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Enhancing Equity in Public Transportation Using Geographic Information Systems and Spatial Optimization

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Abstract

Public transportation is a vital part of urban living. 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 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 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, 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.

Keywords

Equity, Public transportation, GIS, MCLP, Bi-objective model

1 INTRODUCTION

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 (Gray 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 work.

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). Therefore, the question of equity in public transportation can be defined as whether or not people who need public transportation, due to the lack of personal transport, have appropriate accessibility to the public transportation. 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.

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 tries to answer the question: how can the level of equity in public transportation be enhanced? – how can people who need public transportation, due to the lack of personal transport, have enhanced accessibility to public transportation by improving the level of access by adding public transportation facilities in a fixed-route system, such as service stops. GIS and combinations of optimization models will find how many new service stops are required and where they should be located. This improved level of access for the transport disadvantaged exemplifies evidence of enhanced levels of equity. Along these lines, this research first discusses the concept of equity in transportation and the implementation of equity in public transportation.

2 LITERATURE REVIEW

2.1 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 corresponds 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.

2.2 Equity in Transportation

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). Hay and Trinder (1991) 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. Improvements in transportation help to enhance mobility and prosperity in urban areas. Among such enhancements, society believes that minimal mobility should be guaranteed to all urban residents. 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. De Barbieri (2017) recognized that the notion of transportation extends to human rights issues, as it is related to the quality of life, since it influences access to education, employment, and health care.

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. Adorno et al. (2018) discussed that older adult groups are transportation disadvantaged due to their limited transit mobility choices. Falcocchio and 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. 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.

Oswald Beiler and Mohammed (2016) identified that transport agencies are required by local, regional and national governments to avoid unfair impact to low-income and minority groups. Hodge (1995) 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.

2.3 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; 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.

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.

2.4 Access and Accessibility

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. Murray and Davis (2001) presented three major factors relating to access, one of which contributes to being transport disadvantaged. That is, inadequate transportation, which means poor or no access either to public or to personal transportation. This especially addresses 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.

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). Central Ohio Transit Authority (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).

Ibeas et al. (2010) developed a model optimizing bus stop locations to reduce the social cost in the transit system. This research focuses on cost minimization using operational factors such as congestion, fleet size, and number of passengers and bus stops. However, their model does not address equity issues. 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. Delmelle et al. (2012) discussed how to identify bus top redundancy considering any trade-off between accessibility by the addition of stops and efficiency by travel time. They took into account facility attraction, distance deterrence, and competition around the facilities for their analysis, but equity issues were not their topic. 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.

2.5 Optimizing Access

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 et al. (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 (Ramirez 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.

3 MODELING ACCESS

3.1 Planning Context and Data

The city of Columbus in Franklin County, Ohio is currently experiencing enormous growth and is now the thirty-second largest Metropolitan Statistical Area (MSA) in the United States (U.S. Census Bureau 2017). 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 2007). 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.

In order to identify the origin-based transport disadvantaged, socioeconomic data and demographic data are required. As discussed in the literature review, many studies have defined the category of the transport disadvantaged and it includes 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*

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 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 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.

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 and Monroe 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 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. For the origin-based demand, the areas with more socioeconomic and demographic data for the transport disadvantaged (the young, the old, low household income, household with no vehicle, and the disabled) are considered high demand. When these high demand areas are not located within a 400-meter distance to the nearest bus stop, they are defined as a transport disadvantaged area. Areas of destination-based demand is similarly defined, but destination features, such as employment, shopping, amenity facilities, educational institutions, and public service, were used instead of socioeconomic and demographic date. 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.

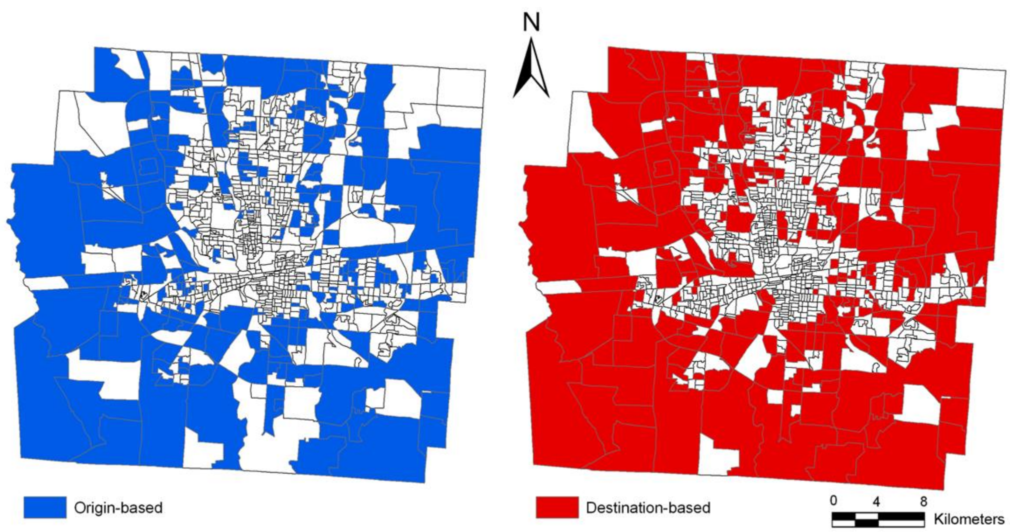


Figure 1. Transport disadvantaged areas.

3.2 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 $$\sum_i a_i Y_i \tag{3.1}$$

Subject to

$$\sum_{j \in N_i} X_j - Y_i \geq 0 \qquad \forall i \tag{3.2}$$

$$\sum_j X_j = p \tag{3.3}$$

$$X_j = \{0,1\} \qquad \forall j \tag{3.4}$$

$$Y_i = \{0,1\} \qquad \forall i$$

where

$i =$ index of demand parcels;

$j =$ index of potential facility locations;

$a_i =$ area for demand parcel i;

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

$= \{ j \mid d_{ij} \leq R \}$

$p =$ 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.

4 ACCESS APPLICATION FOR ACHIEVING EQUITY

The study area was limited to the City of Hilliard, Ohio (see Figure 2). As shown in Figure 1, 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 3 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.

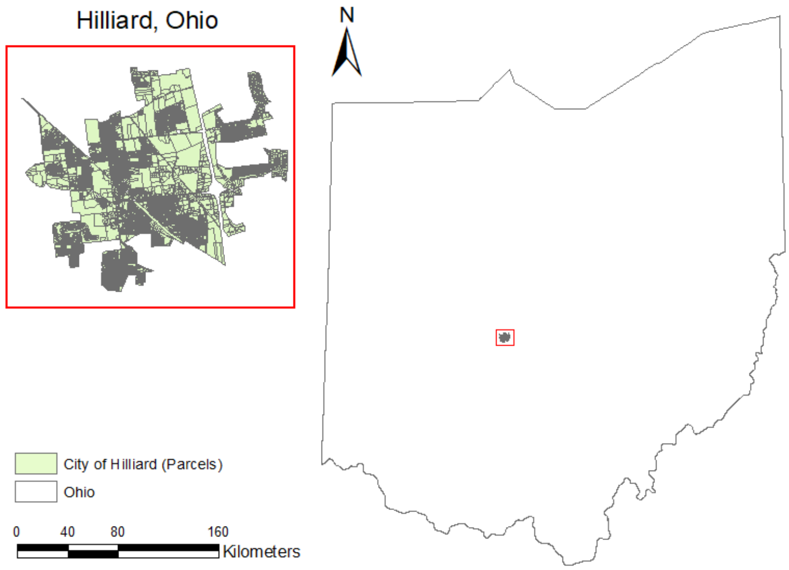


Figure 2. City of Hilliard, Ohio.

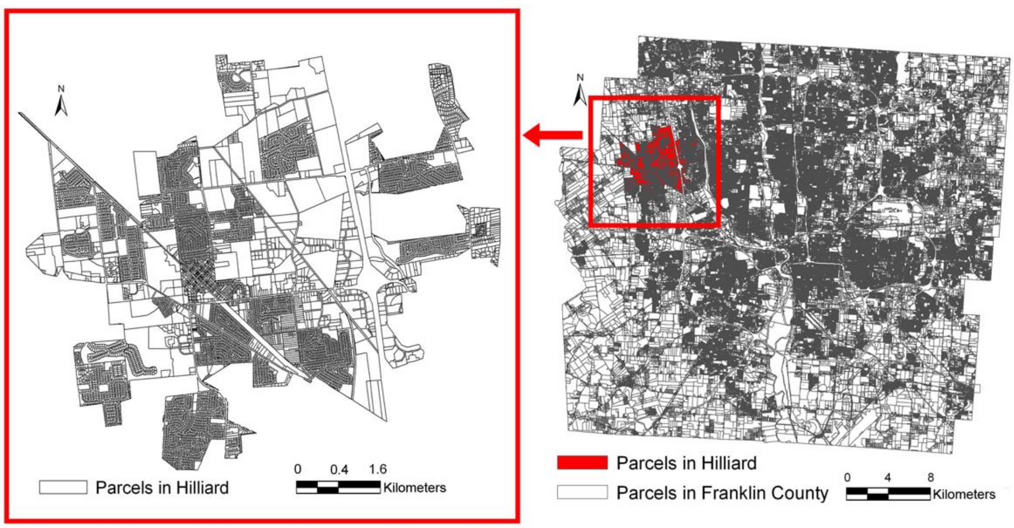


Figure 3. Parcels in the study area.

Figure 4 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.

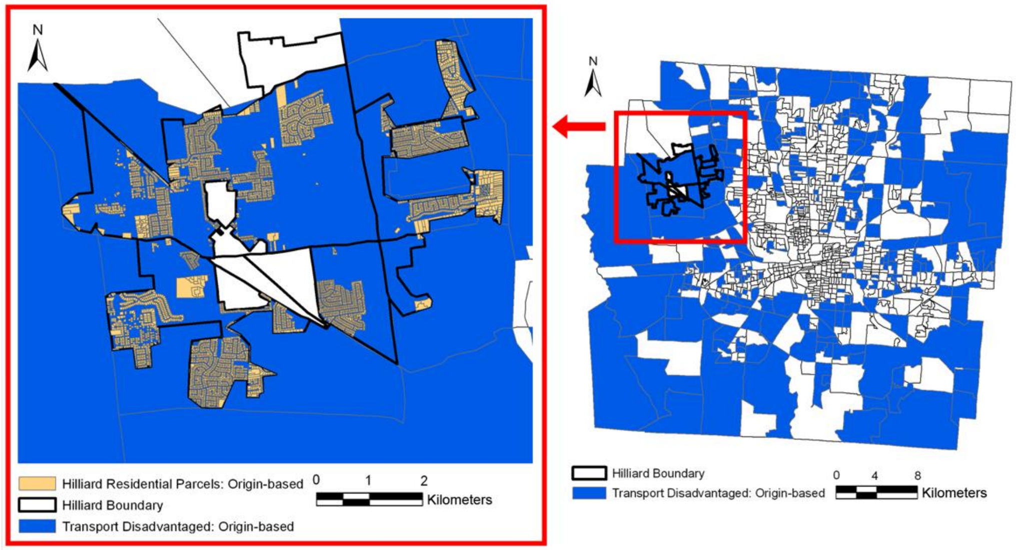


Figure 4. Data transfer to study area (origin-based).

Figure 5 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 land use data, the parcels are classified using characteristics of employment, shopping, amenity facilities, educational institutions, and public service facilities.

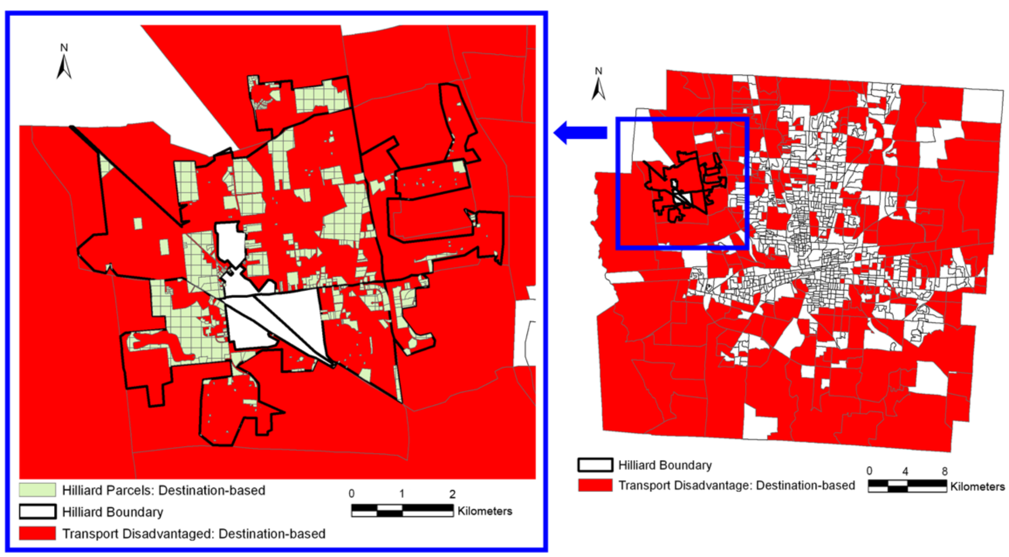


Figure 5. Data transfer to study area (destination-based).

4.1 Origin Access and Destination Access

Figure 6 shows 914 discretized points along the Hilliard road network using PINPS[1] (Cha and Murray 2020 in progress). The MCLP was evaluated with given potential facility sites across the origin-based demand parcels and destination-based demand parcels, respectively, 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 1.

For the origin-based analysis, 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 (see Figure 8). 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.

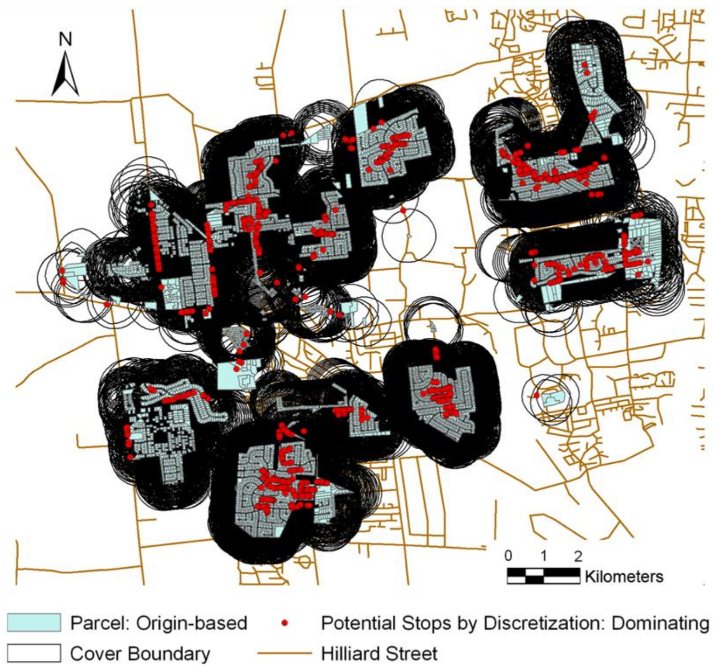


Figure 6. 914 discretized point along road network using PINPS (origin-based).

[1] Polygon Intersection with Network Point Set (PINPS) is a method to discretize a continuous road network to extract potential facilities ensuring complete coverage for polygon-based demand. (Cha and Murray 2020 in progress)

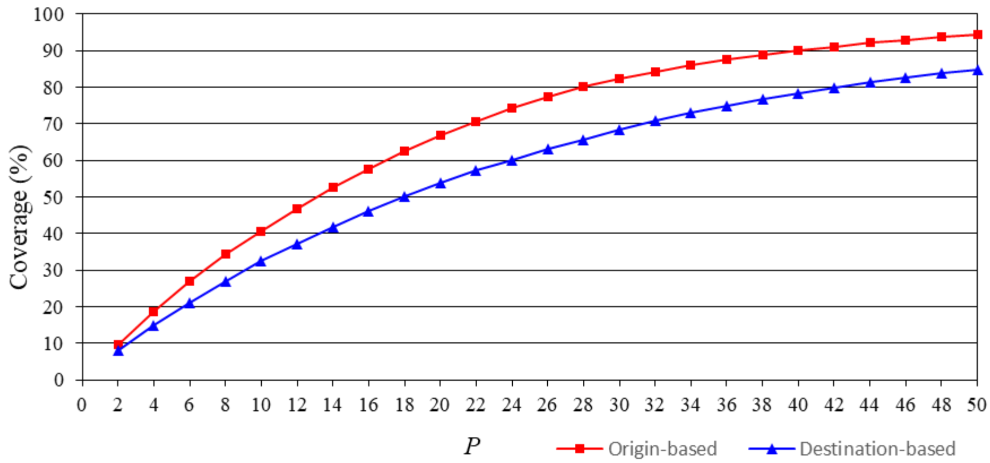


Figure 7. MCLP Tradeoff curve (origin-based & destination-based).

Table 1. MCLP result details (origin-based & destination-based).

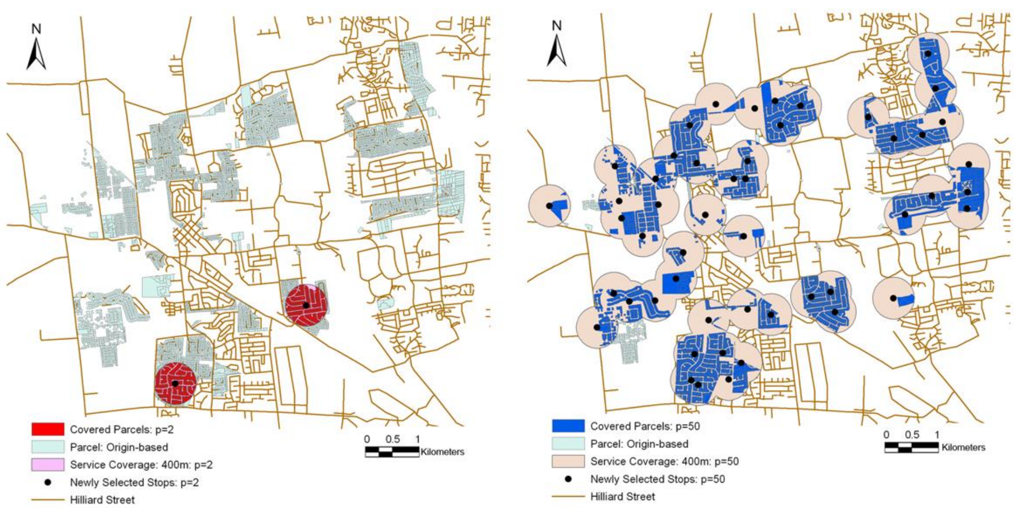
Origin-based					Destination-based				
p	Coverage (%)	Branches	Iterations	Solution Time	*p*	Coverage (%)	Branches	Iterations	Solution Time
2	9.59	0	6812	1.22	2	8.00	0	483	0.03
4	18.59	0	7786	1.70	4	15.06	0	484	0.03
6	26.99	0	7839	1.78	6	21.22	0	481	0.02
8	34.29	0	7854	1.91	8	27.10	0	483	0.01
10	40.62	0	8022	2.09	10	32.54	0	470	0.06
12	46.68	1	8531	11.17	12	37.28	0	452	0.01
14	52.48	0	8655	2.53	14	41.83	0	467	0.02
16	57.58	0	8211	2.38	16	46.16	0	455	0.03
18	62.50	0	7883	2.39	18	50.26	0	439	0.03
20	66.82	0	7201	2.14	20	53.98	0	399	0.02
22	70.70	0	7389	2.33	22	57.24	0	387	0.03
24	74.32	0	5952	1.87	24	60.17	0	377	0.03
26	77.50	0	5466	1.89	26	63.00	0	364	0.03
28	80.19	0	4703	1.63	28	65.71	0	361	0.02
30	82.29	0	4621	1.66	30	68.37	0	348	0.02
32	84.29	0	4209	1.53	32	70.83	0	296	0.03
34	85.99	0	3771	1.36	34	72.93	0	267	0.02
36	87.53	0	3570	1.47	36	74.81	0	264	0.03
38	88.89	0	3348	1.36	38	76.60	0	256	0.03
40	90.09	0	3009	1.50	40	78.37	0	220	0.02
42	91.10	0	3064	1.78	42	79.92	0	217	0.02
44	92.05	1	2693	2.61	44	81.30	0	197	0.05
46	92.87	0	2584	4.75	46	82.56	0	164	0.02
48	93.65	0	2297	2.94	48	83.75	0	164	0.02
50	94.37	0	1879	2.86	50	84.83	0	129	0.02

Figure 7 shows the tradeoff curve demonstrating how the amount of demand coverage changes with an increasing number of potential facilities, in both origin- &

destination-based demand. In general, the curve shows that the percentage of coverage is increasing with a decreasing rate, forming a convex curve.

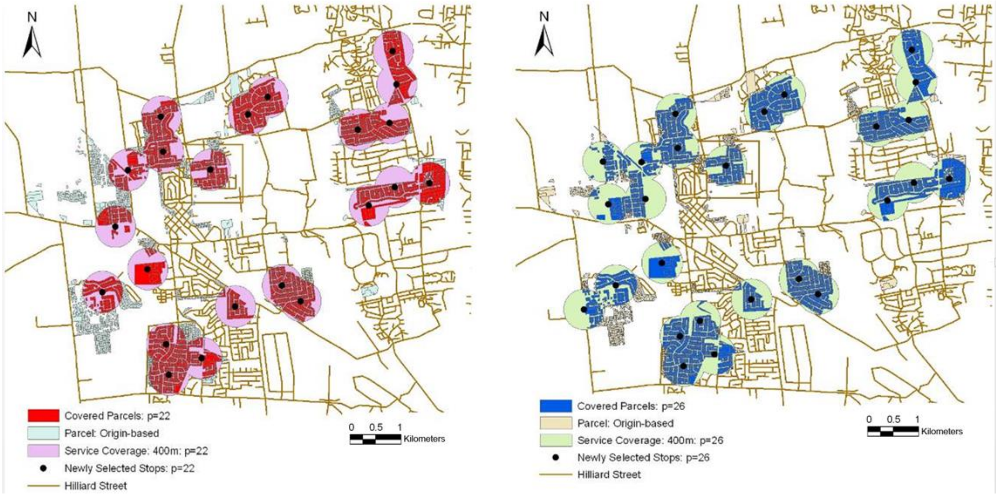
For the origin-based analysis, even though the increasing rate decreases, the total coverage is still increasing up to 70% to 80%, requiring some 25 facilities (transit stops). After a *p* value of 25, the increase rates decreases significantly, so the total coverage does not substantially increase. 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% and in the case of p=26, the coverage levels are 77.50%. These results are shown in Figure 9. This indicates that adding 22 to 26 new bus stops, determined by PINPS and MCLP, to current bus route will enhance the level of equity by providing 70.70% to 77.50% of new coverage to the origin-based transport disadvantaged area.

One miscellaneous finding depicted in Figure 7 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 9 (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 6. 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.



(a) Coverage of 9.59% with p=2 (b) Coverage of 94.37% with p=50

Figure 8. Coverage: Minimum and Maximum within given *p* values (origin-based).



(a) Coverage of 70.70% with *p*=22 (b) Coverage of 77.50% with *p*=26

Figure 9. Appropriate Coverage (origin-based).

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 10 shows 163 discretized points along the Hilliard road network using PINPS approach (Cha and Murray 2020 in progress).

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 1. The table shows that new bus stop coverage varies from 8.00% in the case of *p*=2 and 84.83% in the case of *p*=50 (see Figure 11). 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 7 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 12. In the case of *p*=28, the coverage levels are 65.71%. In the case of *p*=36, the coverage levels are 74.81. This result indicates that adding 28 to 36 new bus stops, determined by PINPS and MCLP, to current bus routes will enhance the level of equity by providing 65.71% to 74.81% of new coverage to the destination-based transport disadvantaged area.

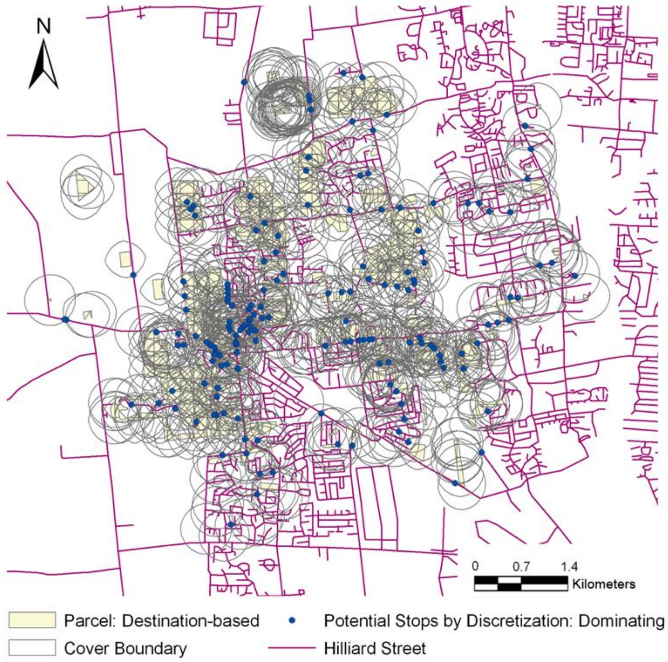
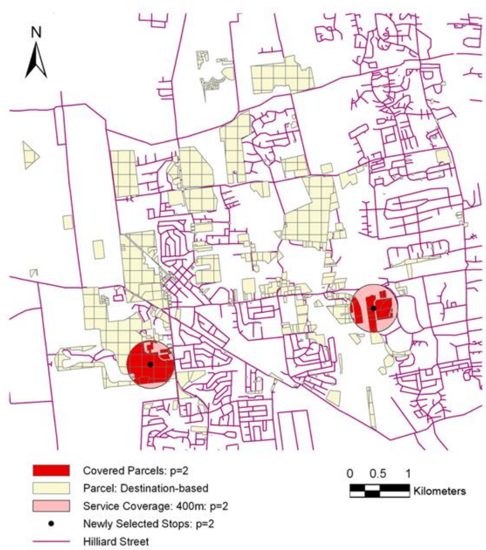
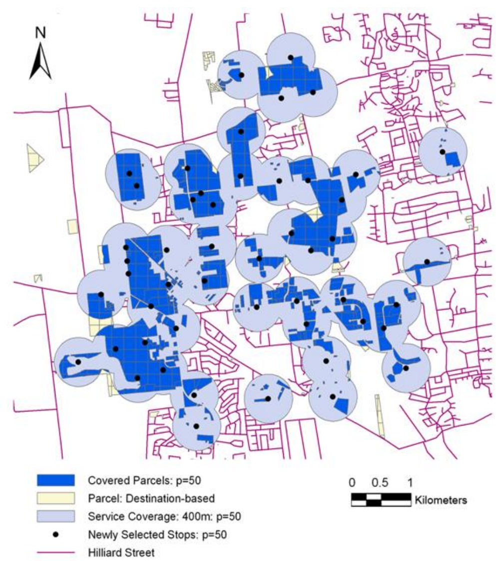


Figure 10. 163 discretized point along road network using PINPS (destination-based).



(a) Coverage of 8.00% with p=2



(b) Coverage of 84.83% with p=50

Figure 11. Coverage: Minimum and Maximum within given p values (destination-based).

(a) Coverage of 65.71% with *p*=28 (b) Coverage of 74.81% with *p*=36

Figure 12. Desirable Coverage (destination-based).

4.2 Bi-Objective MCLP with Origin-Based and Destination-Based Approach

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,[2] 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

[2] Tradeoff curve is used as a synonym of the Pareto curve (solution), non-inferior curve (solution), or non-dominated curve (solution) (Cohon 2003).

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 specific gap points (ReVelle 1993). Thus, this model will be formulated using the weighting method.

4.2.1 Problem Formulation

Maximize $$Z = W\sum_i a_i O_i + (1-W)\sum_m a_m D_m \quad (4.1)$$

Subject to $$\sum_{j\in N_i} x_j - O_i \geq 0 \quad \forall i \quad (4.2)$$

$$\sum_{j\in N_m} x_j - D_m \geq 0 \quad \forall m \quad (4.3)$$

$$\sum_j x_j = p \quad (4.4)$$

$$x_j = \{0,1\} \quad \forall j \quad (4.5)$$

$$O_i = \{0,1\} \quad \forall i$$

$$D_m = \{0,1\} \quad \forall m$$

where

$i =$ index of origin demand parcels;
$m =$ index of destination demand parcels;
$j =$ index of potential facility locations;
$a_i =$ area for origin demand parcel *i*;
$a_m =$ area for destination demand parcel *m*;
$N_i = \{j | d_{ij} \leq R\}$;
$N_m = \{j | d_{mj} \leq R\}$;
$d_{ij} =$ shortest distance from origin demand parcel *i* to potential facility *j*;
$d_{mj} =$ shortest distance from origin demand parcel *m* to potential facility *j*;
$p =$ number of facilities to site;
$R =$ the distance that could be traveled to suitably cover demand parcel: 400m;

$$x_j = \begin{cases} 1, & \text{if a potential facility } j \text{ located} \\ 0, & \text{otherwise;} \end{cases}$$

$$O_i = \begin{cases} 1, & \text{if origin demand } i \text{ is suitably covered} \\ 0, & \text{otherwise;} \end{cases}$$

$$D_m = \begin{cases} 1, & \text{if destination demand } m \text{ is suitably covered} \\ 0, & \text{otherwise.} \end{cases}$$

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).

4.2.2 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 2. Solution details for the bi-objective MCLP.

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

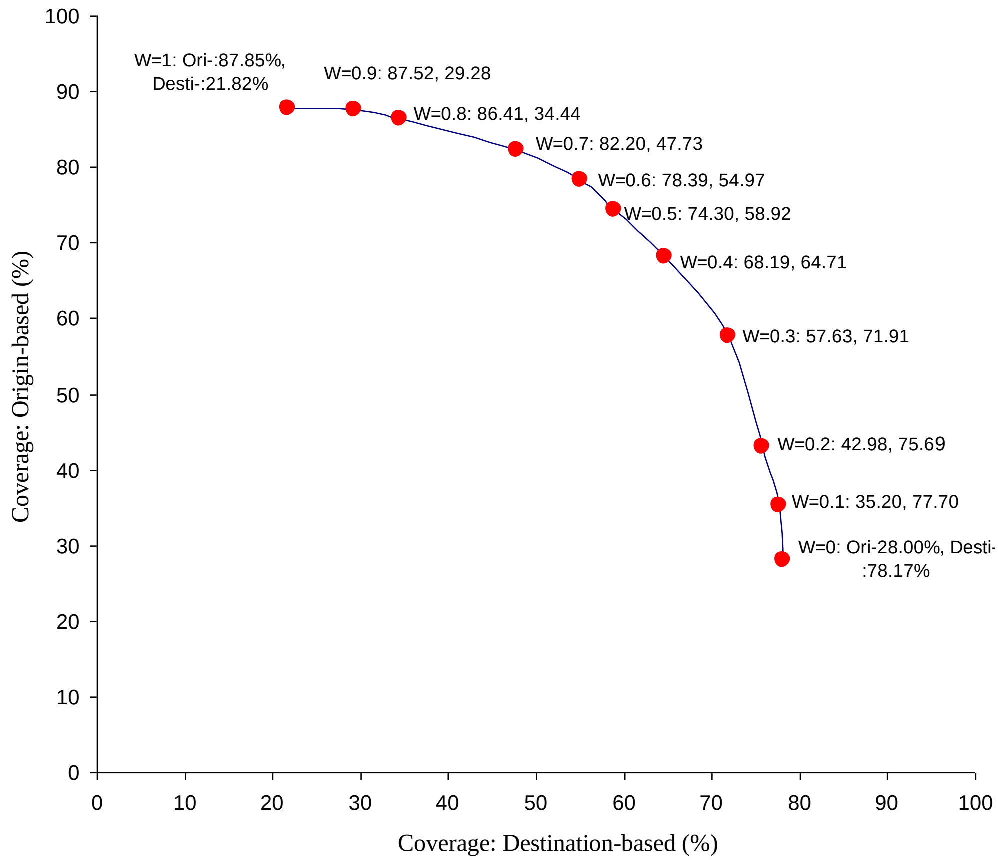
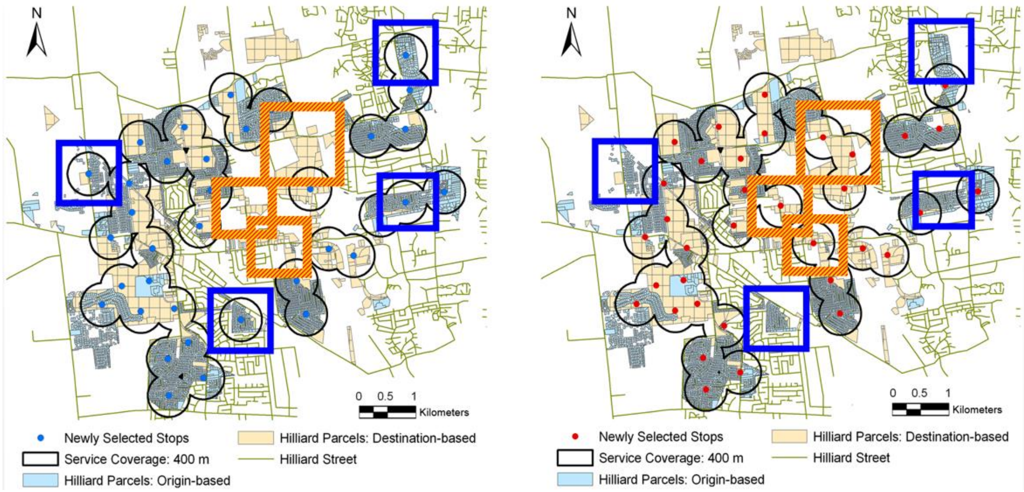


Figure 13. Tradeoff curve for bi-objective MCLP.

The bi-objective MCLP utilized the PINPS method to identify potential bus stop locations and used 36 as a p value. This means that we are trying to cover as many parcels, weighted by origin and destination demand as possible, while only siting 36 additional 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 specified. 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 2 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 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 provides 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. This result ultimately shows that adding 36 new bus stops, determined by PINPS and bi-objective MCLP, to current bus routes will enhance, at certain combinations, the level of equity by providing 68.19% of new coverage to the origin-based transport disadvantaged area and 68.19% of new coverage to the destination-based transport disadvantaged area. These are theoretical statistical findings. The most suitable combination of coverage would be based on specific planning goals.

In Figure 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.



(a) *w*=0.6 (b) *w*=0.4

Figure 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 1. Likewise, when *w*=0, the total coverage is the same as that of destination-based access with *p* =36 in Table 1. However, Table 3 shows that coverage levels for the bi-objective MCLP models are better than single-objective MCLPs respectively.

Table 3. Comparison of coverage between single- and bi-objective MCLP with full weight for either objective.

	Origin-based		Destination-based	
	Single-objective MCLP	Bi-objective MCLP with *w*=1	Single-objective MCLP	Bi-objective MCLP with *w*=0
Coverage with *p* = 36	87.53 %	87.85 %	74.81 %	78.17 %

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 3 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.

5 CONCLUSION

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 consider the addition 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. 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 City of Hilliard, Ohio was selected as a research area because of its proximity to downtown Columbus and identified areas of transport disadvantaged. The Maximal Covering Location Problem (MCLP) was carried out using Polygon Intersection with Network Point Set (PINPS) with varying numbers of possible additional bus stop locations from 2 to 50 for both origin- and destination-based access. These two analyses show that adding 26 bus stops to the current bus route provides new accessibility coverages to transport disadvantaged areas defined by origin-based demand by 77.50% and adding 36 bus stops to the current bus route provides new accessibility coverages to transport disadvantaged areas defined by destination-based demand by 74.81%. This increase coverage explains that the level of equity has been enhanced by the research.

Another important part of this research was the development of a bi-objective MCLP to create a set of new additional 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. When more weight is applied to the origin-based objective, the coverage for the origin-based demand increases. Likewise, when more weight is applied to the destination-based objective, the coverage for the destination-based demand increases. The result of this research shows that adding 36 new bus stops, determined by PINPS and bi-objective MCLP, to current bus routes improved the level of equity by providing 68.19% of new coverage to the origin-based transport disadvantaged area and 68.19% of new coverage to the destination-based transport disadvantaged area in a selected weight combination. However, any combination of weights 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.

The stop locations found 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 suggested in future research.

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