EVALUATION, MODELING AND POLICY ASSESSMENT FOR PARK-AND-RIDE SERVICES AS A COMPONENT OF PUBLIC TRANSPORTATION

DISSERTATION

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By

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ABSTRACT

Traffic congestion in urban areas of the United States has increased significantly since the mid-1970s and is expected to continue this trend in the 21st century. Traffic congestion is a byproduct of car dependency and not the problem in and of itself. Public transportation is recognized as an effective way to overcome car dependency and achieve sustainable cities. An integral component of many transit systems in the United States is park-and-ride services. If well planned, such services could result in increased transit ridership. Market area delineation is an important step when planning for such services. Previous approaches for delineating catchment/market areas, however, are either problematic or have unrealistic data requirements. This research develops a geographic information system (GIS)-based approach for delineating market areas. The results show that this approach performs better than existing approaches.

Siting park-and-ride facilities is another essential step when planning for the associated services. Unfortunately, existing location models cannot be readily used for locating such facilities, as they do not simultaneously address at least three key issues: distance decay, coverage standards, and partial coverage of demand. This research develops a general location model that simultaneously
deals with these issues. The developed model is general in that it can be applied not only for siting desirable facilities such as park-and-ride lots, but also for undesirable ones. The developed model is extended in order to deal with the issues of siting park-and-ride facilities in the context of an existing system and accessibility of selected facility sites to major roadways.

Although selecting appropriate facility locations is critical for achieving more viable park-and-ride services, this by itself may not result in a significant increase in ridership in a given urban area if key supporting elements are not adopted. This research reviews such elements and assesses the potential of Columbus, Ohio (the case study in this research) to achieve successful park-and-ride services. While there are plans to expand park-and-ride services and add elements to the transit system in Columbus, it is not expected that this will result in a significant increase in transit ridership, unless key elements/policies are adopted.
To my wife, Asma, and to my daughters Sahar, Yasmin, and Hadeel

To my parents
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CHAPTER 1

INTRODUCTION

Urban areas of the United States have been experiencing a significant increase in traffic congestion, and this is expected to continue to be the case in the 21st century (Levinson et al. 1997). Traffic congestion is a result of car dependency and not the problem in its own right (Newman and Kenworthy 1999). Public transport is recognized as an effective way to overcome car dependency and achieve sustainable and more livable cities (Newman and Kenworthy 1999). Using public transport as an alternative to the private automobile will likely lead to a reduction in air pollution and energy consumption as well as lessen traffic congestion (Hanson 1995). It is recognized, however, that public transport service is not well suited for low-density areas because there is usually not enough concentrated demand for travel to support fixed route transit service (Sargious and Janarthanan 1983). Providing park-and-ride services is an effective way to extend public transport service to low-density areas where commuters can still use their cars in the beginning of their trip but switch to transit at some point later in the same trip (Kerchowskas and Sen 1977).
Park-and-ride lots are change-of-mode facilities that provide a common location for drivers to transfer from low occupancy vehicles (i.e. private cars) to high occupancy vehicles (e.g. bus) (Noel 1988). Such facilities are usually located at different distances from major activity centers (Bowler et al. 1986). Local lots are relatively close to the major activity center and are usually served by local bus routes, whereas remote lots are relatively far from the major activity centers and are typically served by express transit service (Turnbull 1995). Figure 1.1 shows these two types of park-and-ride facilities in Columbus, Ohio. Most metropolitan regions in the United States recognize the importance of providing and expanding park-and-ride services. Based on a survey on 55 transit agencies in the United States, Turnbull (1995) found that almost all of the agencies were planning for additional park-and-ride facilities. Figure 1.2 shows the spatial distribution of the number of parking spaces in some of the facilities surveyed in Turnbull (1995).

Given the importance of park-and-ride services, they need to be well planned. An important step when planning for such services is the delineation of market areas, geographic areas where users of park-and-ride facilities are likely to originate from (Spillar 1997). One reason why delineation is important is that it would help explain the socioeconomic and travel characteristics of potential users in such areas (Bowler et al. 1986).
Figure 1.1: Local and remote park-and-ride lots in Columbus, Ohio
Figure 1.2: Park-and-ride facilities in major urban areas
(Source: Turnbull 1995)
One approach for delineating market areas is to assume that they could be represented by a geometric shape, such as a parabola or circle (Turnbull 1995), as shown in Figure 1.3. The problem with this approach, however, is that different levels of accessibility that users may have in a given area are not considered. Market areas can also be delineated based on travel cost comparisons (Sargious and Janarthanan 1983), although this does not explicitly consider travel direction. Of course, delineating market areas can be done relatively easily if data on locations of park-and-ride users are available (see Allen 1979). Unfortunately, such data are increasingly difficult to obtain due to privacy issues. Therefore, there is a need for more appropriate market area delineation approaches.

Finding good locations for park-and-ride facilities is another essential step when planning for park-and-ride services (Spillar 1997). Although there is a variety of facility location models (see, e.g., ReVelle et al. 1970), they cannot be readily used for siting park-and-ride facilities. The reason for this is that such models do not simultaneously address at least three key issues: distance decay, coverage standards, and partial coverage of demand. Addressing distance decay is important because it accounts for the fact that the closer facilities are from demand the more likely they would be utilized. Coverage standards are important to consider, as there is a maximum acceptable distance beyond which users would not be willing to use a park-and-ride facility. Finally, because
Figure 1.3: Parabolic and circular market areas
(Source: Bowler et al 1979)
resources are usually limited (i.e. in terms of number of available facilities) it is necessary to address partial coverage. Given this, there is a need for a new location model that simultaneously addresses these issues.

Although selecting appropriate facility locations is important for achieving successful park-and-ride services in a given urban area, this by itself is not expected to result in a significant increase in transit ridership. The reason for this is that there are key supporting elements that need to be provided in order to address other necessary aspects of park-and-ride services (i.e. besides location). For example, High Occupancy Vehicle (HOV) lanes are important to provide in order to achieve travel time savings and travel reliability (Fuhs 1993). Given that many urban areas aspire to increase their transit ridership through providing park-and-ride services, there is a need to examine whether this is achievable given their existing policies.

1.1. Research objectives

As noted above, delineating market areas is an important step when planning for park-and-ride services. Previous approaches for delineating catchment/market areas are either problematic or have unrealistic data requirements. Therefore, this research aims at developing a new market area delineation approach that improves over existing approaches. Siting park-and-ride facilities is another important step when planning for the associated services. As discussed above, facility location models cannot be readily used
for locating such facilities, as they do not simultaneously address at least three important issues, namely, distance decay, coverage standards, and partial coverage of demand. An objective of this research, therefore, is to develop a location model that simultaneously considers these issues. Finally, this research aims at identifying key policies/elements that are considered important for achieving successful park-and-ride services.

One of the few growing cities in the Midwest is Columbus, Ohio (Mid Ohio Regional Planning Commission (MORPC) 1998). In the region’s first congestion summit, conducted to discuss Columbus' transportation future, improving transit options was one of the four main strategies adopted to address traffic congestion (Columbus Chamber of Commerce 2001). In this research, the Columbus, Ohio metropolitan area will be used as a case study.

1.2. Background: Bus-based park-and-ride planning

It is well known that there are different types of transit services, such as bus, light rail, commuter rail, trolley, etc. Each type has distinct features that make it different from the others. For example, one difference between bus and rail service is that rail transit operates on exclusive or semi-exclusive right of ways, which provides a travel time advantage over buses operating in mixed traffic (i.e. buses and cars sharing the roadway) (Gray and Hoel 1992). Thus, park-and-ride services associated with several types of transit services (i.e. rail, bus, etc.) necessarily have different characteristics. For example, catchment/market
areas (geographic area where users of park-and-ride facilities originate from) associated with rail transit service are typically much larger than those associated with bus service. The reason is that rail transit service usually has superior performance with respect to shorter travel time, enhanced comfort, etc. compared to that of bus service, which results in attracting patrons from longer distances (Gray and Hoel 1992). This research, however, focuses on bus-based park-and-ride services, which will be simply referred to as park-and-ride services from here on.

Appropriate planning for park-and-ride facilities can encourage shifts from single occupancy vehicles (SOV) to high occupancy vehicles (HOV) (Spillar 1997). However, there is no universal procedure in the literature for planning park-and-ride services. Nevertheless, there are necessary aspects that should be considered when planning for these services, such as site selection, market area delineation, demand estimation, and facility sizing.

One of the first steps in the planning process is to identify study areas (also called target areas) within major travel corridors in an urban region (AASHTO 1983; MAG 2001). These areas, within which potential sites for park-and-ride facilities are selected, should satisfy several criteria, such as being upstream of traffic congestion and situated between major activity centers and residential areas (AASHTO 1983). Within the study areas, potential sites for park-and-ride facilities are evaluated for potential usefulness (Allen, et al. 1978) as suggested
in Figure 1.4. Accessibility of the site to potential users, accessibility to priority facilities (e.g. HOV), development cost, and stage construction potential are some of the considerations in the selection process (Boweler et al. 1986).

There are also guidelines in the literature to help select potentially good sites, such as locating facilities ahead of congestion, locating facilities such that they are visible, etc. (see Mather 1983). The selected sites should be evaluated such that unpromising sites are removed from consideration (Boweler et al. 1986). Burns (1979) suggests a method for subjectively rating such sites based on location (e.g. proximity to freeways), site (e.g. site expansion potential) and economic (e.g. land cost) considerations. The next step is to predict the demand for the most promising sites (Turnbull 1995). This is important for identifying the sites that would attract single occupancy vehicle users as well as take into account costs (Spillar 1997). There is a range of demand estimation techniques that vary in complexity (see Boweler et al. (1986) for a detailed description). It should be noted, however, that predicting demand is difficult partly because of lack of good techniques (Spillar 1997).

A prerequisite for demand estimation is to delineate market areas for park-and-ride facilities (Turnbull 1995). Such delineation is important because it defines the boundaries within which most users of park-and-ride facilities come from. Analyzing the characteristics of such users, such as vehicle ownership, income, and education, helps predict demand for future park-and-ride facilities. In
Define study areas along major travel corridors

Select park-and-ride sites for potential usefulness within each study area

Evaluate park-and-ride sites based on location, site and economic criteria

Delineate market areas for the promising sites

Predict demand for promising sites and choose sites that would result in high ridership

Based on the predicted demand and other considerations (e.g. maximum walking distance) determine the needed size

**Figure 1.4: Steps important in bus-based park-and-ride planning**
(Source: Boweler et al. 1986; Turnbull 1995; MAG 2001)
addition, delineating market areas reveals important factors that affect utilization of existing park-and-ride facilities. For example, Stevens and Homburger (1984) found that the market area size is a significant factor in utilization of park-and-ride facilities.

Sizing park-and-ride facilities is also an important aspect in planning for park-and-ride facilities (Turnbull 1995). A lot with excess capacity is economically inefficient, whereas a lot without enough capacity loses potential commuters. Predicted demand determines the needed size of the facility (in terms of number of spaces) (Bowler et al. 1986). The maximum size of a park-and-ride facility is typically based on the walking distance commuters are willing to travel after parking their automobiles (Dickins 1991).

It is important to note that implementing park-and-ride services does not necessarily guarantee the success of such services (Turnbull 1995). The reason is that such services by themselves may not be attractive to the extent that single occupancy vehicle (SOV) users would be compelled to switch to high occupancy vehicles (HOV). Therefore, there is usually a need for supporting policies to ensure that park-and-ride services attract as many single occupancy vehicles as possible (Turnbull 1995). There are policies that provide incentives to encourage use of HOVs and park-and-ride facilities. Few examples of such policies are: providing pre-trip and real-time information on traffic conditions and transit alternatives for travelers; altering the timing of traffic signals so that buses
progress with minimal delay; and subsidizing transit fares (TTI et al. 1998; Boweler et al. 1986; Turnbull 1995). On the other hand, there are policies that serve as disincentives to discourage use of SOVs, such as charging relatively high parking fares (Boweler et al. 1986).

In addition to the above policies, a widely used policy in North America is to provide HOV lanes in conjunction with park-and-ride services (TTI et al. 1998). HOV systems have the ability to attract commuters because they provide travel time savings as well as travel time reliability (Fuhs 1993). Travel time savings are achieved because express buses, operating on dedicated lanes, bypass congested freeway segments. Travel time reliability is a result of the low likelihood of traffic accidents along such lanes, which usually cause major delays along mixed traffic roadways (Fuhs 1993). Several urban areas in the United States consider HOV systems very important for the success of park-and-ride facilities. For example, providing park-and-ride facilities accompanied by HOV lanes and express bus service is considered one of the most important characteristics for successful park-and-ride facilities in Phoenix, Arizona (MAG 2001). Figure 1.5 shows cities in the United States where HOV facilities are operating, in development, or in the planning stages.

1.3. Dissertation outline

The dissertation is organized as follows. Chapter 2 presents a new approach for delineating market areas. Then a general location model that can be used
for siting park-and-ride facilities is developed in Chapter 3. This model is extended in Chapter 4 to address more specific issues when siting park-and-ride facilities. Chapter 5 reviews supporting elements of park-and-ride services and examines the potential for achieving successful park-and-ride services for the urban area under study. Finally, conclusions are given in Chapter 6.
Figure 1.5: HOV facilities on freeways and in separate rights-of-ways in the United States

(Source: TTI et al. 1998)
CHAPTER 2

A GIS-BASED APPROACH FOR DELINEATING MARKET AREAS

2.1. Introduction

It is important that park-and-ride services be well planned in order to attract as many single occupancy vehicle users as possible to the transit service (Spillar 1997). In order to achieve this, an important step in the planning process is the ability to identify associated park-and-ride market area boundaries (Turnbull 1995). A market area, also known as a study, service, catchment or commutershed area, is the geographic area from which users of a park-and-ride facility are likely to come (Bowler et al. 1986; Bolger et al. 1992). Delineating such areas is important because they help explain the spatial and socioeconomic characteristics of potential users in the market area as well as their associated travel characteristics (Bowler et al. 1986). This information can then be used, for instance, to predict potential demand for park-and-ride facilities and better plan system integration (Allen 1979).

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1 A modified version of this chapter has been submitted for publication consideration, coauthored with Alan Murray
Interestingly, there are a range of alternative approaches that exist for identifying park-and-ride catchment/market areas. They can be broadly divided into three categories: (1) methods that assume a geometric shape for the market area; (2) methods based on travel cost comparison between travel modes; and (3) methods identifying current or past users.

Turnbull (1995) suggests that a market area can be assumed to have a geometric shape, such as a circle or parabola. A problem with assuming a certain shape, however, is that it fails to consider the different levels of accessibility that users may have in a given area. To illustrate, even though users A and B in Figure 2.1 are at equal distances from the park-and-ride facility, they are not likely to have an equal degree of accessibility to the facility. The reason for this, in this case, is that the street network topology is such that user A would be required to travel a greater distance than user B. Similar circumstances could also arise due to terrain undulation or spatial barriers, but the street network is certainly critical in urban areas.

Sargious and Janarthanan (1983) delineate the boundary of a market area based on travel cost. Such costs include time valuation, travel time, and use fees. That is, potential users of a park-and-ride facility would be included in a market area if they find it advantageous, in terms of travel cost, to drive to that facility and then use transit, as opposed to using their automobile, for the
Figure 2.1: User accessibility within a parabolic market area
duration of their trip. A problem with this approach, however, is that it is not
amenable to explicitly accounting for user travel direction. That is, potential
riders desire a facility in their direction of travel and view backtracking as a
negative. Travel cost approaches do not account for this consideration.

When data on locations of park-and-ride users are available, delimiting a market
area can be done relatively easily. Allen (1979) conducted a license plate
survey to help identify the shapes and sizes of market areas for different types
of park-and-ride lots. The available data were then used to develop estimates
on user travel time/distance to the various types of lots. Such estimates are
suggested as being useful for identifying market areas for similar types of park-
and-ride facilities in locations where data are not available.

Lutin et al. (1981) used survey data to calibrate a market area model. They
suggest that logarithmic/exponential functions can describe the relationship
between the park-and-ride ridership and the distance or time traveled to the
park-and-ride lot. Clearly, if data are available on the locations of park-and-ride
users for a region, such data should be used. However, due to concerns about

\[2\] The locations of park-and-ride users can be identified by geocoding (and mapping) residential
addressees using a commercial GIS. Such addresses used to be easily obtained from agencies
such as the Bureau of Motor Vehicles based on vehicle license plates found at a given park-and-
ride facility.
user privacy, data on user locations are becoming increasingly difficult to obtain. If this is the case, the utilized market area delineation approach cannot rely on user locations as input.

The above review details the range of existing approaches typically used for delineating market areas for park-and-ride facilities. These approaches are either problematic or have unrealistic data requirements. Further, there is no objective method to guide the decision as to what market area approach to use or how to evaluate/compare such approaches.

Geographic information systems (GIS) are known for their capabilities in creating, analyzing, manipulating, storing and representing spatial data (Hanson 1995). These capabilities have been used for delineating retail store trade areas (see O’Kelly 1999), although their use in the analysis of park-and-ride facilities has been limited (the only case we are aware of is the work of Horner and Grubesic 2001). This chapter develops a GIS-based approach to support park-and-ride market area assessment that simultaneously considers accessibility and user travel direction. In addition, this chapter also provides a detailed description and formal specification of the market area delineation approaches, and shows how such clarity is useful for GIS implementation. The next section examines two existing methods for market area delineation.
Following this, a new approach for delineating market areas is developed. Next, the different market area delineation approaches are evaluated. Finally, discussion and conclusions are given.

2.2. Delineating Market Areas

The two commonly used modeling approaches for delineating market area boundaries in park-and-ride studies are detailed in this section. The first is an assumed parabolic shape (a special case of category 1 above) and the second is structured using travel costs (category 2 above).

2.2.1. Parabolic Shaped Boundary

Several studies have assumed parabolic shapes for representing market areas for park-and-ride facilities, which could be attributed to the fact that such shapes represent a user’s tendency to drive to a park-and-ride facility if it is in their direction of travel (Keck and Liou 1976; Christiansen et al. 1981). Of course, by definition the parabolic approach necessarily assumes one major travel destination. The major steps involved in parabolic market area delineation are:

1. Define the parabola surrounding the park-and-ride facility oriented toward the major activity center
2. Determine the maximum extent of travel to the facility
3. Identify potential users in the market area
Specifics associated with each step of the parabolic market area delineation process are now given. In step 1, a parabola is defined for a given park-and-ride facility representing much of the boundary associated with its market area.

The general form of a parabola is:

\[ Ax^2 + Bxy + Cy^2 + Dx + Ey + F = 0 \]  \hspace{1cm} (2.1)

If the parabola is oriented around the y-axis, equation (2.1) can be simplified as follows, assuming that the parabola has its vertex at \((h, k)\) and the directrix is \(y = k - p\):

\[(x - h)^2 = 4p(y - k) \]  \hspace{1cm} (2.2)

If the orientation is around the x-axis, equation (2.1) simplifies to:

\[(y - k)^2 = 4p(x - h) \]  \hspace{1cm} (2.3)

If the vertex is placed at the origin (i.e. \((h, k) = (0, 0)\)), equation (2.2) becomes:

\[ y = \frac{x^2}{4p} \]  \hspace{1cm} (2.4)

In this case \(p\) represents the distance from the focus to the vertex. The interpretation of \(p\) is that it represents the acceptable backtrack distance, which is the distance that users are willing to backtrack to reach a facility. Similar to equation (2.4), if the vertex of the parabola represented by equation (2.3) is placed at the origin, equation (2.3) becomes:

\[ x = \frac{y^2}{4p} \]  \hspace{1cm} (2.5)
Under idealized conditions, equation (2.4) or (2.5) could be used to represent the market area for a park-and-ride facility, assuming that associated parameters are known or can be determined.

With the basic parabola defined in step 1 (shown in Figure 2.2a using equation 2.4), step 2 involves further refining the market area boundary to reflect the maximum distance a user is willing to travel to use a park-and-ride facility. This is typically imposed through the use of a maximum travel distance, \(d_{\text{max}}\), to enclose the parabola. This is illustrated in Figure 2.2b. Given the boundary of the market area defined in steps 1 and 2, it is possible to identify potential users residing within this enclosed area. Mathematically, a user at \((x, y)\) is in the market area if
\[Ax^2 + Bxy + Cy^2 + Dx + Ey + F \leq 0\]
and
\[d[(x, y), (x_f, y_f)] \leq d_{\text{max}},\]
where \((x_f, y_f)\) are the coordinates of the park-and-ride facility.

A minor complicating feature of the associated parabola in practice is that the park-and-ride facility is not likely to be horizontal or vertical relative to the major activity center. What is required in this case is that the market area boundary be rotated about the park-and-ride facility so that it is appropriately oriented toward the major activity center. Such a reorientation is shown in Figure 2.3. The mathematics associated with such a rotation may be found in Larson and Hostetler (1986), among other such introductory calculus texts.
Figure 2.2: Parabolic market area delineation
2.2.2. Market area delineation based on travel costs

An alternative market area delineation approach is based on travel cost structure (Sargious and Janarthananm 1983). Travel costs typically include time valuation, travel time, and use fees. The major steps for delineating a market area for a given park-and-ride facility using travel cost are:

1. Compute automobile travel cost for each potential park-and-ride facility user from their residence to their assumed destination (major activity center or centers).
2. Compute travel cost for the user using park-and-ride.
3. Compare travel costs to delineate the market area.

Step 1 involves the estimation of travel cost using an automobile between the user residence and the activity center(s). Let $c_{im}$ represent the computed automobile travel cost between a user $i$ and activity center $m$. Travel cost associated with the use of park-and-ride is determined in step 2. Let $\hat{c}_i$ represent automobile travel cost between the location of a user $i$ and a park-and-ride facility, and let the transit travel cost between facility and activity center $m$ be represented by $\tilde{c}_m$. The total cost for using park-and-ride can be expressed as $\hat{c}_i + \tilde{c}_m$. Step 3 involves the delineation of the market area by comparing the alternative travel costs. Using the above notation, a user is
Figure 2.3: Parabolic market area orientation
included in a park-and-ride market area if $c_{in} \geq \lambda(c_r + c_m)$. Typically $\lambda=1$, but this parameter could be adjusted to account for slightly higher travel costs using transit ($\lambda>1$) or more stringent requirements for transit ($\lambda<1$).

2.3. Incorporating accessibility and travel direction

The previous section detailed the two primary approaches that have been used to delineate park-and-ride market areas. As noted previously, the parabolic market area approach assumes that users at equal distances from a park-and-ride facility have the same degree of accessibility to the facility. As a result, it is not sensitive to spatial structure. Further, it assumes only one major travel destination. The travel costs market area approach, on the other hand, does not consider travel direction explicitly as it cannot directly determine directional attributes in costing, but does allow one to address multiple travel destinations.

Given these limitations, a new approach is developed which takes into account both accessibility and travel direction.

For each park-and-ride facility, delineating the market area incorporating accessibility and travel direction considerations involves the following major steps:

1. Compute automobile travel time for each potential user from their residence to the park-and-ride facility.
2. Determine whether the facility is in the potential user’s travel direction.
3. Assess whether the user is in the market area.
Figure 2.4 illustrates the above steps in a flowchart. Step 1 involves computing travel time using an automobile from a potential user’s residence to the park-and-ride facility (or vice versa). Let $t_i$ represent the estimated street network-based automobile travel time between a user $i$ and a park-and-ride facility. Step 2 involves determining whether or not the park-and-ride facility is in the potential user’s travel direction. To assess this, the angle $\alpha$, where $0 \leq \alpha \leq 180^\circ$, between the vectors $a$ and $b$ (see Figure 2.5) is calculated as follows:

$$\alpha = \cos^{-1}\left(\frac{\langle -a, b \rangle}{|a| |b|}\right)$$

(2.6)

The acceptable angle, $\Phi$, must be specified in advance. If $\alpha \geq \Phi$, the facility is in the user’s travel direction, whereas $\alpha < \Phi$ indicates that the facility is not in the user’s travel direction. Certainly, it would be possible to devise an evaluative approach that gives increasing importance to $\alpha$ as it approaches $180^\circ$, as this more accurately reflects the degree to which a park-and-ride facility is in a user’s travel direction. However, a cut-off value approach using $\Phi$ is reasonable because direction is only one component of choice to use park-and-ride services. In addition, little is known about choice behavior associated with user willingness to deviate from their travel direction in order to use park-and-ride services.
Inputs:
- locations of users, park-and-ride facility, and major activity center
- street network

Compute automobile travel time between each potential user residence and the park-and-ride facility

Is the park-and-ride facility in the user’s travel direction?

Is it within an acceptable backtrack time?

Is the facility within an acceptable travel time?

Exclude the user from the market area

Include the user in the market area

Figure 2.4: Delineating a market area using accessibility and travel direction
Figure 2.5: Assessing potential user travel direction
Finally, step 3 involves examining the potential park-and-ride facility users for inclusion in the market area. Such users are included in the market area if one of the following conditions is met:

a. \( \alpha \geq \Phi \) \text{ and } \( t[(x, y), (x_f, y_f)] \leq t_{\text{max}} \)

where \( t[(x, y), (x_f, y_f)] \) is the travel time from a user’s residence to a park-and-ride facility using an automobile, and \( t_{\text{max}} \) is the maximum travel time that users are willing to drive to reach the park-and-ride facility.

b. \( \alpha < \Phi \) \text{ and } \( t[(x, y), (x_f, y_f)] \leq t_{\text{back}} \)

where \( t_{\text{back}} \) is the tolerable backtrack travel time.

Condition (a) represents the situation where the park-and-ride facility is in the user’s travel direction \textit{and} also within an acceptable travel time. Condition (b) represents the case when the park-and-ride facility is \textit{not} in the user’s travel direction, but is within an acceptable backtrack travel time. It should be noted that this approach can easily accommodate a travel cost or time consideration as well to further restrict the delineated market area, similar to the travel cost approach.
One important feature of this approach is the ability to determine directional relationships between geographic entities. That is, given the locations of a potential user, a park-and-ride facility and the major activity center, it is possible to assess whether the facility is in the user’s travel direction. This is essential for determining whether such a user is a potential park-and-ride user for a particular facility.

2.4. Comparative evaluation of market area delineation approaches

The market area delineation approaches detailed in the previous sections are now comparatively analyzed. This analysis will be carried out through application in an urban area where park-and-ride services are an integral component of the public transportation system.

2.4.1. Application details

The park-and-ride system in Columbus, Ohio was utilized in the evaluation of the detailed market area delineation approaches. Columbus is one of the few growing cities in the Midwest (MORPC 1998). The Central Ohio Transit Authority (COTA) provides mass transit services for the greater Columbus metropolitan region, with a transit service area of around 552 square miles inhabited by 1,082,450 people (MORPC 2003). COTA maintains 24 park-and-ride facilities containing 2330 spaces (COTA 2001). Additional spaces are also provided at a temporary site and at two parking loops (COTA 2001). Medium
and long-term plans are to add 14 suburban transit centers, which will include park-and-ride lots (COTA 1999). Figure 2.6 shows the locations of existing park-and-ride facilities in Columbus. The utilization of these facilities ranges from 6 percent to full utilization, though they are generally under-utilized as shown in Table 2.1 (COTA 2001).

The analysis was carried out on a Pentium III 700 MHz personal computer with 128 MB RAM. Each approach was implemented using Avenue script in ArcView GIS 3.2. Several scripts were developed to automate repetitive use of GIS functions as well as to facilitate implementing new functionality that is not readily available in GIS. Existing GIS functionality that was used included routing, spatial query and distance measurement. Thus, GIS is clearly more than a visualization tool, though it is no doubt fundamental in depicting market area boundaries. Developed GIS functionality was the ability to determine user travel direction and accessibility (specific details follow in the next section).

An important application detail was the choice of parameters. For the parabolic market area approach, \(d_{\text{max}}\), was based on an estimate that typical users would not likely drive more than 5 miles to reach the facility, as suggested by COTA (1993). The maximum backtrack distance, \(p\), was assumed to be 1 mile, as suggested by Bowler et al (1986). Of course any range of parameter values can
Figure 2.6: Park-and-ride facilities in Columbus, Ohio
<table>
<thead>
<tr>
<th>Park-and-ride facility location</th>
<th>Available spaces</th>
<th>Spaces used</th>
<th>Utilization rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berwick Plaza</td>
<td>60</td>
<td>38</td>
<td>63.3%</td>
</tr>
<tr>
<td>Broad/S. Hampton</td>
<td>68</td>
<td>68</td>
<td>100.0%</td>
</tr>
<tr>
<td>Crosswoods</td>
<td>169</td>
<td>25</td>
<td>14.8%</td>
</tr>
<tr>
<td>Dublin</td>
<td>82</td>
<td>56</td>
<td>68.3%</td>
</tr>
<tr>
<td>Great Southern</td>
<td>84</td>
<td>33</td>
<td>39.3%</td>
</tr>
<tr>
<td>Griggs Dam</td>
<td>28</td>
<td>13</td>
<td>46.4%</td>
</tr>
<tr>
<td>Grove City</td>
<td>150</td>
<td>69</td>
<td>46.0%</td>
</tr>
<tr>
<td>High/Jeffrey</td>
<td>32</td>
<td>16</td>
<td>50.0%</td>
</tr>
<tr>
<td>High/Royal Forest</td>
<td>40</td>
<td>36</td>
<td>90.0%</td>
</tr>
<tr>
<td>Hilliard</td>
<td>100</td>
<td>22</td>
<td>22.0%</td>
</tr>
<tr>
<td>Hilliard-Rome Rd</td>
<td>80</td>
<td>13</td>
<td>16.3%</td>
</tr>
<tr>
<td>Indianola/Morse</td>
<td>105</td>
<td>26</td>
<td>24.8%</td>
</tr>
<tr>
<td>Kingsdale</td>
<td>35</td>
<td>19</td>
<td>54.3%</td>
</tr>
<tr>
<td>Livingston/Barnett</td>
<td>101</td>
<td>51</td>
<td>50.5%</td>
</tr>
<tr>
<td>New Albany</td>
<td>50</td>
<td>19</td>
<td>38.0%</td>
</tr>
<tr>
<td>Northern Lights</td>
<td>60</td>
<td>61</td>
<td>101.7%</td>
</tr>
<tr>
<td>Olentangy/Bethel</td>
<td>150</td>
<td>9</td>
<td>6.0%</td>
</tr>
<tr>
<td>Pickerington</td>
<td>150</td>
<td>133</td>
<td>88.7%</td>
</tr>
<tr>
<td>Reynoldsburg</td>
<td>214</td>
<td>77</td>
<td>36.0%</td>
</tr>
<tr>
<td>Royal Plaza (Gahanna)</td>
<td>60</td>
<td>26</td>
<td>43.3%</td>
</tr>
<tr>
<td>St. Andrew</td>
<td>14</td>
<td>14</td>
<td>100.0%</td>
</tr>
<tr>
<td>St. Peter's</td>
<td>20</td>
<td>15</td>
<td>75.0%</td>
</tr>
<tr>
<td>Westerville</td>
<td>230</td>
<td>57</td>
<td>24.8%</td>
</tr>
<tr>
<td>Westwoods</td>
<td>100</td>
<td>44</td>
<td>44.0%</td>
</tr>
<tr>
<td>Whitehall</td>
<td>148</td>
<td>37</td>
<td>25.0%</td>
</tr>
<tr>
<td>Cleveland and Mecca</td>
<td>12</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Main and Weyant</td>
<td>12</td>
<td>3</td>
<td>25%</td>
</tr>
</tbody>
</table>

Table 2.1: Utilization of park-and-ride facilities in Columbus, Ohio as of April 2001
(Source: Central Ohio Transit Authority (COTA) 2001)
be assessed in the developed approaches. For the travel cost approach, due to limited availability of travel cost data, travel time was used as a proxy for travel cost. Street network-based travel time was determined for both park-and-ride and automobile travel, similar to what was done in Horner and Grubesic (2001). In this study $\lambda=2$, indicating that some leeway is given to park-and-ride users in distinguishing between travel modes. The two alternatives were then compared to delineate the market area, as described previously.

The travel time over the street network was calculated based on travel speeds, which were determined (using look-up tables) based on roadway facility type (e.g. freeway), number of lanes, and area type (downtown, urban area, suburban area, etc.) (USDOT 2000). It should be noted that this is consistent with the practices of local planning agencies (e.g. MORPC) maintaining travel demand forecasting models. For example, a freeway segment with 4 lanes in an urban area was assigned a speed of 45 miles per hour. The implementation of the accessibility and travel direction approach required the specification of associated parameters as well. The maximum travel time, $t_{\text{max}}$, was assumed to be 5 minutes, as suggested by Horner and Grubesic (2001). The maximum backtrack travel time, $t_{\text{back}}$, was assumed to be 1 minute. The maximum allowable travel direction deviation, $\phi$, was set at $90^\circ$. 
2.4.2. Implementation using GIS

In the previous sections several market area delineation approaches (existing and new) were detailed. Unlike previous studies, this research provided a formal and detailed description of each approach, facilitating implementation in a GIS environment. One reason why GIS implementation is facilitated is that delineating market areas involves the use of detailed spatial data. As such, standard GIS functionality is oriented to manage and manipulate data as well as visualize and summarize areal information. Below we detail how GIS was instrumental in implementing aspects of each market area approach.

In defining a parabolic market area, GIS is used to specify the polygon associated with the parabola around a park-and-ride facility. The parameters for doing this are given in equation (1) and by the maximum travel distance, thereby enclosing the parabola. Once this polygon is created, it is possible to use spatial query operators to determine potential users within the market area. Carrying out any of these operations outside of GIS would require the development of computational geometry procedures in addition to database management processing.

Similarly, for the travel cost market area approach, GIS facilitates analysis through the management of the transportation network and subsequent capabilities to work with routes and determine shortest paths from a park-and-ride facility to areas in the region. Again, once market area boundaries are
established from a travel cost evaluation of the network, it is necessary to
generate the polygon defining the market area. With this it is then possible to
conduct spatial queries and provide area summaries.

Finally, the new market area approach based on accessibility and travel
direction also relies extensively on the use of GIS. Two important aspects of
implementation were determining travel time between a user and a park-and-
ride facility and determining whether a facility is in a potential user’s travel
direction. The former was relatively easily applied in GIS using network and
shortest path functionality. Determining whether a facility is in a user’s travel
direction involved developed GIS functionality. Specifically, the location of
potential users, park-and-ride facilities and major activity centers was needed to
evaluate relative spatial proximity. One aspect was distance between these
locations. Another involved assessing whether a facility was in an associated
tavel direction. This was operationalized by creating travel vectors from a
potential user to the park-and-ride facility and from a potential user to its
intended travel destination. Having these vectors then enabled directional
assessment. Again, this is all facilitated by existing GIS functionality.

2.4.3. Market area assessment

2.4.3.1. Visual comparison

The market area results for each approach are given in Figures 2.7-2.9. The
various market area delineation approaches produced differently shaped
catchments for many of the park-and-ride facilities. This is most obvious when visually comparing the parabolic shaped market areas (Figure 2.7) with the two other approaches (Figures 2.8 and 2.9). The reason for these differences is that the latter two approaches incorporate accessibility considerations and do not assume a particular geometric shape, unlike the parabolic approach.

The market areas that resulted from applying the accessibility and travel direction approach (Figure 2.9) are also different from those derived using the travel cost approach (Figure 2.8). The major difference in this case is that the travel cost approach appears to underestimate potential users of park-and-ride facilities. For example, the market areas associated with the Dublin and Crosswood park-and-ride facilities are virtually non-existent for the travel cost approach (Figure 2.8), because travel time using park-and-ride is greater than that using the automobile for almost all the potential users around the park-and-ride facility. In contrast, there is a recognizable market area for the same park-and-ride facilities when the accessibility and travel direction approach is applied (Figure 2.9), due to the fact that this approach explicitly considers travel direction. When the park-and-ride utilization rates in Table 2.1 are considered, it is clear that the Dublin facility is in fact used at a modest rate of 68 percent and to a lesser extent the Crosswood park-and-ride facility is as well (14 percent). However, both have essentially no user base when the travel cost approach is applied, in contrast to the accessibility and travel direction approach.
Figure 2.7: Market areas identified using the parabolic approach
Figure 2.8: Market areas identified using the travel cost approach
Figure 2.9: Market areas identified using the accessibility and travel direction approach
2.4.3.2. **Assessment using regression analysis**

The previous section provided a visual comparison among the market area delineation approaches, and presented evidence suggesting that the accessibility and travel direction approach performed better than the other two approaches. Nevertheless, this comparison is hardly substantiated in a rigorous way. Therefore, a need exists for further comparison of the various approaches. Something that makes sense in this case is a regression-oriented analysis. The reason for this is that supplementary information on the utilization rates of park-and-ride facilities exists (Table 2.1), so it is possible to evaluate the degree to which market area characteristics, both spatial and aspatial, correspond to observed utilization.

Multivariate regression was applied to each of the market area delineation approaches in order to assess their ability to explain the variation in utilization rates of park-and-ride lots in Columbus. The dependent variable, utilization of park-and-ride facilities, was regressed on the following independent variables associated with the market area: households with one vehicle or more; population density; percentage of trips destined to the major activity center; percentage of residential area; percentage of population with access to transit; bus headway at a park-and-ride facility; degree of traffic congestion downstream of the park-and-ride facility; and distance between the park-and-ride facility and the major roadway.
The regression analysis was run using S-plus 2000 and the results are summarized in Table 2.2 for each market area approach. As suggested in Table 2.2, transformations of some of the variables were necessary to ensure that they were approximately normally distributed. Further, many independent variables were not found to be significant or were removed from consideration due to multicollinearity.

The relationship between the dependent variable (utilization of park-and-ride facilities) and the independent variables is significant for each of the approaches, as indicated by the low p-values associated with the F-test shown in Table 2.2. In terms of the explanatory power of regression, the accessibility and travel direction approach resulted in the highest $R^2$ (0.47). This means that the independent variables explain around 47 percent of the total variation in park-and-ride utilization rates using the accessibility and travel direction approach to define catchment areas, as opposed to 41 and 40 percent for the parabolic and travel cost catchment approaches respectively. Table 2.2 also shows the signs of the coefficients of the independent variables, which are useful for determining the manner in which the independent variables affect the dependent variable.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Parabolic</th>
<th>Travel cost</th>
<th>Accessibility and travel direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>18.8615 (2.017) [0.056]</td>
<td>45.933 (3.187) [0.004]</td>
<td>19.132 (2.326) [0.030]</td>
</tr>
<tr>
<td>Distance between the park-and-ride facility and the major roadway**</td>
<td>-8.371 (-2.972) [0.007]</td>
<td>-9.914 (-3.583) [0.002]</td>
<td>-7.122 (-2.553) [0.018]</td>
</tr>
<tr>
<td>Degree of traffic congestion downstream of the park-and-ride facility***</td>
<td>NS</td>
<td>21.051 (1.557) [0.134]</td>
<td>NS</td>
</tr>
<tr>
<td>Percentage of trips destined to major activity center</td>
<td>0.891 (1.629) [0.118]</td>
<td>NS</td>
<td>1.040 (2.293) [0.032]</td>
</tr>
<tr>
<td>F-statistic</td>
<td>7.118 [0.004363]</td>
<td>7.293 [0.003935]</td>
<td>9.251 [0.001315]</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.41</td>
<td>0.40</td>
<td>0.47</td>
</tr>
</tbody>
</table>

* t-values are shown in parentheses, and p-values are shown in brackets
** this variable was transformed as Ln(X)
*** this variable was transformed as –(X⁻³)
NS: not significant

Table 2.2: Regression results for the market area delineation approaches.*
For example, the negative sign of the coefficient of the variable “distance between the park-and-ride facility and the major roadway” indicates that the farther this distance, the lower the anticipated utilization of a park-and-ride facility, which is intuitively expected.

2.5. Discussion and conclusions

Park-and-ride services are considered an integral component of many public transportation systems in the United States. Improvement through planning efforts is essential if the goal is to remove as many vehicles as possible from congested roadways. An important step when planning for park-and-ride services is delineating ridership market areas. Market area delineation approaches that assume a certain shape do not fully consider accessibility issues. Approaches that use travel cost to delineate market areas do not explicitly consider travel direction. This research has developed a GIS-based approach that incorporates accessibility and travel direction considerations in the delineation of the park-and-ride market areas.

In evaluating the various market area delineation approaches, it was shown that the approach developed in this research performed better than existing ones. That is, a visual comparison among the resultant market areas showed that the accessibility and travel direction approach is more realistic than the other approaches. This was confirmed by a quantitative comparison using regression analysis.
analysis. The regression results suggested that the accessibility and travel
direction approach performs better than the other approaches in delineating
market areas, as a better explanation of the variability in utilization of park-and-
ride facilities was achieved. It is important to note, however, that limitations do
exist in the performed regression analysis. One such limitation is that the
sample size was relatively small (24 observations), which reduced the
usefulness of some of the independent variables. Another limitation is that the
various market area delineation approaches were compared based only in one
city, Columbus, Ohio. A comparison based on a number of urban areas would
further confirm the anticipated advantages of the accessibility and travel
direction approach over the others.

GIS are known for their capabilities in representing, creating, analyzing and
displaying spatial data (Hanson 1995). With few exceptions, the capabilities
offered by GIS for delineating park-and-ride market areas have not been
detailed in this literature. This research has shown that a clear description of
market area delineation approaches combined with the use of GIS has resulted
in relatively easy implementation. Further, this research has utilized GIS-based
functionality for examining and visualizing park-and-ride market areas. Finally,
this research has extended GIS capabilities to assist in the development of an
approach that incorporates accessibility and travel direction considerations in
the market area delineation. The capability to effectively and accurately
delineate likely market areas would help in explaining the spatial and socioeconomic characteristics of users in the market area, which is a prerequisite for more detailed locational analysis in the planning of additional park-and-ride services. Planning for such services is important so that they, and ultimately public transportation systems, become more utilized, which would help overcome car dependence and achieve more sustainable existence in urban areas.
CHAPTER 3

MODELING COVERAGE AND DISTANCE DECAY

3.1. Introduction

The location of a facility, be it a fire station, retail store, transportation terminal, etc., very much dictates the success of the services to be provided. Facility siting typically represents a long-term investment due to property acquisition and construction (Owen and Daskin 1998). Therefore, to ensure the success of facilities and make the investment in them worthwhile, it is important that essential features of the situation at hand be modeled properly. The literature details a variety of location models that can be utilized to address a range of planning situations (see ReVelle et al. 1970; Tansel et al. 1983; Owen and Daskin 1998). Most of these models are useful for desirable facility location (e.g. police and fire stations, grocery stores, etc.), but some explicitly deal with undesirable facilities (e.g. nuclear plants, recycling facilities, etc.) (see Erkut and Neuman 1989; Murray et al. 1998). Such facilities are usually locally unwanted, but are a necessary element of regional services.

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3 A modified version of this chapter has been submitted for publication consideration, coauthored with Alan Murray.
While numerous location models exist, there are at least three significant issues that are difficult, if not impossible, to address using existing models when siting certain types of facilities. These issues are distance decay, coverage standards, and partial coverage of demand. Distance decay, “the attenuation of a pattern or process with distance” (Johnston et al. 2000), is a central concept in modeling, such as transportation, migration, and location theory (Olsson 1970; Fotheringham and O’Kelly 1989). It is important to incorporate distance decay in order to achieve more effective locational configurations in that one recognizes that the likelihood of utilization of services is often dependent upon being relatively close to those services. That is, when siting facilities, considering distance decay ensures that sites are as close to expected demand as possible. As such, one expects greater participation/use from potential demand that is closer to services offered. Alternatively, in the case of siting undesirable facilities, incorporating distance decay ensures that facilities are as far from affected people as possible.

Another key issue in some siting situations is a coverage standard, a maximum acceptable distance between a user and their closest facility. This issue is crucial for many applications, such as locating emergency services (Toregas et al. 1971), warning sirens (Murray and O’Kelly 2002) and transit stops (Murray 2001). In the case of emergency services, it is not unusual to find a coverage standard for response time of 8 minutes or less to an accident or fire after a call
for service has been placed (Murray and O'Kelly 2002). Coverage is an important issue to consider when siting service facilities because otherwise selected sites might be too far from demand (Church and Meadows 1977). As such, it would be impossible to ensure service response within acceptable standards. In the case of undesirable facilities, a coverage standard can be thought of as an impact zone within which facilities would have a negative impact. As an example, toxic waste sites are observed as having a negative impact on population within 10 miles from a site, and a nuclear reactor has an impact zone extending some 22 miles (Kohlhase 1991). Thus, considering coverage is important in order to minimize the negative impact of such facilities on local residences and businesses (e.g. loss in property value, exposure to risk, etc.).

A final issue in facility siting is partial coverage of regional demand. This situation was first modeled in Church and ReVelle (1974) recognizing that limited resources typically prevent complete coverage from being provided. Thus, partial coverage of demand is a byproduct of not being able to serve an entire region by located facilities within a maximum service standard. However, one would like to cover as much potential demand as possible. That is, due to budgetary restrictions we are not able to site enough facilities to provide a minimum level of service, but we would like to do the best we can with available
resources. Alternatively, for undesirable facility location, not all areas may be impacted, which is clearly a desired situation. Thus, one must be able to mitigate and objectively model spatial inequities in service coverage or impact.

Distance decay, coverage standards, and partial coverage issues arise in a range of planning contexts. One example is park-and-ride facility siting. Distance decay is important because the closer a park-and-ride lot is to potential ridership demand, the more likely it will be used (Spillar 1997). The maximum service coverage standard is applicable because there is a travel time/distance beyond which park-and-ride users are unwilling to use the facility (Allen 1979; Stevens and Homburger 1984). Further, since resources are limited and park-and-ride facilities cannot be established everywhere in a region, only partial coverage of demand is typically possible. Unfortunately, existing location models do not simultaneously address these issues. Another context in which these three issues may arise is locating recycling centers. Such facilities have been gaining importance in the United States, as they reduce the need for landfill sites, save energy, and help decrease emissions of greenhouse gases, among other benefits (Moon 1994; EPA 2003). However, recycling facilities typically have negative impacts (e.g. pollution, odor, noise, etc.) on those who reside near such centers (Flahaut et al. 2002; Columbus Dispatch 2002). Thus, distance decay, coverage standards, and partial coverage are of particular importance here, because the farther an undesirable facility is from residences
and/or businesses, the less likely it will have a negative impact. However, there are costs associated with getting to these facilities, so they should not be too far away from points of waste generation (residences and businesses). While several location models deal with siting undesirable facilities (see, e.g., Erkut and Neuman 1989; Murray et al. 1998; Flahaut et al. 2002), they do not simultaneously address the above issues.

Given the need to deal with distance decay, coverage standards and partial coverage in a single modeling framework, this chapter develops a general approach that can be used for siting both desirable and undesirable facilities. The next section reviews relevant facility location models. The following section describes developed spatial optimization models that can be used to address distance decay and coverage. Next, application results are presented. Finally, conclusions are given.

3.2. Modeling background

There are a number of useful models for locating desirable and undesirable facilities. However, as noted previously, these models do not simultaneously address distance decay, coverage standards, and partial coverage issues. Below, we review models most relevant to these concerns.
3.2.1. Desirable facility location models

A well known approach for addressing a service coverage standard is through the use of the location set covering problem (LSCP) detailed in Toregas et al. (1971). The objective of the LSCP is to find the minimum number of facilities (and their location) needed to cover all demand. The following notation is introduced before presenting the mathematical formulation:

- \( i \) = index of demand areas
- \( j \) = index of potential facility sites
- \( d_{ij} \) = distance or travel time between demand area \( i \) and potential facility site \( j \)
- \( S \) = maximum acceptable service distance (or time)
- \( N_i = \{ j \mid d_{ij} \leq S \} \)

Decision variables:

\[
X_j = \begin{cases} 
1 & \text{if a facility is located at site } j \\
0 & \text{otherwise}
\end{cases}
\]

Location Set Covering Problem (LSCP)

Minimize \( \sum_j X_j \) \hspace{1cm} \text{(3.1)}

Subject to:

\[
\sum_{j \in N_i} X_j \geq 1 \quad \forall i, \text{ (3.2)}
\]

\[
X_j \in \{0, 1\} \quad \forall j. \text{ (3.3)}
\]
The objective (3.1) minimizes the total number of required facilities needed to completely cover demand areas. Constraints (3.2) ensure that every demand area \( i \) is covered by a facility within the stipulated coverage standard. Constraints (3.3) are integrality requirements.

While the LSCP is useful for identifying how many facilities are needed and where they should be sited in order to maintain a minimum coverage standard, it does not consider distance decay. Failing to do this will undoubtedly result in selecting sites that are not as close to demand as possible. Additionally, the LSCP requires that all demand be covered, as structured in Constraints (3.2). As such, the LSCP does not allow for maximizing partial coverage when the number of facilities is constrained.

In response to the fact that only partial coverage may be provided in some planning situations, the maximal covering location problem (MCLP) was proposed by Church and ReVelle (1974). The following additional notation is introduced before presenting the MCLP:

\( a_i = \) demand in area \( i \)
\( p = \) number of facilities to be located

Decision variables:

\[
Z_i = \begin{cases} 
  1 & \text{if area } i \text{ is covered} \\
  0 & \text{otherwise}
\end{cases}
\]
Maximal Covering Location Problem (MCLP)

Maximize \( \sum_{i} a_i Z_i \) \hspace{1cm} (3.4)

Subject to:

\( Z_i \leq \sum_{j \in N_i} X_j \quad \forall i, \) \hspace{1cm} (3.5)

\( \sum_{j} X_j \leq p, \) \hspace{1cm} (3.6)

\( X_j \in \{0, 1\} \quad \forall j, \)

\( Z_i \in \{0, 1\} \quad \forall i. \) \hspace{1cm} (3.7)

The objective (3.4) maximizes the demand covered. Constraints (3.5) track whether demand area \( i \) is covered or not by a sited facility within the stipulated coverage standard. Constraint (3.6) establishes that the number of facilities located not exceed a specified limit. Constraints (3.7) are integrality conditions.

The MCLP recognizes that complete coverage may be unattainable, so it attempts to maximize the demand suitably covered by a set number of facilities. Ignored in the MCLP, however, is that the farther a potential user is from a facility (within the maximum distance), the less likely it may be utilized (see Church and Roberts 1983). That is, the MCLP does not consider distance decay. This is evident in the objective (3.4) as \( a_i \) is not discounted based on distance from its service facility. As a result, selected sites are not ensured to be as close to demand as possible to the extent that such flexibility exists.
One way to indirectly address distance decay is to minimize average travel distance. A model for addressing minimal average travel distance is the $P$-median problem (PMP), introduced by Hakimi (1965) and later formulated by ReVelle and Swain (1970). The PMP finds the location of $p$ facilities such that the total demand-weighted travel distance between facilities and service areas is minimized. The following additional decision variables are introduced before presenting the mathematical formulation of the PMP:

\[ Y_{ij} = \begin{cases} 
1 & \text{if demand in area } i \text{ is served by a facility at site } j \\
0 & \text{otherwise}
\end{cases} \]

**P-Median Problem (PMP)**

Minimize $\sum_{i} \sum_{j} a_{ij}d_{ij}Y_{ij}$ \hspace{1cm} (3.8)

Subject to:

\[ \sum_{j} X_{j} = p , \] \hspace{1cm} (3.9)

\[ \sum_{j} Y_{ij} = 1 \quad \forall i , \] \hspace{1cm} (3.10)

\[ Y_{ij} - X_{j} \leq 0 \quad \forall i, j , \] \hspace{1cm} (3.11)

\[ X_{j} \in \{0, 1\} \quad \forall j , \]

\[ Y_{ij} \in \{0, 1\} \quad \forall i, j . \] \hspace{1cm} (3.12)

The objective (3.8) minimizes the total demand weighted distance between areas and facilities. Constraint (3.9) specifies the number of facilities available to site. Constraints (3.10) require every demand area to be assigned to a facility. Constraints (3.11) limit assignment to open facilities only. Constraints (3.12) are integrality conditions.
As structured above, the PMP indirectly accounts for distance decay. It could, however, be slightly modified to directly address distance decay by a priori adjustment of $a_i$ based on distance between $i$ and $j$. Thus, the objective would become:

Minimize $\sum_i \sum_j \hat{a}_{ij} Y_{ij}$ \hspace{1cm} (3.13)

where $\hat{a}_{ij}$ is the demand in area $i$ that would be anticipated to use facility $j$ based on relative proximity. Thus, objective (3.13) would replace (3.8) in the PMP.

Other concerns, however, remain unaccounted for. The PMP considers neither partial coverage nor coverage standards. Partial coverage is not possible to allow in the PMP, because all demand must be assigned to a facility in Constraints (3.10). Coverage, on the other hand, is possible to address in the context of the PMP.

The distance constrained PMP (DCPMP) was introduced in Toregas et al. (1971) as a way to account for maximum proximity standards. This is achieved by modifying Constraints (3.10) in the PMP as follows:

$$\sum_{j \in N_i} Y_{ij} = 1 \hspace{1cm} \forall i$$ \hspace{1cm} (3.14)
Thus, the DCPMP consists of (3.8)-(3.12) specified for the PMP, but replacing Constraints (3.10) with Constraints (3.14). As such, demand may only be assigned to facilities within the stipulated coverage standard in (3.14). With the DCPMP, one can address distance decay, indirectly or directly, and a coverage standard. It is not possible, however, to consider partial coverage with either the DCPMP or the PMP as all demand must be assigned to a facility. Further, the DCPMP may be infeasible if the number of facilities is not sufficient to provide complete coverage.

None of the above models simultaneously address distance decay, coverage standards and partial coverage. Another option is to consider a spatial interaction based location-allocation model. A review of much that has been done in this area is given in Fotheringham and O’Kelly (1989). An origin constrained model variant is presented here, not unlike that detailed in Yamashita (1993). The following additional notation is used:

\[ S_{ij} = \text{demand in area } i \text{ assigned to facility } j \]
\[ w_j = \text{attraction of facility } j \]
\[ \beta = \text{distance decay parameter} \]
\[ \propto = \text{attraction parameter} \]
\[ f(\beta, d_{ij}) = \text{function relating spatial proximity} \]

Spatial Interaction Location-Allocation (SILA)

Minimize \[ \sum_i \sum_j d_{ij} S_{ij} \] (3.15)
Subject to

\[
S_{ij} = \left[ \frac{a_i w_j f(\beta, d_{ij})}{\sum_{k \in N_j} w_k f(\beta, d_{ik}) X_k} \right] X_j \quad \forall i, j, \quad (3.16)
\]

\[
\sum_{j \in N_i} S_{ij} = a_i \quad \forall i, \quad (3.17)
\]

\[
\sum_j X_j = p, \quad (3.18)
\]

\[
S_{ij} \geq 0, \quad (3.19)
\]

\[X_i = \{0, 1\} \quad \forall j.\]

The objective (3.15) minimizes the average travel distance between demand \(i\) and facility \(j\). Constraints (3.16) specify the interaction between demand \(i\) and facility \(j\). Note that \(f(\beta, d_{ij})\) is typically an exponential function (Fotheringham and O’Kelly 1989). Constraints (3.17) ensure that the sum of flows out of a demand area to open facilities equal known demand in area \(i\). Constraint (3.18) guarantees that exactly \(p\) facilities are located. Constraints (3.19) are non-negativity and integrality requirements.

Evaluating SILA with respect to our three modeling concerns, an aspect of distance decay and coverage standards are represented. However, all demand must be covered, as structured by Constraints (3.17), which may be infeasible when the number of facilities available is limited. Thus, SILA and the DCPMP are similar in that they both consider distance decay indirectly and coverage
standards, but do not consider partial coverage. A distinction between the two is that SILA allows partial assignments of demand, likely to be non-closest facilities given the facility attraction weights, $w_j$. Nevertheless, if it is assumed that facilities have equal attraction, the location-allocation patterns of SILA would likely be similar, if not identical, to those of the DCPMP. Unlike the DCPMP, modifying $a_i$ using $\hat{a}_{ij}$ is complicated. However, as with the DCPMP (and the PMP), partial coverage remains an issue that cannot be addressed using SILA.

### 3.2.2. Undesirable facility location models

Distance decay, coverage standards and partial coverage concerns also arise when siting undesirable facilities. Many of the previous models cannot be directly applied to address aspects of undesirable facility location due to objective orientation or constraint structure. In this section we review existing models for locating undesirable facilities that most closely address the three issues of interest in this chapter.

One way in which impact associated with undesirable facilities can be dispersed is using the anti-covering location problem (ACLP), originally formulated in Moon and Chaudhry (1984). If a zone of impact can be established (which is assumed by the coverage standard, $S$, in the case of undesirable facilities), then we can consider the maximum number of facilities that could be located so that no area is within more than one impact zone. It should be noted that demand areas and
potential facility sites are typically assumed to be the same in undesirable instances (e.g. \( i = j \)). The following additional notation is introduced before presenting the ACLP:

\[ c_j = \text{benefit associated with the use of location } j \]
\[ R_i = \{ j \mid d_{ij} \leq S \& i \neq j \} \]
\[ r_i = \text{coefficient for imposing locational restrictions} \]

Anti-Covering Location Problem (ACLP)

Maximize \[ \sum_j c_j X_j \] \hspace{1cm} (3.20)

Subject to:

\[ r_i X_i + \sum_{j \in R_i} X_j \leq r_i \hspace{1cm} \forall i, \] \hspace{1cm} (3.21)

\[ X_j = (0,1) \hspace{1cm} \forall j. \] \hspace{1cm} (3.22)

The objective (3.20) maximizes the total weighted selection of location sites. Constraints (3.21) prohibit more than one facility from being sited within the impact zone of a demand area. Constraints (3.22) are integrality requirements.

It is worth noting that Murray and Church (1997) detail approaches for better structuring and solving the ACLP.

Although the ACLP accounts for coverage standards and, consequently, results in dispersed sites, it does not explicitly track demand impacts by a particular facility. As such, distance decay is not accounted for. An important concern may be that the ACLP does not allow for the specification of the number of
facilities to be located. Nevertheless, it is likely that only partial impact on demand will result. Given this, one could not address the three concerns of interest using the ACLP.

Murray et al. (1998) developed a PMP-based model that considers both accessibility to sites as well as the impact of undesirable facilities on regional population. Before introducing this model, the following notation is introduced:

\[ \lambda_1 = \text{objective weight associated with no facility impact} \]
\[ \lambda_2 = \text{objective weight associated with average weighted distance to a facility} \]
\[ \Phi_i = \begin{cases} 1 & \text{if no facility is located in impact area of demand } i \\ 0 & \text{otherwise.} \end{cases} \]

P-Median Impact Problem (PMIP)

Maximize \[ \lambda_1 \sum_i a_i \Phi_i - \lambda_2 \sum_j \sum_i a_i d_{ij} Y_{ij} \] (3.23)

Subject to:

\[ \sum_j X_j = p, \quad (3.24) \]
\[ \sum_j Y_{ij} = 1 \quad \forall i, \quad (3.25) \]
\[ Y_{ij} - X_j \leq 0 \quad \forall i, j, \quad (3.26) \]
\[ \sum_{j \in N_i} X_j + \Phi_i \leq 1 \quad \forall i, \quad (3.27) \]
\[ X_j \in \{0, 1\} \forall j, \quad (3.28) \]
\[ Y_{ij} \in \{0, 1\} \forall i, j, \]
\[ \Phi_i \in \{0, 1\} \forall i. \]
The objective (3.23) maximizes the total weighted population that is not impacted by an undesirable facility site and minimizes the total weighted distance between demand and facilities. The constraints are similar to those of the PMP except for (3.27). These constraints limit the impact of an undesirable facility \( j \) on a demand \( i \) to at most one facility (within a coverage standard).

The PMIP does not account for distance decay. However, \( \hat{a}_{ij} \) could be utilized in (3.23), similar to (3.13) for the PMP, to appropriately address distance decay. Further, the PMIP requires that every user be assigned to a facility, as structured in Constraints (3.25). As such, partial coverage is not possible in the PMIP.

### 3.3. Model formulation

The previous section detailed the extent to which existing models could simultaneously address suitable coverage, partial coverage, and distance decay. A summary of their capabilities is given in Table 3.1. No existing model is capable of sufficiently encapsulating all three concerns. Thus, there is a need for a new model(s) to achieve this. We begin by presenting a potential spatial interaction based model for addressing our concerns.
Spatial Interaction Coverage (SIC)

Maximize or Minimize \( \sum_i \sum_j S_{ij} \) \hspace{1cm} (3.29)

Subject to

\[
S_{ij} = \left[ \frac{a_i w_i^\alpha f(\beta, d_{ij})}{\sum_{k \in N_j} w_i^\alpha f(\beta, d_{ij})X_k} \right] X_j \quad \forall i, j, \hspace{1cm} (3.30)
\]

\[
a_i \geq \sum_{j \in N_i} S_{ij} \quad \forall i, \hspace{1cm} (3.31)
\]

\[
\sum_j X_j = p, \hspace{1cm} (3.32)
\]

\[
S_{ij} \geq 0, \quad \forall i, j, \hspace{1cm} (3.33)
\]

\[X_j = \{0, 1\} \quad \forall j.\]

The objective (3.29) maximizes or minimizes demand assigned to facilities, depending on whether siting desirable or undesirable facilities is of interest. This objective differs substantially from that of the SILA, and can be thought of as a type of coverage objective. Constraints (3.30) specify the interaction between demand \(i\) and facility \(j\). These constraints account for distance decay within a coverage standard, and allow for partial assignment of demand (i.e. demand \(i\) could be distributed over more than one facility within the coverage standard). Constraints (3.31), combined with (3.30), consider both partial coverage and coverage standards by preventing assignment of demand when there are no open facilities within a coverage standard. The remainder of the formulation is similar to that of the SILA.
<table>
<thead>
<tr>
<th></th>
<th>Desirable facilities</th>
<th>Undesirable facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LSCP (Toregas et al. 1971)</td>
<td>PMP (Hakimi 1965)</td>
</tr>
<tr>
<td>Partial demand coverage</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Coverage distance</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Distance decay</td>
<td>NO</td>
<td>Maybe</td>
</tr>
</tbody>
</table>

Table 3.1: Select issues considered in location models
While the SIC does structure the necessary modeling issues of suitable coverage, partial coverage, and distance decay, it is a non-linear spatial optimization problem. As such, it is anticipated to be extremely difficult to solve for even small problem instances (see Fotheringham and O’Kelly 1989). If we assume \( w_j = 1 \), then we can pursue a more general linear model structure. Such an assumption is reasonable in both desirable and undesirable situations if it is believed that facilities have equal attraction and/or users would not travel farther than necessary to reach a facility.

Before discussing the developed linear model formulation, additional decision variables are introduced:

\[
\hat{Y}_i = \begin{cases} 
1 & \text{if area } i \text{ is assigned to a facility} \\
0 & \text{otherwise}
\end{cases}
\]

\( E_i \) accounts for coverage greater than one for a demand area.

Maximal/Minimal Covering-Distance Decay Problem (MCDDP)

Maximize or Minimize \( \sum_i \sum_{j \in N_i} \hat{a}_{ij} Y_{ij} \) \hspace{1cm} (3.34)

Subject to:

\[
\sum_j X_j = p,
\]

\( Y_{ij} \leq X_j \quad \forall i, j \in N_i \), \hspace{1cm} (3.35)

\[
E_i + \hat{Y}_i = \sum_{j \in N_i} X_j \quad \forall i,
\]

\( \sum_{j \in N_i} Y_{ij} = \hat{Y}_i \quad \forall i, \) \hspace{1cm} (3.36)

\[
(\vert N_i \vert - 1) \hat{Y} \geq E_i \quad \forall i,
\]
Objective (3.34) maximizes or minimizes the demand covered by facilities, depending on whether we are interested in desirable or undesirable siting. That is, when siting desirable facilities, there is typically an intent to maximize service coverage, whereas in the case of undesirable facilities minimizing coverage impact is often a concern. As detailed previously, it is possible to address distance decay using $\hat{d}_{ij}$, determined a priori. Constraint (3.35) ensures that only $p$ facilities are located. Constraints (3.36) require demand assignment to a facility only if it is open and within the stipulated coverage area. Constraints (3.37)-(3.39) are critical in this formulation. Collectively, these constraints track whether demand is covered, in which case it must be accounted for in the model. The challenge here is being able to simultaneously deal with a minimization or maximization problem, as the constraints must work properly in either case. Constraints (3.40) are integrality and non-negativity constraints.

What the MCDDP provides is a general model structure capable of addressing suitable coverage, partial coverage and distance decay in either a desirable or undesirable facility siting context. Further, this is a linear formulation that can be solved using commercial optimization software. One
final note is that the MCDDP can be simplified in the case of maximization. In such a circumstance, it is possible to replace Constraints (3.37)-(3.39) with:

\[ \sum_{j \in N_i} Y_{ij} \leq 1 \quad \forall i. \quad (3.41) \]

This would result in a slightly smaller problem as $3n$ constraints are replaced with $n$ constraints.

### 3.4. Park-and-ride and recycling in Columbus, Ohio

In this research, park-and-ride lots (desirable) and recycling centers (undesirable) are examined using the MCDDP.

#### 3.4.1. Park-and-ride in Columbus, Ohio

Columbus, Ohio, one of the few growing cities in the Midwest, is considered here for expanding park-and-ride services. The Central Ohio Transit Authority (COTA) provides public transportation services for the greater Columbus metropolitan region. The transit service area is around 552 square miles, inhabited by 1,082,450 people (MORPC, 2003). COTA maintains 24 park-and-ride facilities containing 2,330 spaces (COTA 2001), and has proposed adding 14 park-and-ride lots to the existing system as part of their medium and long-term plans (COTA 1999).
The MCDDP is capable of encapsulating the critical features of siting park-and-ride facilities. Thus, the MCDDP is utilized here for finding the best locational configuration of park-and-ride lots given existing demand. In this case we are interested in siting 38 facilities (i.e. \( p = 38 \))\(^4\). A prerequisite for determining where the park-and-ride facilities should be located is identifying potential sites. This was achieved using guidelines for siting park-and-ride facilities, among which are (Mather 1983; Turnbull 1995):

- Park-and-ride facilities should be located in congested travel corridors
- Park-and-ride facilities should be located in advance of areas experiencing major traffic congestion
- Locate park-and-ride lots in areas with high levels of travel demand to the major activity centers
- Lots should be located at least 4 to 5 miles from the major activity center being served.

ArcView GIS 3.2 was used to facilitate this process, so potential sites are identified to satisfy the above criteria. Further details are provided in the next section.

### 3.4.2. Recycling in Columbus, Ohio

Recycling is an important activity in the United States because it reduces the need for landfill sites, saves energy, etc. (EPA 2003). In Columbus, Ohio, two types of facilities are used for recycling: residential and business recycling (Solid Waste Authority of Central Ohio (SWACO) 2003).

Residential recycling facilities are basically drop-off boxes where people

\(^4\) The intent here is to assess an ideal configuration for the region as population growth and change has occurred over time.
dispose of recyclable materials. Business recycling facilities are plants where processing and sorting of collected materials take place (SWACO 2003). We are interested in the latter as it is considered undesirable.

As with locating park-and-ride facilities (desirable), we apply the MCDDP to determine the best locational configurations for recycling facilities (undesirable). It is assumed for illustrative purposes that 5 centers are to be located in Columbus (i.e. $p = 5$). According to SWACO (2003), unlike the case of park-and-ride facilities, there are no adopted guidelines for siting recycling facilities either at the local or state levels. Therefore, we identified potential recycling facility sites based on suitable landuse types, such as junkyards, landfills, industrial and commercial (excluding downtown). Landuse data for Franklin County, Ohio from 1998 was utilized to achieve this, obtained from the Center for Urban and Regional Analysis (CURA) at Ohio State University.

### 3.5. Application results

The analysis was carried out on a Pentium III/1000 personal computer with 512 MB RAM. ArcView GIS 3.2, a commercial GIS package, was used for spatial data manipulation, analysis and visualization. Avenue, a scripting language within ArcView, was used to produce MCDDP instances in text file format. Cplex version 6.6 was then used to solve the optimization model. Results were exported from Cplex for display and analysis in ArcView.
Census data (2000) at the block level was used as a proxy for demand/impact. There are 17,417 blocks in our utilized area of Franklin County, Ohio, which contains Columbus as well as other smaller cities. Demand areas were represented as block centroids, but only those areas likely to use park-and-ride services were included. This was done based on the Census Transportation Planning Package (CTPP) data, where areas not having trips destined to downtown were excluded. Potential demand $a_i$ was assumed to equal the number of persons in each block. Additionally, in both cases (desirable and undesirable facilities), block centroids were used to represent potential facility sites.

For example, park-and-ride potential sites were identified as a subset of census blocks centroids using the guidelines stated in the previous section.

### 3.5.1. Siting park-and-ride facilities

The MCDDP is first applied for siting park-and-ride lots in order to maximize potential ridership covered by located facilities. There are some implementation issues worth noting. One issue is $N_i$, which involves determining potential park-and-ride sites that are accessible from demand areas, both with respect to relative proximity and travel direction. Chapter 2 details how coverage areas for park-and-ride facilities can be determined.

---

5 This is considered reasonable given the intent to increase transit ridership.
Thus, this approach is utilized here. Another implementation issue is specifying a functional form to account for distance decay. The exponential and power functions are well known and are typically used to reflect distance decay (Fotheringham and O'Kelly 1989). The exponential function will be used here. Operationally, potential ridership demand is a function of total residents in an area as follows:

\[ \hat{a}_{ij} = a_i e^{-\beta d_{ij}} \]  

(3.42)

Here, \( \beta \) is assumed to equal one.

There are 153 potential facility locations satisfying park-and-ride siting guidelines. Using the area coverage approach of detailed in Chapter 2, 1,078 blocks were identified as potential demand areas for park-and-ride services. This equates to 77,444 potential park-and-ride users. Potential park-and-ride sites and demand areas are shown in Figure 3.1. The number of variables and constraints in the MCDDP for park-and-ride was 3,463 and 3,310, respectively. The problem took 0.30 seconds to solve and required 1268 iterations. Clearly, the MCDDP is easily solved, no doubt due to the linear formulation of the problem. Recall that the objective in the case of siting desirable facilities is to maximize demand covered by located facilities. Applying the MCDDP for siting park-and-ride lots resulted in covering 16 percent of potential park-and-ride demand (12,328 of the total 77,444 people). Figure 3.2 shows the resulting locational configuration of selected
park-and-ride sites. As expected, selected sites tend to lie within demand clusters, which is due to the fact that the objective is to maximize coverage. These results highlight how the MCDDP addresses the three issues of concern: distance decay, partial coverage, and coverage standards. First, sites are selected as close to demand as possible. Second, not all demand is assigned to a facility (partial coverage). Finally, all demand areas within the coverage standard of a selected site are in fact assigned to that site.

3.5.2. Siting recycling facilities

The minimization version of the MCDDP was applied for locating recycling facilities, where we assume that 5 facilities are to be located (i.e. \( p = 5 \)). Euclidean distance was used to assess spatial proximity. This is reasonable because the impact of undesirable facilities is somewhat averse to network structure. The maximum impact distance, \( S \), was assumed to equal one mile.

For recycling center siting in Columbus, the total residential population is 1,068,978 for the 17,417 blocks in the region. The number of potential facility sites is 162. Demand areas and potential recycling sites are shown in Figure 3.3. The number of variables and constraints in the MCDDP for recycling facilities is 49,375 and 63,165, respectively. The optimal
Figure 3.1: Potential park-and-ride sites and demand areas
Figure 3.2: Resulting configuration of selected park-and-ride sites (p = 38)
configuration of sites is shown in Figure 3.4. The solution time for the MCDDP was again very minimal (36 seconds and required 539 iterations). Recall that the objective is to minimize the impact of recycling facilities on the regional population. The application of the MCDDP has resulted in impacting less than 0.1 percent of the population (922 of 1,068,978 people). This is due to the selected sites being located away from demand concentrations, as shown in Figure 3.4. These results demonstrate how that the MCDDP simultaneously addresses distance decay, partial coverage of demand and coverage standards in the context of undesirable facility location.

3.6. Conclusions

Distance decay, coverage standards, and partial coverage of demand are key issues that need to be considered in certain facility location applications. Unfortunately, existing models do not simultaneously deal with these issues. This chapter presented two models that simultaneously address these concerns. The developed models are general in that they can be applied for siting both desirable and undesirable facilities. In this chapter, the Maximal/Minimal Covering-Distance Decay Problem (MCDDP) was applied for locating park-and-ride facilities (desirable) and recycling facilities.
Figure 3.3: Potential recycling sites and demand areas
Figure 3.4: Resulting configuration of selected recycling sites (p = 5)
(undesirable) in Columbus, Ohio due to its linear structure and associated solvability. Two distinct spatial patterns of selected sites were produced in these applications. In the case of park-and-ride facility siting, selected sites closely follow demand clusters, which is important if such services are to be attractive and well utilized. In contrast, in the case of recycling facilities, selected sites were away from demand clusters, which is also important when minimizing impact is of concern.

There are at least three important features of the MCDDP. First, the general MCDDP formulation can be used in two different facility siting contexts, desirable and undesirable. Second, the MCDDP, unlike existing location models, simultaneously addresses distance decay, partial coverage of demand and coverage standards. Finally, the MCDDP is a linear formulation, which means that it can be utilized to solve moderately sized problems using commercial optimization software. All are important considerations in location modeling.
CHAPTER 4

SITING NEW PARK-AND-RIDE FACILITIES IN AN EXISTING SYSTEM

4.1. Introduction

Distance decay, coverage standards and partial coverage of demand are key issues that need to be simultaneously addressed in facility siting situations. Unfortunately, most existing location models do not deal with these issues simultaneously. Models that could potentially address these issues are non-linear and, therefore, difficult to solve. Chapter 3 developed the Maximal Covering Distance Decay Problem (MCDDP) to simultaneously address these issues using a linear model. As was shown in Chapter 3, the MCDDP can be applied in two different facility siting contexts: desirable and undesirable. Additionally, due to its linear structure, it can be easily solved using commercial optimization software for moderately sized planning problems.

The MCDDP is a general model that deals with basic concerns in siting desirable and undesirable facilities. Given the need to address specific concerns in a particular siting application, one could consider various model extensions. In this chapter we are interested in addressing two additional concerns when siting park-and-ride facilities: siting new park-and-ride facilities...
in the context of an existing system and locating such facilities as close as possible to major roadways. Thus, extensions to the MCDDP are proposed here.

Siting new park-and-ride facilities in the context of an existing system is important because it may be desirable to keep as many existing facilities as possible, if not all of them. For example, in Columbus, Ohio, Central Ohio Transit Authority (COTA) has plans to expand the existing park-and-ride system to increase transit ridership (COTA 1999). Therefore, it is important that one incorporate the notion of complementing an existing system in this planning situation. Creating the ability to represent existing park-and-ride lots in a model is also important because it provides a useful mechanism for assessing system changes. That is, questions such as “how far is the existing system from an ideal system” could be addressed.

Siting park-and-ride facilities as close as possible to major roadways is another important consideration because the more accessible such facilities are to major roadways, the more likely they will be utilized. The importance of this was highlighted in the findings detailed in Chapter 2 using a regression oriented analysis as well as noted in other studies. For example, Spillar (1997) suggests that park-and-ride facilities should be located adjacent to freeways and high speed arterials. Other studies are more specific in that they
suggest that such facilities should be located within one mile of freeways (Kerchowskas and Sen 1977; MAG 2001). Thus, there is a need to consider this issue in any model applied for siting park-and-ride facilities.

Maximizing coverage of demand, siting new park-and-ride facilities in the context of an existing system and accounting for the accessibility of selected sites to major roadways may represent competing or conflicting objectives. These latter two objectives may be conflicting because some of the existing facility sites may not be near major roadways, and if such facilities are to be maintained, then system structure may not be ideal. Complementing an existing system may also conflict with providing coverage to as much potential ridership demand as possible. The reason for this is that an existing system may not cover as much demand as possible. Finally, maximizing coverage may conflict with locating park-and-ride sites as close to major roadways as possible as potential park-and-ride demand is not necessarily located near major roadways. Thus, multiple objectives complicate the planning situation because there are trade-offs associated with differing levels of importance attached to each objective.

This chapter presents a multiobjective formulation that integrates the above objectives into a single optimization model. This model is essentially an
extension of the MCDDP and is presented in the next section for siting park-and-ride facilities. This is followed by a review of multiobjective programming. Then, application results are presented. Finally, conclusions are given.

4.2. Model formulation

The previous section discussed the importance of representing existing facilities as well as accounting for good access to major roadways when siting park-and-ride facilities. This section presents an extension of the MCDDP that considers these issues. Before presenting the model, the following notation is introduced:

\( i \) = index of demand areas
\( j \) = index of potential facility sites
\( a_i \) = demand in area \( i \)
\( \hat{a}_i \) = demand in area \( i \) anticipated to use facility \( j \) based on relative proximity
\( p \) = number of facilities to be located
\( d_{ij} \) = distance or travel time between demand area \( i \) and potential facility site \( j \)
\( S \) = maximum acceptable service distance (or time)
\( N_i \) = set of park-and-ride potential sites accessible (travel time/distance and direction wise) to a demand area
\( T_j \) = shortest travel time from a facility \( j \) to a major road

Decision variables:

\[ X_j = \begin{cases} 
1 & \text{if a facility is located at site } j \\
0 & \text{otherwise}
\end{cases} \]

\[ Y_{ij} = \begin{cases} 
1 & \text{if demand in area } i \text{ is served by a facility at site } j \\
0 & \text{otherwise}
\end{cases} \]

\[ \hat{Y}_i = \begin{cases} 
1 & \text{if area } i \text{ is assigned to a facility} \\
0 & \text{otherwise}
\end{cases} \]

\( E_i \) = accounts for coverage greater than one for a demand area
\( \Psi = \) set of sites \( j \) representing an existing park-and-ride facility

Multi-Objective Maximal Covering Distance Decay Problem (MO-MCDDP)

Maximize \( \Phi_1 = \sum_i \sum_{j \in N_i} \hat{a}_{ij} Y_{ij} \) \hspace{1cm} (4.1)

Minimize \( \Phi_2 = \sum_j T_j X_j \) \hspace{1cm} (4.2)

Maximize \( \Phi_3 = \sum_{j \in \Psi} X_j \) \hspace{1cm} (4.3)

Subject to:

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

\[ Y_{ij} \leq X_j \quad \forall i, j \in N_i, \] \hspace{1cm} (4.5)

\[ E_i + \hat{Y}_i = \sum_{j \in N_i} X_j \quad \forall i, \] \hspace{1cm} (4.6)

\[ \sum_{j \in N_i} Y_{ij} = \hat{Y}_i \quad \forall i, \] \hspace{1cm} (4.7)

\[ \left| \frac{N_i - 1}{X_j} \right| \hat{Y} \geq E_i \quad \forall i, \] \hspace{1cm} (4.8)

\[ X_j = (0,1) \quad \forall j, \] \hspace{1cm} (4.9)

\[ \hat{Y}_i = (0,1) \quad \forall i, \]

\[ Y_{ij} = (0,1) \quad \forall i, j, \]

\[ E_i \geq 0 \quad \forall i. \]

The MO-MCDDP is a multi-objective formulation. The first objective (4.1) maximizes the demand covered by park-and-ride facilities. The second objective (4.2) minimizes total travel time between facility sites and major roadways. The third objective (4.3) maximizes the number of existing park-and-ride facilities selected. Constraint (4.4) ensures that only \( p \) facilities are located. Constraints (4.5) require demand assignment to a facility only if it is
open and within the stipulated coverage area. Constraints (4.6)-(4.8) track whether demand is covered, in which case it must be accounted for in the model. Constraints (4.9) are integrality and non-negativity constraints.

The MO-MCDDP is an extension of the maximization version of the MCDDP presented in Chapter 3. In addition to simultaneously considering distance decay, coverage standards, and partial coverage of demand, an important feature of the MO-MCDDP is its capability for siting park-and-ride facilities given an existing system. As will be shown next, this is useful for evaluating current service provision. Additionally, the MO-MCDDP addresses the concern of siting park-and-ride facilities as close to demand as possible.

Given that the MO-MCDDP is a multiobjective formulation, one can examine trade-offs between the different objectives. That is, using the MO-MCDDP, a range of alternative locational configurations for park-and-ride facilities can be generated by identifying non-inferior solutions. This means that not only different configurations of new facilities can be identified, but different mixes of existing and new facilities can be identified as well.

4.3. Multiobjective programming

Facility location decisions often involve conflicting or competing objectives, necessitating trade-offs to be made (Drezner 1995; Murray et al. 1998). For example, it is likely that there is a trade-off between maximizing coverage of
park-and-ride users and siting park-and-ride facilities as close as possible to major roadways, as noted previously. The reason for this is that the greater the coverage, the less likely that selected sites will be close to roadways as people do not tend to choose to live near major roadways. Developing a multi-objective formulation is a useful way to quantify trade-offs between conflicting objectives (Daskin 1995). Solving a multi-objective formulation involves identifying non-inferior solutions. Daskin (1995) defines an inferior solution as follows: “a solution $a$ is inferior if there exists some other solution $b$ that is as good as $a$ in terms of all of the objectives and $b$ is strictly better than $a$ in terms of at least one objective.” There are a number of approaches that can be used to determine non-inferior solutions, the weighting method and the constraint method being the most popular (Cohon 1978). The weighting method will be used in this research.

The weighting method provides an approach for obtaining non-inferior solutions by varying the weights associated with each objective (Cohon 1978). In the case of the MO-MCDDP, there are three objectives, $\Phi_1$, $\Phi_2$, and $\Phi_3$. Let $w_1$, $w_2$, and $w_3$ represent the corresponding importance weights of $\Phi_1$, $\Phi_2$, and $\Phi_3$, respectively. Thus, the objective function of the MO-MCDDP can be expressed as:

$$\text{Maximize} \quad w_1 \Phi_1 - w_2 \Phi_2 + w_3 \Phi_3$$

(4.10)
Assigning values to $w_1$, $w_2$, and $w_3$ (which represent the relative importance of the objectives) and solving the MO-MCDDP gives a non-inferior solution. Varying the values of $w_1$, $w_2$, and $w_3$ and solving the MO-MCDDP again possibly gives another non-inferior solution. However, the uniqueness of a solution depends on the obtained value of individual objectives. The idea is that we want to evaluate a range of weights in order to obtain the entire set of non-dominated or non-inferior solutions. The reason for this is that any non-dominated solution may be of interest in a planning or policy context and are all equally valid. Choosing from among non-dominated solutions requires judgment regarding the relative importance of each objective being considered (Cohon 1978). While the entire set of non-dominated solutions is theoretically what we seek to obtain, in practice we generally identify a representative subset (Murray et al. 1998). The reason for this is that there are an infinite number of weights one can select and potentially a large number of associated non-dominated solutions.

4.4. **Park-and-ride in Columbus, Ohio**

The park-and-ride system in Columbus, Ohio will be examined in this chapter. As noted previously, COTA provides transit services for the Columbus, Ohio region, with a service area of around 552 square miles (MORPC 2003). COTA currently maintains 24 park-and-ride facilities and is planning to add 14 facilities according to medium and long range plans (COTA 1999, 2001).
The MO-MCDDP is utilized here for siting park-and-ride facilities in the context of the existing system. Identifying potential sites is important before determining where park-and-ride facilities should be located. The literature provides guidelines for siting park-and-ride facilities, such as locating park-and-ride facilities in advance of areas experiencing major traffic congestion; locating such facilities in congested travel corridors; and siting park-and-ride lots at least 4 to 5 miles from the major activity center being served (see Kerchowskas and Sen 1977; Mather 1983; Turnbull 1995). These guidelines were used for identifying potential park-and-ride sites, as was done in Chapter 3.

4.5. Application results

The analysis was conducted using a Pentium III/1000 personal computer with 512 MB RAM. ArcView GIS 3.2 was utilized for performing spatial data manipulation, analysis and visualization. Avenue, a programming language within ArcView, was used to create MO-MCDDP instances in text file format. Solving the optimization model was achieved using Cplex version 6.6, and the results were exported to ArcView for analysis and display purposes.

Census data (2000) at the block level was used for demand representation, where block centroids were used to represent demand areas. Demand areas

---

6 The number of persons in each block was used as an estimate for potential demand $a_i$. This is considered reasonable given the goal of increasing transit ridership.
unlikely to use park-and-ride services were excluded. This was achieved using Census Transportation Planning Package (CTPP) data, where areas that do not have trips destined to downtown were excluded. Potential facility sites were also represented by block centroids. That is, park-and-ride potential sites were identified as a subset of census block centroids using the guidelines stated in the previous section, which was facilitated using ArcView. Further, existing park-and-ride sites were also considered as potential sites and their locations were geocoded in ArcView. Major roadway intersections were represented by a point theme in ArcView, which was necessary to address major roadway access in the MO-MCDDP.

Additional implementation details are as follows. $T_j$ was determined for each potential site $j$ using the shortest path function in ArcView. Determining $N_i$ involved identifying potential park-and-ride sites that are accessible (in terms of relative proximity and travel direction) from demand areas. The approach developed in Chapter 2 was utilized here to achieve this. Specifying a functional form to account for distance decay was another implementation issue. Two of the well known functions used for representing distance decay are the power and exponential functions (Fotheringham and O'Kelly 1989).
The latter will be used here. Operationally, potential ridership demand is a function of total residents in an area as follows:

\[
\hat{a}_{ij} = a_i e^{-\beta_{ij}}
\]

(4.11)

In this research, \(\beta\) is assumed to equal one.

The MO-MCDDP is applied for siting new park-and-ride lots in the context of the existing system. There are 171 potential park-and-ride facility sites. Using the analysis presented in Chapter 2, 1,078 blocks were identified as potential demand areas for park-and-ride services, equating to 77,444 potential park-and-ride users. Recall that the MO-MCDDP is a multi-objective formulation. It was solved using the weighting method, similar to what was done in Murray et al. (1998). The number of variables and constraints in the MO-MCDDP is 2,461 and 2,291, respectively. The solution time was very minimal, which can be attributed to the linear formulation of the MO-MCDDP. Specifically, it took 0.43 seconds in the worst case and required up to 1,736 iterations, depending on the assigned weights of each objective.

The weighting method was used to generate non-inferior solutions. Table 4.1 shows the generated non-inferior solutions. Each row represents a non-inferior solution and corresponds to a unique locational configuration of park-and-ride facilities. The first three sections in Table 4.1 represent the solutions associated with varying two objective weights at a time and holding a third
constant (zero in this case). Based on this, trade-off curves for pairs of objectives can be produced. Figures 4.1-4.3 show these curves, where the points on each curve represent non-inferior solutions. These figures are useful for visualizing the trade-offs between two objectives at a time. As an example, Figure 4.1 represents the trade-off between providing coverage and travel time between park-and-ride facilities and major roadways. Because these are conflicting objectives, increasing coverage results in greater travel time between park-and-ride facilities and major roadways (i.e. less accessibility).

The point on the upper right corner, for instance, represents a case where maximizing coverage is an extremely important objective relative to minimizing travel time between facilities and major roadways. Another observation is that as the slope of the curve increases, the gain in coverage may not be significant compared to the loss in accessibility. This suggests that the two points on the upper right corner of the curve may not represent very favorable trade-off solutions.

The MO-MCDDP is useful for siting new park-and-ride facilities in the context of an existing system. There are three broad trade-offs worth considering. One is where maintaining existing facilities is not important, i.e. there is great flexibility to relocate as many existing facilities as necessary.
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Table 4.1: MO-MCDDP results for the Columbus park-and-ride system ($p=38$).
Figure 4.1: MO-MCDDP trade-off curve for coverage and travel time ($p=38$)
Figure 4.2: MO-MCDDP trade-off curve for coverage and existing facilities objectives (p=38)
Figure 4.3: MO-MCDDP trade-off curve for existing facilities and travel time ($p=38$)
This is an extreme case. A second general trade-off is where the existing system is extremely important to maintain, so the task becomes one of finding an optimal configuration for new facilities only that best complements existing facilities. A third general trade-off is where a compromise between these two extremes is sought as urban growth and change would no doubt mean that some existing facilities should be reconsidered. Thus, a balance between the three objectives is likely our goal so as to maintain some of the existing facilities while covering an acceptable percentage of demand and locating facilities not far from major roadways. Below we show how the modeling results (Table 4.1) correspond to these three broad cases.

In the first general case, keeping existing facilities is not important, so $w_3 = 0$. The solution corresponding to $w_1 = 1$, $w_2 = 100$ and $w_3 = 0$ in Table 4.1 represents this extreme case. Figure 4.4 illustrates the resulting locational configuration. Here the model suggests maintaining only six of the existing facilities, while the remaining 18 facilities are to be relocated. This solution shows how the MO-MCDDP can be used for simultaneously evaluating an existing system and locating new facilities. However, there are other trade-off solutions possible even when $w_3 = 0$, likely more than the other five shown in Table 4.1.

On the other end of the spectrum, it may be desirable to keep most, if not all, of the existing facilities when siting new park-and-ride lots. In this case, more
importance would be given to objective 4.3. This can be achieved by increasing the value of $w_3$, and will no doubt result in keeping more of the existing facilities, assuming no relative change in other weights. The solution associated with $w_1=1$, $w_2=100$ and $w_3=500$ in Table 4.1 represents this extreme case where all existing facilities are maintained. Figure 4.5 shows the corresponding locational configuration. Basically, this case illustrates how the MO-MCDDP can be used for determining where the new facilities should be located given the existing system. Just like the previous case, however, it is possible that other trade-off solutions exist, see for example the solutions associated with $w_1=1$, $w_2=0$ and $w_3=500$ and $w_1=0$, $w_2=100$ and $w_3=0$ in Table 4.1.

The third case suggests compromise—relocating some of the existing facilities, while maintaining acceptable coverage and reasonable accessibility to major roadways. Of course, there are many solutions in Table 4.1 that may satisfy this criteria. For example, the solution corresponding to $w_1=1$, $w_2=200$, and $w_3=100$ represents a reasonable solution given that most of the potential users would be covered (15230 of 16579), almost half of the existing facilities would be maintained (10 of 24), and total travel time between selected sites and major roadways is significantly less than that of the worst case scenario (17.86 compared to 26.5 minutes). Figure 4.6 shows the locational configuration that corresponds to this solution. As with the two previous cases, there are also many trade-off solutions that can be considered reasonable compromises.
Figure 4.4: Park-and-ride sites ignoring the existing facilities ($\rho = 38$, $w_1=1$, $w_2=100$, $w_3=0$)
Figure 4.5: Park-and-ride sites maintaining existing facilities ($p = 38$, $w_1=1$, $w_2=100$, $w_3=500$)
Figure 4.6: Trade-off configuration of selected park-and-ride sites ($p = 38$, $w_1=1$, $w_2=200$, $w_3=100$)
4.6. **Comparison to MCDDP results**

Comparison of application results for the MCDDP and the MO-MCDDP suggests noteworthy differences. As was shown in Figure 3.2, applying the MCDDP resulted in one locational configuration for park-and-ride facilities, whereas the MO-MCDDP is capable of producing a range of alternatives depending on the relative importance of the objectives (see Table 4.1). For example, Figures 4.4-4.6 show three of many possible locational configurations of park-and-ride sites that can be identified using the MO-MCDDP. These configurations are different from that obtained by applying the MCDDP. The reason for this is that we are interested in multiple objectives in the case of the MO-MCDDP and, therefore, resultant locational configurations are highly dependent on the relative importance of each objective. For example, the locational configuration shown in Figure 4.5 (MO-MCDDP) is clearly different from that in Figure 3.2 (MCDDP). The reason for this is that in the former case keeping existing facilities is very important relative to the other objectives, whereas maximizing coverage is the single objective in the latter case. That is, Figure 4.5 shows a locational pattern that does not necessarily follow demand concentrations, which is unlike that in Figure 3.2, where selected sites followed demand clusters in accordance with the objective to maximize coverage.

However, a similar locational configuration to that found using the MCDDP could be generated using the MO-MCDDP. For example, placing greater importance
on the coverage objective (4.1) in the MO-MCDDP results in a configuration (Figure 4.4) that is similar to that when using the MCDDP (Figure 3.2) in the sense that selected sites in both cases seem to follow demand clusters.

Another difference between the MCDDP and the MO-MCDDP is that, unlike the MCDDP, the MO-MCDDP can be used for siting new park-and-ride facilities in an existing system, which is useful for performance evaluation, for example. It should be noted, nevertheless, that the MCDDP is not structured to deal with existing park-and-ride facilities, as it is a general model that addresses basic concerns when siting desirable and undesirable facilities.

As the results demonstrate, the significance of the MO-MCDDP stems from its ability to generate many alternative locational configurations for park-and-ride facilities. Additionally, as was also shown, quantifying trade-offs between objective pairs helps better understand how placing more importance on one objective affects the other. This is helpful for decision makers to better understand the decision making context and allows them to make more informed decisions.

4.7. Conclusions
Park-and-ride services are an integral element of public transportation in the United States. Locating park-and-ride facilities is an important step when planning for such services. In addition to covering as much potential demand as
possible, siting park-and-ride facilities in the context of an existing system and addressing the need to have selected sites as close as possible to major roadways are important considerations. This chapter has extended the MCDDP to account for park-and-ride application specific objectives. The objectives are competing and/or conflicting, but are integrated into one model.

Solving the MO-MCDDP enables one to produce a range of alternative locational configurations of park-and-ride facilities. Trade-off curves were also generated, which was useful for visualizing the effect of placing more importance on one objective relative to another. Both tabular and graphic approaches are important for decision makers as it allows them to take the appropriate course of action(s) given associated trade-offs.

One of the features of the MO-MCDDP is that it can be used for siting park-and-ride facilities in the context of an existing system. This is essential for examining a spectrum of cases between the two extremes of siting park-and-ride facilities regardless of the existing system and siting new facilities while maintaining all existing ones.
CHAPTER 5

POLICY EVALUATION

5.1. Introduction

Park-and-ride services are an integral component of many transit systems in the United States. If well-planned, such services could result in greater transit ridership. Delineating market areas and finding optimal locations for park-and-ride facilities are important steps when planning for such services. Market area delineation helps identify factors affecting the utilization of park-and-ride facilities. Such factors are important to consider when siting these facilities. In addition, understanding these factors is important as it helps reach more responsive policy decisions. Chapter 2 developed a new approach for market area delineation, and Chapters 3-4 developed models for siting park-and-ride facilities. These models can be used for evaluation and planning of park-and-ride facilities, which should be useful for urban areas aspiring to increase their transit ridership. For example, Central Ohio Transit Authority (COTA) plans to add new park-and-ride facilities to help increase transit ridership (COTA 1999). The Multiobjective Maximal Covering Distance Decay Problem (MO-MCDDP), developed in Chapter 4, was applied for siting these facilities. As was shown in Chapter 4, the MO-
MCDDP is useful from a policy standpoint because it could provide policy makers with insights regarding what locational configurations of park-and-ride facilities to adopt. It is important to note, however, that there are other aspects of policy that should be addressed.

While finding an optimal locational configuration for park-and-ride facilities in an urban area is important, this by itself may not result in a significant increase in transit ridership. The reason for this is that there are key supporting elements that need to be provided in conjunction with park-and-ride services in order for them to be more attractive (Turnbull 1995). One such element is High Occupancy Vehicle (HOV) lanes (see Fuhs 1993). Several urban areas (METRO 2003a, Virginia DOT 2003) provide HOV lanes in conjunction with park-and-ride services along major roadways, which result in significant travel time savings.

Another example of a supporting element for park-and-ride services is parking management and pricing policies. Because availability of parking in downtown areas is an important factor that greatly influences transit share (Gray and Hoel 1992; Strauss 1993; Turnbull 1995; Morrall 1996), adopting such policies is important to discourage downtown parking and, therefore, could make transit and park-and-ride services more attractive. For example, adopting parking management and pricing policies enabled cities such as Portland, Oregon, Boston, Massachusetts and San Francisco, California to reduce automobile traffic entering major activity centers (TMIP 2003). Thus, if an urban area aspires
to have successful transit with integrated park-and-ride services, elements such as HOV lanes and parking policies, should be undertaken in conjunction with park-and-ride services.

As noted throughout this research, Columbus, Ohio seeks to increase transit ridership (MORPC 1998). In the region’s first congestion summit conducted to discuss Columbus' transportation future, improving transit options was one of the four main strategies adopted to address traffic congestion (Columbus Chamber of Commerce 2001). One way in which Columbus has been attempting to achieve this is through planning for additional park-and-ride facilities (COTA 1999). However, focusing only on park-and-ride services without appropriate supporting policies could limit the potential impacts of this strategic directional emphasis.

This chapter reviews key elements necessary to support park-and-ride services. Although there are numerous such potential elements/policies (see Gray and Hoel 1992), we review those that are most relevant to bus-oriented park-and-ride services: HOV lanes, preferential treatment for HOVs, express bus services parking management and parking pricing, Intelligent transportation systems (ITS), employer based programs/transit subsidies, transit centers, and ride-sharing programs. The next section reviews how these policies can be related to park-and-ride services. This is followed by a discussion of prospects for Columbus given existing and potential policies. Finally, conclusions are given.
5.2. **Supporting elements for park-and-ride services**

Traffic congestion, deteriorating air quality and declining mobility are major issues facing urban regions in the United States (Levinson et al. 1997; TTI et al. 1998). A major cause for these problems is continued reliance on the private automobile (Newman and Kenworthy, 1999). Given this, several urban regions have explored various policies to encourage alternative modes of transportation and discourage the use of the private automobile. Policies that are most related to transit and park-and-ride services are reviewed here.

5.2.1. **HOV lanes**

A widely used policy in North America for alleviating traffic congestion is to provide High Occupancy Vehicle (HOV) lanes (see TTI et al. 1998; Mirchandani et al. 2000). HOV lanes, often provided in conjunction with park-and-ride services, have the ability to attract commuters mainly because they provide travel time savings as well as travel time reliability (Fuhs 1993). Travel time savings are achieved because express buses, operating on HOV lanes, bypass congested freeway segments. Travel time reliability means that commuting time is approximately the same every day along HOV lanes (Fuhs 1993).

Several urban areas in the United States consider HOV systems as very important for the success of park-and-ride facilities (Batz 1986; Fuhs 1993). For
example, providing park-and-ride facilities accompanied by HOV lanes and an express bus network is considered one of the most important characteristics for successful park-and-ride services in Phoenix, Arizona (MAG 2001). Another example is METRO, the transit authority in Harris County, Texas, which maintains HOV lanes on six of Houston’s major freeway corridors (TTI et al. 1998). Built primarily for buses, HOV lanes in the Houston area are provided in conjunction with park-and-ride services and express bus service. Compared to a peak hour average operating speed of 24 miles per hour, the operating speed on HOV lanes is 50-55 miles per hour, which translates into savings of 12-22 minutes per trip (METRO 2003a). In northern Virginia, HOV lanes are provided along I-66, I-95, I-395 and the Dulles Toll Road (Virginia DOT 2003). Park-and-ride facilities along these corridors have direct access to these lanes, which results in considerable time savings for HOVs. For example, average travel time using general use lanes on I-66 is 69 minutes as opposed to 41 minutes when using HOV lanes (Virginia DOT 2003).

5.2.2. Preferential treatment for HOVs

There are other types of preferential treatment than HOV lanes that could be used in conjunction with or separately from such lanes in order to encourage ridesharing. Examples of such treatments, which may be used in combination with park-and-ride services, are preferential toll charges and signal priority (Batz 1986). Preferential toll charges involve increasing the toll on a roadway for Single Occupant Vehicles (SOV) and/or reducing it for HOVs. Signal priority
treatment involves changing the timing of traffic signals on arterials so that buses progress with minimal delay. Such treatment can be used to support park-and-ride services and, if applied properly, can result in considerable travel time savings (Batz 1986). An urban area where there are plans to provide signal priority treatments in conjunction with park-and-ride services is Clark County, Washington (Clark County 1999).

5.2.3. Express bus services

One of the most commonly used transit services in combination with park-and-ride and HOV lanes is an express bus service. Such services are usually oriented toward downtown (or other significant employment areas), where the average bus speeds when using HOV lanes are 50-55 mph (TTI et al. 1998). Several urban areas run express bus services supported by park-and-ride services and HOV lanes. For example, rush hour express buses run from park-and-ride facilities along New Jersey Route 495 into New York City, which is the best “people-carrying” road lane in the United States (20,000 people per hour) (Leman et al. 1994). Another successful express bus service is operated by Sound Transit (ST), the major transit agency in Seattle, Washington, where the ST express service has celebrated the “…boarding of the 20 millionth rider in only three years of operation” (APTA 2003).
5.2.4. Parking management and pricing

Parking management and pricing strategies are important in order to encourage commuters to shift to HOVs, as the availability and cost of parking are very important factors that affect travel behavior and mode choice (Strauss 1993; Morrall 1996). Parking management and pricing strategies include restricting on-street parking, reducing the supply of parking at major activity centers, and charging higher parking prices for single occupant vehicles (SOV), among others (Gray and Hoel, 1992). One of the promising transit projects that applied such strategies is in Minneapolis, Minnesota where monthly rates for SOVs were $90 as compared to $10 for the HOVs (Turnbull 1995). In addition, using parking management and pricing strategies enabled cities such as Boston, San Francisco, and Portland to reduce automobile traffic entering major activity centers (TMIP 2003).

5.2.5. Intelligent transportation systems (ITS)

ITS are diverse technologies whose integration with transportation systems could help enhance road safety and efficiency as well as economic productivity (ITS America 2003). One way ITS can be used to enhance transit service in general, and park-and-ride services in particular, is by providing real time information to travelers. Such information includes, but is not limited to, pre-trip, en-route, and at terminal information (Spillar 1998). Obviously, availability of such information helps make transit a more viable travel option.
Pre-trip information helps travelers make informed decisions about their trip (Spillar 1998). One way to provide such information is through the Internet (TCRP 1998). In-vehicle/en-route information helps travelers make informed decisions on what travel options to use. En-route information can be made available either by variable message signs at the roadside or individually within the car, or by other means (TCRP 1998). Such information includes number of available spaces at park-and-ride lots, when the next bus departs from a park-and-ride facility, status of traffic congestion downstream of a given park-and-ride facility, etc. (TCRP 1998).

Information can also be provided to travelers at park-and-ride facilities. Such information can be provided using electronic signs through a high-tech computerized kiosk (Spillar 1998), which could result in more convenient park-and-ride services. As an example, information about bus status (e.g. arrival time) provided at park-and-ride facilities is a service welcomed by the public in Minnesota as it helps reduce anxiety associated with waiting for bus arrival (Wright 1995). Related to this, there is a recently developed concept called smart parks, where ITS technologies are integrated into park-and-ride lots to provide more convenient and attractive services (Spillar 1998). Some of the features described above as well as others form the basis for this concept. Munch, Germany and West Midlands, Great Britain represent two cases where
park-and-ride facilities were successfully integrated with ITS (Spillar 1998). One of the areas that have on-going plans to integrate ITS technologies in the United States is Silicon Valley (Hall and Thakker 1998).

5.2.6. Employer based programs

Employer based programs can also be used to encourage the use of alternative modes of transportation (Turnbull 1995). Such programs include in-house transportation coordination, information dissemination, company ridematching programs, company vanpool programs and transit subsidies (TTI et al. 1998). We focus on transit subsidies as it is probably the most relevant to transit and park-and-ride services. Providing transit subsidies for employees is one way employers can encourage the use of transit. A San Diego, California example illustrates a successful implementation of this strategy. The San Diego Trust & Savings Bank, located in downtown, offered its employees up to $100 a month as a transit subsidy (Comsis Corporation and Institute for Transportation Engineers 1993). This resulted in increasing the transit share to 37 percent among the bank’s employees, significantly higher than that of other employers (Comsis Corporation and Institute for Transportation Engineers 1993).

5.2.7. Providing transit centers

Providing facilities exclusively for park-and-ride facilities may not necessarily result in attracting many SOVs (MAG 2001). One reason for this is that there are other activities commuters may need to do on their way to work (shopping, day
care, car wash, day care, banking services, post office). Thus, a strategy for several urban areas has been to provide transit stations/centers that not only include park-and-ride facilities but also offer other services (Urban Transportation Monitor 1990). Such transit centers also provide more destination options and intermodal connections for travelers, which may result in attracting more commuters to use transit in general and park-and-ride services in particular (MAG 2001).

5.2.8. Ride-sharing programs

Regional ridesharing programs include facilitating services such as carpooling and vanpooling (Gray and Hoel 1992). Park-and-ride facilities could be used as staging areas to form vanpools, which is the case in the Washington DC region (Turnbull 1995). A hurdle to ridesharing, however, is that commuters depend on their private automobiles because of the possible need for a ride home in case of an emergency (MORPC 2003). To overcome this, several urban areas provide Guaranteed Ride Home programs in order to provide a backup means of transportation for people who use transit or other ridesharing options (MORPC 2003).

5.3. Park-and-ride services in Columbus, Ohio

As with other major urban areas of the United States, the Columbus, Ohio region is experiencing traffic congestion problems (MORPC 1998). Traffic congestion was rated as the number one issue concerning residents in the 2000 City of
Columbus Citizen Satisfaction Survey (Columbus Chamber of Commerce 2001). This region is one of the few growing areas in the Midwest and is the fastest growing in Ohio (MORPC 1998). It is experiencing population and employment growth, and this is expected to continue through the next 25 years (COTA 1999). This growth has resulted in further reliance on private automobiles (MORPC 1998). The vehicle-miles of travel (VMT) in the region are expected to grow by 63 percent by the year 2020 and the amount of time people spend in their cars is expected to increase by 77 percent (Columbus Chamber of Commerce 2001).

The Central Ohio Transit Authority (COTA) provides mass transit services for Central Ohio, with a transit service area of around 552 square miles inhabited by 1,082,450 people (COTA 2001; MORPC 2003). COTA aspires to improve mobility throughout the Columbus area and provide a viable alternative to the automobile (COTA 1999). One of the transit services that COTA offers is park-and-ride. COTA maintains 24 park-and-ride facilities containing 2330 spaces (COTA 2001). Medium and long-term plans are to add 14 park-and-ride lots (COTA 1999).

5.4. Prospects for Columbus

As noted previously, COTA intends to expand the geographic coverage of park-and-ride services. In addition, COTA plans to add other elements to the transit
system in order to make it more attractive. In this section we examine prospects for considerable increase in transit utilization as a result of park-and-ride services in Columbus.

5.4.1. Park-and-ride system given existing and proposed COTA plans/policies

As noted previously, COTA plans to expand its geographic coverage of park-and-ride service by adding 14 facilities. In Chapter 4, the MO-MCDDP was used to find an ideal locational configuration for the proposed facilities in support of this long range plan. In addition to adding park-and-ride facilities to the transit system, COTA intends to provide ITS elements, such as automatic vehicle locator (AVL) systems, and real time information, some of which already operating (MORPC 2003). Further, COTA has plans to introduce signal priority for buses, which could result in reducing bus travel time along roadways (COTA 1999). Finally, there are plans to add transit centers, which is necessary for making transfers between transit routes, as well as providing other services (e.g. day care, health care, banking) (COTA 2003). Given this, it is reasonable to assume that adding such features could result in an increase in the utilization of park-and-ride services, and transit more generally.
5.4.2. Supporting park-and-ride policies

Although COTA adopts plans to expand the park-and-ride system and add important elements to the transit system, such plans do not involve the complete array of possible supporting elements/policies. Here, we describe the significance that such elements could have in Columbus.

5.4.2.1. HOV lanes

As noted previously, one of the most important elements that should be provided in order to achieve successful park-and-ride services is HOV lanes (MAG 2001; BMI 2003). One indication of the importance of providing HOV lanes is their fast growth in major urban areas in North America, as shown in Figures 5.1-5.2. Providing HOV lanes could result in travel time savings and less traffic congestion (Fuhs 1993). A successful example is along the I-395 Shirley Highway corridor in suburban northern Virginia, where introducing HOV lanes resulted in reducing traffic congestion and increasing transit ridership (Fuhs and Obenberger 2001).

Recognizing the importance of providing HOV lanes, several agencies across the United States have explicit policies in this regard. Washington State DOT is one of the agencies that have a relatively comprehensive set of policies to encourage the use of HOVs (see Washington State DOT 2003). For example, a policy related to providing HOV lanes states: “Evidence exists that during peak hours of operation, the HOV lane will move more people than the per lane average of the
adjacent general purpose lanes.” Another policy related to converting general purpose lanes to HOV lanes is, “When new capacity options are proposed, one of the alternatives to be considered shall be the conversion of a general-purpose lane to an HOV lane.”

Although several major travel corridors in Columbus, such as Interstate 71 and State Route 315 shown in Figure 5.3, experience traffic congestion, HOV lanes are not provided along such corridors (nor are they provided on other major roads). Providing HOV lanes along these roadways would likely result in less traffic congestion, as well as travel time savings for buses, vanpools, etc. There is little doubt that HOV lanes would help make park-and-ride a more competitive travel option. This would be expected to be the case for the Olentangy park-and-ride facility (Figure 5.3), for example.

Given the importance of providing HOV lanes, Columbus should adopt policies that facilitate this. Providing HOV lanes is not necessarily an expensive option, given the possibility of converting general purpose lanes into HOV lanes. Examples of urban areas successfully converting general purpose lanes to HOV lanes include Long Island Expressway, I-90 in Seattle, and I-80 in Morris County, New Jersey (TTI et a. 1998).
Figure 5.1: Growth in total kilometers of operating HOV lanes on freeways and in separate right of ways.

(Source: TTI et al. 1998)
Figure 5.2: HOV facilities on freeways with a separate right-of-way in the United States

(Source: TTI et al. 1998)
Figure 5.3: Bus vs. automobile travel time when considering park-and-ride
5.4.2.2. Parking management and pricing

Parking supply/cost is an important factor that influences travel behavior and mode choice (Gray and Hoel 1992; Strauss 1993; Turnbull 1995; Morrall 1996). Table 5.1 illustrates how transit share is affected by change in parking cost. Thus, to make transit a more viable option, urban areas need to adopt policies to control the use of parking in major activity centers. Portland, Oregon, for example, has specific policies to manage parking supply, one of which states, “Manage and optimize the efficient use of public and commercial parking in the central city, regional centers, town centers, main streets and employment centers…” (METRO 2003b). Applying such policies in Portland resulted in reducing automobile traffic entering major activity centers (TMIP 2003).

Although controlling the supply and price of parking is important, it appears that there are no adopted policies in Columbus for reducing and/or pricing parking spaces in the downtown areas. According to a parking study (see Cambridge Systematics and Burgess & Niple 1996), downtown Columbus has a substantial amount of downtown parking compared to other cities. For example, Columbus provides 2.57 parking spaces per 1,000 square feet of commercial space, compared to 2.40 in Dallas, 1.46 in Portland, 1.81 in Raleigh and 1.95 in Cleveland (Figure 5.4a). In addition, according to the same study, Columbus

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7 Note that these costs represent 1972-1973 dollars, so accounting for inflation the last entry of $5 would be roughly $21 today.
<table>
<thead>
<tr>
<th>Increase in average parking cost</th>
<th>% change Auto driver trips</th>
<th>% change in Transit trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.25</td>
<td>-4</td>
<td>+3</td>
</tr>
<tr>
<td>0.50</td>
<td>-8</td>
<td>+6</td>
</tr>
<tr>
<td>0.75</td>
<td>-12</td>
<td>+10</td>
</tr>
<tr>
<td>1.00</td>
<td>-15</td>
<td>+13</td>
</tr>
<tr>
<td>1.50</td>
<td>-20</td>
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</tr>
<tr>
<td>5.00</td>
<td>-37</td>
<td>+55</td>
</tr>
</tbody>
</table>

Table 5.1: Projected changes in travel behavior resulting from a parking tax in Washington, D.C.

(Source: Erlich 1973)
Figure 5.4: Parking availability and cost
(Source: Cambridge Systematics and Burgess & Niple 1996)
downtown parking is considerably less expensive than these cities. The average cost of parking is $4.17 per day, compared to $7.50 in Portland, $5.50 in Sacramento, $8.00 in Cleveland, and $5.50 in Cincinnati (Figure 5.4b).

Given that parking is relatively plentiful and cheap in the Columbus downtown area, adopting a parking management/pricing policy seems to be very important in order to help achieve successful transit and park-and-ride services.

5.4.2.3. Express bus services

According to a park-and-ride site selection study conducted by Maricopa Association of Governments, frequent express bus services (buses at most 15 minutes apart), preferably provided in combination with HOV lanes, are an important component of a successful park-and-ride system (MAG 2001). There are several successful examples of express bus services in conjunction with park-and-ride facilities and HOV lanes. An extensive express bus service utilizing HOV lanes runs along New Jersey Route 495, the best “people-carrying” road lane in the United States (20,000 people per hour) (Leman et al. 1994). Houston METRO runs an extensive system of express buses (with a high frequency of 5 minutes) in conjunction with 16 major park-and-ride lots and HOV lanes (TTI et al. 1998).

Although COTA runs express bus services, they do not necessarily provide a competitive option. One reason for this is that, with few exceptions, they do not
have high frequency of service (see Table 5.2). Another reason for this is that they do not operate in conjunction with HOV lanes. Thus, if successful park-and-ride services are to be achieved in Columbus, express bus services should be provided in conjunction with other elements, such as HOV lanes and should have high frequency of service.

5.5. Conclusions

Park-and-ride services are an important component of transit systems in the United States. Although finding optimal locations for park-and-ride facilities is important when planning for these services, providing key supporting elements is essential for achieving successful services. This chapter has reviewed such policies/elements, mostly related to transit and park-and-ride services. Columbus, Ohio, the case study in this research, was examined to identify its potential for achieving successful park-and-ride services given existing and potential policies.

While COTA is adopting some of these policies in Columbus, there are key elements/policies that are still not considered, such as HOV lanes and parking pricing. This chapter has described the significance of providing these policies. Hence, we believe that adopting these policies is important if successful park-and-ride services are to be achieved in the Columbus region.
<table>
<thead>
<tr>
<th>Park-and-ride facility</th>
<th>Express Routes</th>
<th>Average Frequency (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westerville</td>
<td>33, 36, 37, 40</td>
<td>10</td>
</tr>
<tr>
<td>Berwick Plaza</td>
<td>46, 65</td>
<td>15</td>
</tr>
<tr>
<td>Crosswood</td>
<td>31</td>
<td>15</td>
</tr>
<tr>
<td>High/Jeffrey</td>
<td>31</td>
<td>15</td>
</tr>
<tr>
<td>High/ Royal Forest</td>
<td>31</td>
<td>15</td>
</tr>
<tr>
<td>Northern Lights</td>
<td>35, 37, 38</td>
<td>15</td>
</tr>
<tr>
<td>Renoldsburg</td>
<td>45, 47</td>
<td>17</td>
</tr>
<tr>
<td>WhiteHall</td>
<td>43</td>
<td>20</td>
</tr>
<tr>
<td>Hilliard</td>
<td>67</td>
<td>25</td>
</tr>
<tr>
<td>Royal Plaza</td>
<td>41</td>
<td>25</td>
</tr>
<tr>
<td>Kingsdale</td>
<td>60</td>
<td>27</td>
</tr>
<tr>
<td>Broad/ Southampton</td>
<td>53</td>
<td>30</td>
</tr>
<tr>
<td>Olentangy</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>St Andrew</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>St Peter</td>
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<td>30</td>
</tr>
<tr>
<td>Westwoods</td>
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</tr>
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<td>Grove City</td>
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</tr>
<tr>
<td>Hilliard--Rome Rd</td>
<td>57</td>
<td>35</td>
</tr>
<tr>
<td>Dublin</td>
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<td>40</td>
</tr>
<tr>
<td>GriggsDam</td>
<td>58</td>
<td>40</td>
</tr>
<tr>
<td>New Albany</td>
<td>39</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 5.2: Frequency of express buses serving park-and-ride facilities in Columbus
(Source: Central Ohio Transit Authority (COTA) 2003)
CHAPTER 6

CONCLUSIONS

Park-and-ride services are an integral component of many transit systems in the United States. If well planned, they could produce increased transit ridership. An important step when planning for such services is delineating market areas for park-and-ride facilities. Unfortunately, existing market area delineation approaches do not simultaneously consider accessibility and travel direction. Market area delineation approaches that assume a certain shape do not fully consider accessibility issues. Approaches that use travel cost to delineate market areas do not explicitly consider travel direction. This research has developed a GIS-based approach that simultaneously considers accessibility and travel direction. It was shown in Chapter 2, through a visual comparison and regression oriented analysis, that the developed approach is an improvement over existing techniques. The developed approach has utilized and extended the capabilities of GIS, which resulted in facilitating subsequent analyses, such as analyzing factors affecting utilization of park-and-ride services. In addition to developing a new market area delineation approach, this research provided a detailed description and formal specification for existing market area delineation techniques, which should be useful for implementation purposes.
Another important step when planning for park-and-ride services is siting the facilities providing the service. There are at least three key issues that need to be addressed when siting such facilities: distance decay, coverage standards, and partial coverage of demand. Addressing distance decay is important because it accounts for the fact that the closer facilities are from demand, the more likely they would be utilized. Coverage standards are also important to consider, because there is a maximum acceptable distance beyond which users would be unwilling to use a park-and-ride facility. Finally, due to resource limitations (i.e. in terms of number of available facilities) it is imperative to address partial coverage. As was demonstrated in Chapter 3, existing location models either do not simultaneously address these key issues or are virtually impossible to solve due to non-linearities. Chapter 3 presented a linear location model, the Maximal Covering Distance Decay Problem (MCDDP), that simultaneously addressed distance decay, coverage standards, and partial coverage of demand. The MCDDP required minimal computational effort in the problems evaluated. As was shown in Chapter 3, another feature of the MCDDP is that it can be applied in two distinct facility siting contexts: desirable and undesirable. That is, not only was the MCDDP applied for siting park-and-ride facilities (desirable), but it also was utilized for locating recycling facilities (undesirable).

The MCDDP is a general model that addresses basic concerns when siting desirable and undesirable facilities. Depending on the siting context, there may
be additional concerns that need to be modeled. In the case of park-and-ride facilities, in addition to maximizing coverage, siting facilities in the context of an existing park-and-ride system and selecting sites as close to major roadways as possible are important considerations. An existing system no doubt presents challenges when siting new park-and-ride facilities because it may be desirable to keep as many as possible, if not all, of the existing facilities. Siting park-and-ride facilities as close as possible to major roadways is also important because the more accessible such facilities are to major roadways, the more likely they will be utilized. Given this, Chapter 4 extended the MCDDP to address multiple objectives, labeled the Multiobjective Maximal Covering Distance Decay Problem (MO-MCDDP). The MO-MCDDP considers three competing objectives: coverage maximization, minimizing travel time between selected sites and major roads, and maximizing existing facilities. It was shown that the MO-MCDDP is a useful tool for decision makers, because it can be used to generate a range of solutions for the location problem based on the relative importance of each objective.

While it is important for an urban area to find an ideal configuration for park-and-ride facilities to attract more transit ridership, this by itself may not result in a significant increase in ridership. The reason for this is that there are supporting elements/policies that need to be provided/adopted in order for park-and-ride services to be successful. Such elements/policies include, but are not limited to, HOV lanes and parking pricing. Chapter 5 has reviewed several
elements/policies associated with transit and park-and-ride services, as well as examined the potential of Columbus, Ohio, the area under study, to achieve successful park-and-ride services. Although there are plans for Columbus to increase transit ridership, i.e. through expanding the park-and-ride system and providing other elements (ITS, transit centers, etc.), there are key elements that are not accounted for under existing policies/plans. For example, although important, HOV lanes and parking management/pricing strategies are not presently part of future plans in Columbus. Unless such key elements/policies are considered, we believe that it would be difficult for the central Ohio region to achieve successful park-and-ride services.

This research has attempted to find ways for achieving successful park-and-ride and transit services. This is essential in order to help overcome car dependency. This, in turn, could help achieve more sustainable existence and better quality of life in cities.
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