 meter-spaced potential facilities have
both better coverage and computational efficiency than those with 200 meter-spaced
potential facilities, based on shorter solution times and less numbers of iterations and branches. As shown in Figure 5.6, one notable difference from the origin-based approach is that coverage by PINPS is constantly higher than other two approaches in all ranges of $p$ values. This is more consistent result that is expected.

Figure 5.6: Tradeoff curves for comparison between PINPS, 200 meter-, and 100 meter-spaced potential facility points (Polygon-based approach: Destination-based)
<table>
<thead>
<tr>
<th>$p$</th>
<th>PINPS Complete Coverage (%)</th>
<th>Branches</th>
<th>Iterations</th>
<th>Solution Time</th>
<th>200 meter-spaced Complete Coverage (%)</th>
<th>Branches</th>
<th>Iterations</th>
<th>Solution Time</th>
<th>100 meter-spaced Complete Coverage (%)</th>
<th>Branches</th>
<th>Iterations</th>
<th>Solution Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8.00</td>
<td>0</td>
<td>483</td>
<td>0.03</td>
<td>7.40</td>
<td>0</td>
<td>610</td>
<td>0.13</td>
<td>7.52</td>
<td>0</td>
<td>648</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>15.06</td>
<td>0</td>
<td>484</td>
<td>0.03</td>
<td>13.95</td>
<td>0</td>
<td>626</td>
<td>0.08</td>
<td>14.27</td>
<td>0</td>
<td>640</td>
<td>0.16</td>
</tr>
<tr>
<td>6</td>
<td>21.22</td>
<td>0</td>
<td>481</td>
<td>0.02</td>
<td>19.65</td>
<td>0</td>
<td>626</td>
<td>0.08</td>
<td>20.14</td>
<td>0</td>
<td>705</td>
<td>0.11</td>
</tr>
<tr>
<td>8</td>
<td>27.10</td>
<td>0</td>
<td>483</td>
<td>0.01</td>
<td>25.12</td>
<td>0</td>
<td>660</td>
<td>0.06</td>
<td>25.71</td>
<td>0</td>
<td>733</td>
<td>0.11</td>
</tr>
<tr>
<td>10</td>
<td>32.54</td>
<td>0</td>
<td>470</td>
<td>0.06</td>
<td>30.05</td>
<td>0</td>
<td>661</td>
<td>0.20</td>
<td>31.14</td>
<td>0</td>
<td>798</td>
<td>0.13</td>
</tr>
<tr>
<td>12</td>
<td>37.28</td>
<td>0</td>
<td>452</td>
<td>0.01</td>
<td>34.76</td>
<td>0</td>
<td>682</td>
<td>0.13</td>
<td>36.06</td>
<td>0</td>
<td>812</td>
<td>0.13</td>
</tr>
<tr>
<td>14</td>
<td>41.83</td>
<td>0</td>
<td>467</td>
<td>0.02</td>
<td>38.99</td>
<td>0</td>
<td>653</td>
<td>0.11</td>
<td>40.47</td>
<td>0</td>
<td>790</td>
<td>0.11</td>
</tr>
<tr>
<td>16</td>
<td>46.16</td>
<td>0</td>
<td>455</td>
<td>0.03</td>
<td>43.00</td>
<td>0</td>
<td>694</td>
<td>0.13</td>
<td>44.48</td>
<td>0</td>
<td>804</td>
<td>0.09</td>
</tr>
<tr>
<td>18</td>
<td>50.26</td>
<td>0</td>
<td>439</td>
<td>0.03</td>
<td>46.92</td>
<td>0</td>
<td>672</td>
<td>0.12</td>
<td>48.40</td>
<td>0</td>
<td>836</td>
<td>0.11</td>
</tr>
<tr>
<td>20</td>
<td>53.98</td>
<td>0</td>
<td>399</td>
<td>0.02</td>
<td>50.63</td>
<td>0</td>
<td>691</td>
<td>0.13</td>
<td>52.12</td>
<td>0</td>
<td>866</td>
<td>0.16</td>
</tr>
<tr>
<td>22</td>
<td>57.24</td>
<td>0</td>
<td>387</td>
<td>0.03</td>
<td>53.97</td>
<td>0</td>
<td>745</td>
<td>0.13</td>
<td>55.61</td>
<td>0</td>
<td>865</td>
<td>0.16</td>
</tr>
<tr>
<td>24</td>
<td>60.17</td>
<td>0</td>
<td>377</td>
<td>0.03</td>
<td>57.19</td>
<td>0</td>
<td>700</td>
<td>0.19</td>
<td>58.85</td>
<td>0</td>
<td>881</td>
<td>0.17</td>
</tr>
<tr>
<td>26</td>
<td>63.00</td>
<td>0</td>
<td>364</td>
<td>0.03</td>
<td>60.15</td>
<td>0</td>
<td>706</td>
<td>0.13</td>
<td>61.83</td>
<td>0</td>
<td>859</td>
<td>0.16</td>
</tr>
<tr>
<td>28</td>
<td>65.71</td>
<td>0</td>
<td>361</td>
<td>0.02</td>
<td>62.90</td>
<td>0</td>
<td>670</td>
<td>0.11</td>
<td>64.58</td>
<td>0</td>
<td>867</td>
<td>0.14</td>
</tr>
<tr>
<td>30</td>
<td>68.37</td>
<td>0</td>
<td>348</td>
<td>0.02</td>
<td>65.55</td>
<td>0</td>
<td>643</td>
<td>0.08</td>
<td>67.16</td>
<td>0</td>
<td>796</td>
<td>0.16</td>
</tr>
<tr>
<td>32</td>
<td>70.83</td>
<td>0</td>
<td>296</td>
<td>0.03</td>
<td>67.86</td>
<td>0</td>
<td>611</td>
<td>0.06</td>
<td>69.53</td>
<td>0</td>
<td>910</td>
<td>0.22</td>
</tr>
<tr>
<td>34</td>
<td>72.93</td>
<td>0</td>
<td>267</td>
<td>0.02</td>
<td>69.87</td>
<td>0</td>
<td>583</td>
<td>0.06</td>
<td>71.62</td>
<td>0</td>
<td>768</td>
<td>0.20</td>
</tr>
<tr>
<td>36</td>
<td>74.81</td>
<td>0</td>
<td>264</td>
<td>0.03</td>
<td>71.67</td>
<td>0</td>
<td>579</td>
<td>0.08</td>
<td>73.58</td>
<td>0</td>
<td>762</td>
<td>0.14</td>
</tr>
<tr>
<td>38</td>
<td>76.60</td>
<td>0</td>
<td>256</td>
<td>0.03</td>
<td>73.30</td>
<td>0</td>
<td>587</td>
<td>0.06</td>
<td>75.41</td>
<td>0</td>
<td>794</td>
<td>0.16</td>
</tr>
<tr>
<td>40</td>
<td>78.37</td>
<td>0</td>
<td>220</td>
<td>0.02</td>
<td>74.81</td>
<td>0</td>
<td>578</td>
<td>0.06</td>
<td>77.10</td>
<td>0</td>
<td>808</td>
<td>0.26</td>
</tr>
<tr>
<td>42</td>
<td>79.92</td>
<td>0</td>
<td>217</td>
<td>0.02</td>
<td>76.26</td>
<td>0</td>
<td>593</td>
<td>0.06</td>
<td>78.58</td>
<td>0</td>
<td>689</td>
<td>0.14</td>
</tr>
<tr>
<td>44</td>
<td>81.30</td>
<td>0</td>
<td>197</td>
<td>0.05</td>
<td>77.61</td>
<td>0</td>
<td>535</td>
<td>0.08</td>
<td>79.89</td>
<td>3</td>
<td>645</td>
<td>0.23</td>
</tr>
<tr>
<td>46</td>
<td>82.56</td>
<td>0</td>
<td>164</td>
<td>0.02</td>
<td>78.90</td>
<td>0</td>
<td>561</td>
<td>0.06</td>
<td>81.14</td>
<td>2</td>
<td>641</td>
<td>0.22</td>
</tr>
<tr>
<td>48</td>
<td>83.75</td>
<td>0</td>
<td>164</td>
<td>0.02</td>
<td>80.12</td>
<td>0</td>
<td>550</td>
<td>0.08</td>
<td>82.36</td>
<td>2</td>
<td>722</td>
<td>0.25</td>
</tr>
<tr>
<td>50</td>
<td>84.83</td>
<td>0</td>
<td>129</td>
<td>0.02</td>
<td>81.25</td>
<td>0</td>
<td>540</td>
<td>0.06</td>
<td>83.54</td>
<td>0</td>
<td>615</td>
<td>0.16</td>
</tr>
</tbody>
</table>

| Average | 0 | 344.96 | 0.03 | 0 | 630.24 | 0.10 | 0.28 | 770.16 | 0.16 |

**Table 5.2:** MCLP result details: PINPS, 200 meter-spaced, and 100 meter-spaced (Polygon-based approach: Destination-based)
This part discusses the comparison between PINPS, 200 meter-, and 100 meter-spaced potential facility locations based on the point-represented demand using origin-based access. Before comparing MCLP results by polygon-based approach and by point-represented approach in a big picture, details of MCLP results by PINPS, 200 meter-spaced, and 100 meter-paced potential facilities based on point-represented approach will be discussed.

Figure 5.7: Tradeoff curves for comparison between PINPS, 200 meter-, and 100 meter-spaced potential facility points (Point-represented approach: Origin-based)
<table>
<thead>
<tr>
<th>$p$</th>
<th>PINPS</th>
<th>200 meter-spaced</th>
<th>100 meter-spaced</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coverage by Objective (%)</td>
<td>Branches</td>
<td>Iterations</td>
</tr>
<tr>
<td>2</td>
<td>10.53</td>
<td>0</td>
<td>7394</td>
</tr>
<tr>
<td>4</td>
<td>20.41</td>
<td>0</td>
<td>7820</td>
</tr>
<tr>
<td>6</td>
<td>29.37</td>
<td>0</td>
<td>7854</td>
</tr>
<tr>
<td>8</td>
<td>37.04</td>
<td>0</td>
<td>8240</td>
</tr>
<tr>
<td>10</td>
<td>44.01</td>
<td>0</td>
<td>8372</td>
</tr>
<tr>
<td>12</td>
<td>50.86</td>
<td>0</td>
<td>8278</td>
</tr>
<tr>
<td>14</td>
<td>57.07</td>
<td>0</td>
<td>7903</td>
</tr>
<tr>
<td>16</td>
<td>62.13</td>
<td>0</td>
<td>7762</td>
</tr>
<tr>
<td>18</td>
<td>66.87</td>
<td>0</td>
<td>7428</td>
</tr>
<tr>
<td>20</td>
<td>71.33</td>
<td>0</td>
<td>6970</td>
</tr>
<tr>
<td>22</td>
<td>75.20</td>
<td>0</td>
<td>5959</td>
</tr>
<tr>
<td>24</td>
<td>78.67</td>
<td>0</td>
<td>5572</td>
</tr>
<tr>
<td>26</td>
<td>81.76</td>
<td>0</td>
<td>5218</td>
</tr>
<tr>
<td>28</td>
<td>84.12</td>
<td>0</td>
<td>4396</td>
</tr>
<tr>
<td>30</td>
<td>86.20</td>
<td>0</td>
<td>4385</td>
</tr>
<tr>
<td>32</td>
<td>88.08</td>
<td>0</td>
<td>3931</td>
</tr>
<tr>
<td>34</td>
<td>89.57</td>
<td>0</td>
<td>3383</td>
</tr>
<tr>
<td>36</td>
<td>90.89</td>
<td>0</td>
<td>3296</td>
</tr>
<tr>
<td>38</td>
<td>92.00</td>
<td>0</td>
<td>2571</td>
</tr>
<tr>
<td>40</td>
<td>92.86</td>
<td>1</td>
<td>2664</td>
</tr>
<tr>
<td>42</td>
<td>93.65</td>
<td>0</td>
<td>2583</td>
</tr>
<tr>
<td>44</td>
<td>94.40</td>
<td>0</td>
<td>2067</td>
</tr>
<tr>
<td>46</td>
<td>95.03</td>
<td>0</td>
<td>1709</td>
</tr>
<tr>
<td>48</td>
<td>95.53</td>
<td>0</td>
<td>1418</td>
</tr>
<tr>
<td>50</td>
<td>95.93</td>
<td>0</td>
<td>1266</td>
</tr>
</tbody>
</table>

Average | 0.04 | 5137.56 | 2.28 | 7.12 | 6393.80 | 6.95 | 17.40 | 7904.40 | 12.48

Table 5.3: MCLP result details: PINPS, 200 meter-spaced, and 100 meter-spaced (Point-represented approach: Origin-based)
As seen in Figure 5.7 and Table 5.3, the coverage levels between three approaches do not differ much. Coverage by approach with PINPS has slight better coverage than the method with 200 meter-spaced potential facilities, but has less coverage than the method with 100 meter-spaced potential facilities. This is expected because the potential facilities derived from PINPS are not related to the covering boundaries any more when the $N_i$ set is evaluated. An earlier part of this research already showed that polygon-based demand is best covered by PINPS because PINPS were originally extracted from covering boundaries that are derived from polygon demand objects. Thus, as long as the polygon demand is not associated with covering boundaries, PINPS is only one method for discretization of a continuous road network to create potential facilities. PINPS is no better of a solution in terms of coverage level.

However, in terms of computational complexity, PINPS still offers better efficiency. Results with PINPS have averages of 2.28 seconds of solution time, 5137.56 iterations, and 0.04 branches while the method with 200 meter-spaced potential facilities have 6.95 seconds of solution time, 6393.80 iterations, and 7.12 branches, and the method with 100 meter-spaced potential facilities have 12.48 seconds of solution time, 7904.40 iterations, and 17.40 iterations. Given this, PINPS can provide more efficient computation while maintaining as much coverage as other approaches that come with greater computational burden. This can be interpreted in a different way. In origin-based analysis, PINPS has only 914 potential facility locations while the method with 200 meter spacing has 3541 potential facility locations and the method with 100 meter spacing has 4813 potential
facility locations. Therefore, PINPS enables application of the MCLP to offer competitive coverage with far less number of facilities, even if PINPS is not associated with polygon-based demand.

This part discusses the comparison between PINPS, 200 meter-, and 100 meter-spaced potential facility location based on the point-represented demand using destination-based access. Through this chapter up to now, both results by origin-based and destination-based approaches have been analyzed and it turns out that they have similar performance patterns, even though result details are somewhat different. Therefore, in this section, the comparison of MCLP results between polygon-based approach and point-represented approach will be focused on using destination-based approach.

According to Table 5.2 and Table 5.4, two sets of approaches by polygon-based and point-represented approaches have similar patterns in terms of computation complexities. Both have average solution times of 0.03 seconds for PINPS; polygon-based has 0.1 second and point-represented has 0.16 seconds for the method with 200 meter spacing; polygon-based has 0.16 second and point-represented has 0.16 seconds for the method with 100 meter spacing. For the number of iterations and branches, they have similar results to each other. However, the coverage patterns are notably different.

As seen in Figure 5.8, complete coverage of parcels by PINPS derived facilities applied to polygon-based approach is better than complete coverage of parcels by PINPS to
point-represented approach. This is consistent along all ranges of \( p \) values. Coverage by completely covered parcels by PINPS based on polygon-based approach exceeds those by the method with 200 meter spacing by point-represented approach and by the method with 100 meter spacing by point-represented approach, because PINPS, even when dealing with point-represented approach, is superior to the other approaches with 200 and 100 meter spaced potential facilities. For the comparison of regularly spaced potential facilities between polygon-based approach and point-represented approach, both methods with 200 meter- and 100 meter-spaced potential facilities by polygon-based approach have better coverage over those by point-represented approach respectively. Therefore, considering the fact that computation complexities between polygon-based and point-represented approaches are similar, it can be concluded that polygon-based approaches by each type of potential facility provide a better coverage level to completely cover the associated polygon demand objects than point-represented approach. Other than coverage and computation efficiency, polygon-based approaches have the advantage in that they provide the value of complete coverage directly from objective values of model in contrast to the fact that further spatial processing is necessary to obtain complete coverage from point representation approach.
Figure 5.8: Comparison between polygon-based and point-represented approaches
Table 5.4: MCLP result details: PINPS, 200 meter-spaced, and 100 meter-spaced (Point-represented approach: Destination-based)
Murray and O’Kelly (2002) discussed that in coverage models, point representation could cause over-estimation of the actual coverage that identified optimal facilities would provide to an area. This research also shows this in all cases. Figure 5.9 shows that coverage levels by objective value are always far over-estimating the demand being covered by identified transit stops than what would truly be covered on the ground. This also shows that coverage levels by objective value over-estimate actual coverage even though the difference is not as big as in the case of complete coverage. This is demonstrated with graphical examples in Figure 5.10. Figure 5.10 (a) shows covered parcels by which are counted in the MCLP objective value. Once the centroid is included inside the service coverage, the parcel is considered to be receiving suitable service. Likewise, when the centroid is not included in the service coverage, the parcel is not considered covered by the service even though some portion of parcel is still covered. According to (a) and (c) in Figure 5.10, it is intuitively very clear that coverage by point-represented approach is always over-estimated than the coverage by polygon-based approach when complete coverage is compared.
Figure 5.9: Coverage by objective value, actual coverage, and complete coverage in the point-represented approach
Figure 5.10: Covered parcels by objective value, actual coverage, and complete coverage
5.3. Summary

This chapter focused on the following two topics: One is an examination of the advantages to PINPS with polygon demand compared to other approaches, such as approaches with randomly placed potential facilities in a regular manner. This part also included a comparison of the MCLP results between polygon-based approach and point-represented approach. The other topic is the use of a bi-objective MCLP to create a set of new service stop locations with two separate objectives featured as origin- and destination-based demands. This integrated set maximizes the two separate objectives simultaneously and provides choices of weight between the objectives depending on planning strategy.

Further examination involved two detailed comparisons. One comparison is between potential facility types created by PINPS and random selection in a regular basis based on polygon demand. The other comparison more importantly contrasts the use of polygon-based approach and point-represented approach. In the first case, it is found that PINPS provides better coverage and more computational efficiency. In the second case, PINPS with polygon-based approach offers the highest coverage and slightly better computational efficiency, guaranteeing direct provision of complete coverage from the objective value from MCLP. Approaches with point-represented demand result in error of over-estimation of the actual coverage, especially of complete coverage. There have been notable gaps between areas obtained by objective values and areas of completely covered
demand, which implies that coverage obtained by objective values of the model is not closely related with complete coverage and the error was significant.
6. CONCLUSION

6.1. Summary and contribution

Mobility and accessibility to opportunities and resources throughout an urban environment are important for the well-being of its citizens and the general vitality of a community. If there are individuals and households who are not able to afford or use personal transportation, public transportation should be an alternative. For this reason, provision of appropriate transport to the people who need it is one of the most important roles of public transportation agencies. The issue of equity has arisen because there are people who need public transportation but do not have proper access to it. Research has shown that there are certainly people who are isolated from the locations which provide the mobility and accessibility that public transportation provides. It is known that the most efficient and feasible way to enhance access of public transportation to support the transport disadvantaged is to adjust the location of service facilities.

To this end, modeling approaches were developed in this research. In order to enhance equity in public transportation, the regions characterized as transport disadvantaged need to be identified in terms of origin-based and destination-based demand. This evaluation is
based on access defined as an opportunity to use the transport system in terms of proximity to service and cost (Murray et al. 1998). Origin-based transport disadvantaged areas are determined to be those heavily populated by the young, the old, low income earners, those with no vehicle and the disabled. Destination-based transport disadvantage areas are evaluated by employment, shopping, amenity facilities, educational institutions, and public service facilities. Both origin- and destination-based transport disadvantaged areas are characterized by having high levels of need paired with a low level of access to public transit.

The study area preparation is followed by model development, application, and analysis. First, PINPS was the most significant contribution of this research. The location of potential facility sites has been an issue over time and has been developed in various ways. CIPS (Church 1984) was developed to discretize continuous space to locate potential facility sites for coverage of point-based demand. Murray and Tong (2007) extended this discretization approach to line- and polygon-based demand with PIPS. Both approaches above utilize the entire continuous space for potential facility sites, but prove that a discrete set of finite points dominates the remaining continuous space. That is, they are more efficient than other potential locations. However, further enhancement is necessary to apply these methods to specific planning environments, such as line-based continuous space. This research developed PINPS by extending PIPS to suit the discretization of continuous network spaces.
The City of Hilliard, Ohio was selected as a research area because of its proximity to downtown Columbus and identified areas of transport disadvantaged. PINPS was then derived from the road network data layer in conjunction with covering boundaries from the city’s parcel data layer using ArcGIS. PINPS created a large number of potential facilities, and removal of redundant locations substantially decreased the number of potential facilities by 98.5%. The MCLP with polygon-based demand was carried out using PINPS with varying $p$ from 2 to 50 for both origin- and destination-based access. The tradeoff curve shows that similar to other MCLP results, the rate of coverage decreased more notably after 70% to 80% of total demand, which means that the addition of more facilities does not necessarily produce cost-effective coverage. This suggests that coverage of 70% to 80% of the underserved transport disadvantaged in the region is the most practical for the economics of planning purposes.

The results of the MCLP are interesting. Coverage by objective values only includes completely covered parcels within the given service coverage standard. That is, if a parcel is partially covered by a located transit stop, the model does not count the demand located in that parcel as part of the objective function. We would not necessarily consider this to be a realistic assessment. The fact that the use of the MCLP with PINPS for polygon-based demand ensures complete coverage in the objective value is the most closely identified. In addition, it was found that the gap between complete coverage by objective values and actual coverage vary according to the size of individual parcels. The bigger the parcels, the bigger the gaps.
Another important part of this research was the development of a bi-objective MCLP to create a set of new service stop locations integrating two separate objectives of maximizing coverage of origin- and destination-based demand. This consolidated set maximizes coverage for both origin- and destination-based objectives simultaneously. By differing the assigned weight to each objective, combinations of maximal coverage for both objectives are shown to vary on the Pareto curve. Thus, any combination on the Pareto curve can be selected based on the planning strategy of the decision makers, and associated preferences. This method is functional when multiple objectives need to be considered to create one optimized set of results, which is very common in real planning environments.

In chapter 5, various comparisons of differing approaches were carried out. First, results of the MCLP based on polygon-based approach with PINPS were compared to those with randomly located potential facilities in a regular basis, such as 200 meter-spaced and 100 meter-spaced points on the road network, to assess coverage and computational efficiency. Another comparison was made between the MCLP based on polygon-based approach and point-represented approach. In the first case, PINPS proved to be more computationally efficient. PINPS certainly offered better coverage but the other two approaches also resulted in high coverage performance. Overall, PINPS was superior to other approaches in terms of both coverage and computational efficiency. In the second case, PINPS with polygon-based demand provided the highest coverage and slightly
better computational efficiency as compared to other approaches, such as PINPS with point-represented demand, 200 meter-spaced potential facilities with both polygon-based and point-represented demand, and 100 meter-spaced potential facilities with both polygon-based and point-represented demand. This is an important contribution from this research. The MCLP results using PINPS based on polygon-based demand provided the best coverage over all other approaches with the most computational efficiency. Besides, the MCLP with PINPS and polygon-based demand directly produced the complete coverage from objective values of MCLP, but the approach with point-represented demand does not ensure complete coverage from objective values directly. This requires further spatial processing to obtain a complete coverage estimate. Also, the use of point-represented access results in error between objective values and actual coverage that is remarkable. Therefore, for a study that requires polygon demand objects with potential facilities to be located along networks, adopting the MCLP with PINPS and polygon-based demand will offer the most reasonable solution.

6.2. Future Study

During the research, a couple of ideas have been born for improving this research. First, a method to remove redundant points was developed when PINPS was created. This method successfully removed dominated points and reduced the number of intersection points considerably. The resulting point sets enabled the MCLP to solve problems more efficiently. However, the proposed method for the removal did not completely remove all dominated points, even though the remaining points did not appear to be numerous.
Assuming that any larger research area can be adopted for future research, this incomplete removal might cause computational burdens for a huge data set. Therefore, developing a method to remove all redundant points could be helpful to adopt.

Next, this research mainly focused on identifying the optimal locations of new service stops to maximize coverage for the transport disadvantaged areas. Therefore, the stop locations suggested in the research maximized both origin-based and destination-based demand to enhance the level of equity among the population. This is useful when the planning goal is to newly discover only equity-oriented service stop locations or when the modeling development is an objective of the research in an academic context. However, for real planning purposes, the currently operated stop locations would need to be incorporated. All the features, such as equity factors by origin- and destination-based demand and normal demand from current service stops, would need to be factored into the analysis. To this end, developing another multi-objective method to add maximization of current regular demand, which is located in mostly densely populated or commuting areas, is necessary. This future suggestion will require a thorough examination regarding the demand coming from those who are not transportation disadvantaged, especially what factors compose the demand and how the demand is measured. Once the property of demand is prepared, a multi-objective model could be evaluated. This comprehensive research will be expected to offer more real planning-oriented approach.
REFERENCES


128


Ohio Department of Transportation (ODOT) (2007). Status of Public Transit in Ohio


