A GIS-Based Approach for Delineating Market Areas for Park-and-Ride Facilities

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ABSTRACT

Park-and-ride services are an integral component of many public transit systems in the United States. A necessary step when analyzing and planning for such services is to delineate catchment areas for park-and-ride facilities. Previous approaches for delineating catchment/market areas are either problematic or have unrealistic data requirements. This paper develops a geographic information system (GIS)-based approach for delineating market areas. The detailed approach simultaneously accounts for park and ride facility accessibility and user travel direction. It is shown that the developed approach performs better than existing approaches. Further, this paper demonstrates how GIS functionality may be developed and utilized to support the analysis of park and ride services.

Key words: public transportation, GIS, park and ride, transportation planning, market area
1. INTRODUCTION

Traffic congestion has been and is expected to continue to be a major concern for urban areas of the United States (1). The main reason for traffic congestion is continued reliance on the private automobile (2). Using public transit is a potentially effective way to overcome car dependency and would likely contribute to a more sustainable existence of urban areas (2). Public transit, however, is not well suited for low-density areas because there is usually not enough travel demand to support fixed route transit service (3). Nevertheless, park and ride services can extend public transportation to low-density areas. That is, park and ride users could start their trip in a low-density area using an automobile and then switch to transit at a park and ride facility later in the same trip (4). Park and ride services are beneficial to the user, operator, and transportation system as well as to communities (5). Thus, many transit agencies across the United States consider park-and-ride services an essential element of their transit systems (6, 7, 8).

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 (9). In order to achieve this, an important step in the planning process is the ability to identify associated park-and-ride market area boundaries (6). A market area, also known as a study, service, catchment or commutershed area, is the geographic area which users of a park-and-ride facility are likely to come from (10, 11). Delineating such areas is important because they help explain the spatial and socioeconomic characteristics of users in the market area as well as travel characteristics (10). This information can then be used, for instance, to predict potential demand for park and ride facilities and better plan system integration (12).

Interestingly, there is a range of alternative approaches that exist for identifying park and ride catchment/market areas. They can be broadly divided into three approaches: (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 (6). 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 1 are at equal distances from the park and ride facility, they are unlikely to have an equal degree of accessibility to the facility. More specifically, the travel time between A and the facility could well be different from that between B and the facility, given street network topology and natural barriers.

Sargious and Janarthanan (1983) delineate the boundary of a market area based on travel cost (3). Such costs include value of time, 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 duration of their trip. A problem with this approach, however, is that it does not explicitly account for user travel direction.

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 (12). 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 (13). They suggest that logarithmic/exponential functions can describe the relationship between the park-and-ride ridership and the distance/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 user privacy, data on user locations are becoming increasingly difficult to obtain. If this is the case, the analyst must select a market area delineation approach that does not rely on user locations as input. Unfortunately, there is no objective method to guide such a decision.

Geographic information systems (GIS) are known for their capabilities in creating, analyzing, manipulating, storing and representing spatial data (14). These capabilities have been used for delineating market areas (15), although their use in the analysis of park and ride facilities has been limited. This paper develops a GIS-based approach to support park and ride market area assessment that simultaneously considers accessibility and user travel direction. The next section examines two existing methods for market area delineation. Following this, a new approach for delineating market areas is developed. Next, the implementation of these approaches is described and a comparison between existing approaches and the developed approach is carried out. Finally, conclusions and future research directions are given.
2. DELINEATING MARKET AREAS
Two commonly used approaches for delineating market area boundaries in park and ride studies are detailed in this section. The first is an assumed parabolic shape and the second is structured using travel costs.

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 (16, 17). 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. A parabola is defined for each facility to represent the market area for that facility. The general form of a parabola is:

\[ Ax^2 + Bxy + Cy^2 + Dx + Ey + F = 0 \]  

If the parabola is oriented around the y-axis, equation (1) can be simplified as follows, assuming that the parabola has its vertex at \((h, k)\) and the directrix is \(y = k - p\)

\[(x - h)^2 = 4p(y - k)\]  

If the orientation is around the x-axis, equation 1 can be simplified to

\[(y - k)^2 = 4p(x - h)\]

If the vertex is placed at the origin (i.e. \((h, k) = (0, 0))\), equation (2) becomes:

\[ y = \frac{x^2}{4p} \]

Figure 2.a illustrates this case. Similarly, if the vertex of the parabola represented by equation (3) is placed at the origin, equation (3) becomes:

\[ x = \frac{y^2}{4p} \]

where \(p\) is the distance between the focus of the parabola and the vertex. Equation (4) or (5) can be used to represent the market area for a park and ride facility, where \(p\) would represent the backtrack distance (distance that users are willing to backtrack to reach the facility).

Step 2 is needed now to further define the market area boundary. That is, the maximum extent of travel to the facility, \(d_{\text{max}}\), is used for determining the market area boundary in the opposite direction of the parabola vertex, as shown in Figure 2.a. Finally, in Step 3, the users within the boundary of the market area defined in Steps 1 and 2 are identified. As mentioned above, the general form of a parabola can be simplified to equations (4) or (5) depending on whether the parabola is oriented around the x- or y-axis. However, in practice the parabola associated with a park and ride facility is not likely to be perfectly horizontal or vertical relative to the major activity center, as shown in Figure 2.b. Thus, the general form (equation (1)) is needed in this step to identify the users inside the parabola boundary. That is, for a given user with x and y coordinates, they would be included in the parabola boundary if

\[ Ax^2 + Bxy + Cy^2 + Dx + Ey + F \leq 0 \]

In addition, users in the “open end” of the parabola should be checked whether they are beyond \(d_{\text{max}}\). That is, exclude the users from the market area if

\[ d((x, y), (x_f, y_f)) > d_{\text{max}} \]

where \(x_f\) and \(y_f\) are the coordinates of the park and ride facility, and \(x\) and \(y\) are the coordinates of the user examined.
2.2 Market Area Delineation based on Travel Costs

Another way for delineating market areas is, as suggested by Sargious and Janarthanan (1983), by comparing travel costs between the automobile and the park-and-ride modes. As mentioned before, these costs include value of time, travel time, and use fees. The major steps for delineating the market area for a given park and ride facility are:

1. compute the travel cost using the automobile for a potential park and ride facility user between the user location and the major activity center
2. compute the travel cost for the same user using park and ride
3. if the user's travel cost in an automobile is greater than that associated with park and ride travel, this individual would be included in the market area.

Step 1 is about calculating the travel cost using the automobile between the user location and the major activity center. Let \( c_{im} \) be the automobile travel cost between a user \( i \) and a major activity center \( m \). Step 2 is to calculate travel cost using the park and ride mode. Let \( c_{ip} \) and \( c_{pm} \) be the automobile travel cost between the location of a user \( i \) and a park and ride facility \( p \), and the bus travel cost between \( p \) and a major activity center \( m \) respectively. Thus, the park-and-ride cost can be expressed as \( c_{ip} + c_{pm} \). Step 3 is to delineate the market area by comparing the above two costs. That is, if a user does not have a travel cost advantage when using the park-and-ride mode, such a user would be excluded from the market area. Expressed mathematically, exclude \( i \) if

\[
c_{im} > c_{ip} + c_{pm}
\]

3. DEVELOPED APPROACH FOR MARKET AREA DELINEATION

The previous section examined two of the existing approaches for delineating park and ride market areas. As was stated before, the problem with the parabolic shaped market area approach (see Section 2.1) is that it assumes that users at equal distances from a park-and-ride facility have the same degree of accessibility to the facility. A shortcoming of using travel costs to delineate market areas (see Section 2.2) is that it does not consider travel direction explicitly when delineating market areas. Therefore, a new approach is developed to simultaneously account for these two issues. The developed approach is similar to the parabolic shaped market area approach in that it recognizes that commuters are likely to utilize park-and-ride facilities if such facilities are in their direction of travel. However, it is different in that it does not assume a certain shape for the market area. That is, it recognizes that the spatial features around the park and ride facility (e.g. effect of natural barriers) influence the market area shape. The suggested approach is also different from the approach that uses travel costs to delineate market areas in that it explicitly considers the travel direction.

For a given urban area, the major steps involved in the developed approach are:

1. For each potential user around a park and ride facility, determine whether the facility is in the user’s travel direction.
2. Delineate the market area for each facility by including two types of users: (1) users that the facility is in their travel direction and are within an acceptable travel time from the facility; and (2) users who the facility is opposite to their travel direction but are within an acceptable backtrack time to the facility.

The first step is to determine whether a park and ride facility is in the user’s travel direction. To achieve this, the location of the major activity center relative to the facility is determined first. The reason is that the location of the major activity center (destination) dictates the travel direction of the users around the park and ride facility, provided that such users are destined to the major activity center. Having determined the users’ general direction of travel, the issue becomes of assessing whether the facility is in the user’s travel direction. To assess that, the orientation of each user relative to the facility is calculated.

The inclination, \( \delta \), of the line emanating from the park and ride facility towards the major activity center, as shown in Figure 3, is used to represent the location of the major activity center relative to the facility. Based on \( \delta \), an x'-y' coordinate system is established at each park and ride facility in order to determine the orientation of users relative to that facility (as Figure 3 shows, the x'- and y'-axes result from rotating the x-axis and the y-axis by \( \delta + 90^\circ \)). The orientation of users relative to the facility is then determined to find out whether the facility is in the user’s travel direction. For example, the orientation, \( \alpha \), of user A, shown in Figure 3, indicates that this user is upstream of the facility and, therefore, the facility is considered in their direction of travel. Step 1 is summarized in Figure 4.
Step 2 delineates the market area by including two types of users
a. Users within an acceptable street network-based travel time from a park-and-ride facility and the facility is in their direction of travel (it is assumed here that the facility is in the user’s travel direction if $0 \leq \alpha \leq 180$). That is,
\[ t_{ip} \leq T \quad \text{and} \quad 0 \leq \alpha \leq 180 \]

Where,
\[ t_{ip} \] is the street network-based automobile travel time between a user $i$ and a park and ride facility $p$, and $T$ is the maximum travel time users are willing to drive to a park and ride facility

b. Users who are within the backtrack travel time from a park and ride facility and the facility is opposite to their travel direction. That is,
\[ t_{ip} \leq BT \quad \text{and} \quad 180 < \alpha < 360 \]

where $BT$ is the tolerable backtrack time.

4. IMPLEMENTATION OF MARKET AREA DELINEATION APPROACHES

The procedures for delineating market areas discussed in Sections 2 and 3 are implemented here using ArcView 3.2. The data used for the implementation are from Columbus, Ohio. This data include the locations of park and ride facilities, as shown in Figure 5, census block information as well other data.

4.1 Parabolic Shaped Market Areas

As was discussed before, the general form of a parabola and maximum extent of travel, $d_{max}$, can be used to determine whether a user should be included in the parabolic market area. $d_{max}$ was based on the fact that typical users would not likely drive more than 5 miles to reach the facility. The backtrack distance was assumed to be 0.5 miles. Because this procedure cannot be readily implemented in ArcView, it was operationalized using Avenue, the associated ArcView scripting language. Using the developed Avenue script, the resulting market areas are shown in Figure 6.

4.2 Travel Cost Based Market Areas

Due to limited data on travel cost, travel time was used to implement this approach. Using ArcView 3.2, market areas for park and ride facilities in Columbus, Ohio were delineated according to this approach. However, this approach cannot be readily applied using GIS software. The reason is that there are a large number of centroids (census block centroids represent users) in the vicinity of the park-and-ride lots as well as a relatively large number of park-and-ride facilities involved. This entails performing the same GIS functions repeatedly (such as finding the shortest path between each centroid in a market area and a park-and-ride facility), which would be very time-consuming. Therefore, an Avenue script was developed to automate this procedure. The script starts by producing tentative market areas. Then, it refines such market areas based on the procedure described in Section 2.2. Figure 7 shows the resulting market areas after executing the developed script.

4.3 Market Areas According to the Developed Approach

The procedure described in Section 3 was implemented using ArcView 3.2. For each park and ride facility, a tentative market area was identified using the service area function in ArcView Network Analyst by selecting census block centroids (centroids represent users) with $t_{ip} \leq 5$ minutes of travel time. The tentative market area was created for practical reasons so that centroids in close proximity to the facility are examined for inclusion/exclusion, i.e. rather than examining all the centroids in the urban area.

Then, in order to determine whether the facility is in the user’s travel direction, the location of the major activity center relative to the facility was determined first. This was achieved by measuring $\delta$ (see Figure 3) for each
park and ride facility. That is, \( \delta \) was measured from the horizontal to a line theme that represents travel direction at the park and ride facility.

To calculate the orientation, \( \alpha \), of each centorid relative to the facility, a unique \( x'-y' \) coordinate system was constructed based on the line theme, where the \( x' \)-axis is a result of rotating the line theme by 90° counterclockwise. Then, as described in Section 3, the market areas were delineated by excluding the centroids from the tentative market area if the facility is not the user’s travel direction (i.e. \( 180 < \alpha < 360 \) and \( t_{ip} > 1 \) minute (the backtrack time (\( BT \)) was assumed to be 1 minute (19)). \( t_{ip} \) was calculated using the shortest path functionality in ArcView.

There are two issues to consider when attempting to operationalize this procedure. First, some of the functions needed were not available in ArcView. For example, there is no readily available functionality in ArcView to determine whether the park and ride facility is in the user’s travel direction (which entails establishing a unique \( x'-y' \) coordinate system for each park and ride facility, calculating the user orientation (\( \alpha \)), etc.). Second, the available functions in ArcView, such as “calculating shortest path,” were not practical to perform without automation, given the great amount of repetition needed. Therefore, there was a need to program the procedure above such that new functionality is created and the repetitive functions are automated. This was done in ArcView using the associated Avenue scripting language. Two Avenue scripts were written for this purpose. The first one delineates the market areas regardless of travel direction. The second script refines the market areas based on the user travel direction and backtrack time. Figure 8 summarizes the implementation procedure and Figure 9 shows the resultant market areas.

5. COMPARISON BETWEEN MARKET AREA DELINEATION APPROACHES

Two different ways are presented to compare the developed approach with the parabolic shaped and the travel cost market area delineation approaches. That is, based on geometric/spatial comparison as well as regression analysis, it is shown that the developed approach results in a more realistic representation of market areas than the two commonly used approaches.

5.1 Geometric/Spatial Comparison

A geometric/spatial comparison is helpful to show that the developed approach is an improvement over the existing approaches. As Figure 10 shows, the developed approach and the travel cost approach are more realistic than the parabolic shaped approach in terms of the shape of the market area. The reason is that, unlike the parabolic shaped approach, these approaches account for the influence of spatial features (represented by a natural barrier shown in Fig 10.a). That is, according to the developed approach and the travel cost approach (shown in Figure 10.c and 10.d), user B would not be included in the tentative market area because of their need to travel for an unreasonably long time, \( t_{BP} \) around the natural barrier to reach the facility \( P \). This is not captured by the parabolic shaped approach because the only criterion used for inclusion is whether the user is within the boundary of the parabola (i.e. regardless of accessibility considerations).

It could be shown from Figure 10 that the developed approach is better than the travel cost approach as well. As Figure 10.d shows, unlike the travel cost approach (Fig 10.c), the developed approach explicitly considers the fact that users are likely to use the park and ride facility if it is in their travel direction. Consider user A in Figure 10.c. A possible situation is that such a user has a disadvantage in terms of travel time if they use the facility (i.e. \( t_{Am} < t_{AP} + t_{PA} \)). According to the travel cost approach, such a user would be excluded from the market area. However, as Figure 10.d shows, the developed approach would still include such a user because it may be still appealing to such a user to use the facility, i.e. due to the fact that the facility is in their travel direction. In other words, as shown in Figure 10.d, user A would be still included in the market area because \( 0 \leq \alpha \leq 180 \).

In summary, the above comparison showed that the developed approach performs better than the parabolic shaped and travel cost approaches in delineating park and ride market areas.

5.2 Comparison Using Regression Analysis

In addition to the geometric comparison above, we suggest that the coefficient of determination (\( R^2 \)) be used to compare between market area delineation approaches. In the following we show why \( R^2 \) is an appropriate measure.
When performing regression analysis, $R^2$ represents how well the independent variables explain the variability in the dependent variable (20). There are two issues to consider when attempting to explain variability in the dependent variable: the analyst should find promising independent variables to explain as much variation as possible in the dependent variable, and such independent variables should capture reality as much as possible. Although the first issue is important, we are concerned with the second one in this section. If the analyst finds the “right” independent variables, the issue becomes of how to represent them accurately. This is important because even if the “right” independent variables were identified, they would not have an explanatory power (i.e. low $R^2$) if they do not accurately capture the “true” independent variables. To represent the independent variables accurately, market areas have to be delineated such that they are as close as possible to the “true” market areas.

To illustrate, consider “number of people in the market area” as an independent variable to help explain the variability in the utilization of park and ride facilities. This variable is logical to consider because the more populous the market area the more likely commuters would use the park and ride facility. The hypothetical situation depicted in Figure 10.a suggests that the park and ride facility is more accessible to the users on the left side of the natural barrier than to those on the right. For example, even though users A and B seem to have an equally good accessibility to the facility, user B needs to travel for a much longer distance to reach to the facility than user A does. Unlike the market area shown in Figure 10.b, the way the market area is delineated in Figure 10.d reflects this. That is, the users who are not likely to use the lot, due to poor accessibility, are excluded, such as user B.

Therefore, it is fair to say that the market area shown in Figure 10.d results in better representation of the independent variable than in Figure 10.b, because it excludes unlikely users. If the “number of people in the market area” variable is indeed important, the accuracy of representation is likely to result in better explanation of the variation in the dependent variable, and hence a higher $R^2$. Therefore, it seems logical to use $R^2$ as a measure to compare between different market area approaches, because the better the market area is delineated the more accurately the independent variables are measured, and therefore the higher the $R^2$.

5.2.1 Summary of Regression Results
Multivariate regression analysis was performed and is summarized here, but described in detail in another paper. Before performing regression analysis, correlation analysis among independent variables was done, and the variables that have high correlation with each other were not all included in the regression equation.

Having done correlation analysis, multivariate regression was run for each one of the market area delineation methods. The dependent variable, percentage of utilization at park-and-ride facilities, was regressed on a number of independent variables, such as the percentage of residential landuse in the market area, proximity of park-and-ride facilities to freeways, and percentage of households in the market area with one or more vehicles. Table 1 represents the overall results for each of the market area delineation methods.

From Table 1, the developed approach for delineating market areas has shown to be the most appropriate, both in terms of $R^2$ and the number of statistically significant explanatory variables. That is, the suggested approach resulted in the highest $R^2$ (0.58). It also resulted in a larger number of significant variables than the parabolic shaped as well as the travel cost approaches.

6. DISCUSSION AND CONCLUSIONS
Park and ride services are considered an integral component of many public transport systems in the United States. Planning for such services is important so that as many single occupancy vehicle users as possible are attracted to such services. An important step when planning for park and ride services is market area delineation. This paper has examined existing market area delineation approaches and developed a new approach for delineating such areas. In addition, this paper has suggested ways to evaluate different market area delineation approaches.

Existing market area delineation approaches are either inadequate or are very difficult to obtain data for. Approaches that assume a certain shape for the market area do not fully consider accessibility issues. Approaches that use travel cost to delineate market areas do not explicitly consider travel direction. The developed approach has considered these issues simultaneously. Although GIS can be used to delineate market areas, such areas are generic and do not reflect the special nature of park and ride market areas. The developed approach extended the capabilities of GIS where park and ride market areas can be readily delineated. This new GIS capability could be used to delineate market areas according to the new approach as well as to the existing approaches.

It was shown in two different ways that the suggested approach results in a better delineation of market areas compared to the existing approaches. Firstly, the new approach was compared to the existing approaches
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based on geometric and spatial characteristics of the market areas. Secondly, regression analysis was used to evaluate the different approaches.

Research is still needed to improve the methods of delineating market areas. That is, in addition to factors, such as travel time/cost and direction, there is still a need to explore other factors so that market areas are better delineated. This would result in better planning for park-and-ride services, which would lead to more utilized public transportation systems.

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FIGURE 2  Parabolic market area definition.
FIGURE 3  User and park and ride facility orientation according to the developed approach.
Determine the location of the major activity center relative to the park and ride facility

Establish an x’, y’ coordinate system for the park and ride facility

Based on the x’, y’ coordinate system, determine the orientation of the park and ride facility user

Based on the orientation, assess whether the park and ride facility is in the user’s travel direction

Location of park and ride facility

Location of major activity center

Location of users around the park and ride facility

FIGURE 4 User orientation determination.
FIGURE 5  Park and ride facilities in Columbus, Ohio.
FIGURE 6  Parabolic market areas.
FIGURE 7: Market areas according to the travel cost approach.
Create a tentative market area $MA_v$ for each park and ride

Determine the travel direction at each park and ride facility

Specify an $x'$-$y'$ coordinate system for each park-and-ride facility based on travel

Determine the orientation of the users in $MA_v$ relative to the $x'$-$y'$ coordinate system

Divide $MA_v$ into upstream ($MA_{US}$) and downstream ($MA_{DS}$) areas based on the $x'$-

Refine $MA_v$ by excluding the users that are in $MA_{DS}$ and beyond tolerable backtrack

**FIGURE 8:** Market area delineation according to the developed approach.
FIGURE 9: Market area delineation using the new approach.
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FIGURE 10: Alternative market area boundaries.

a) Hypothetical situation

b) Parabolic shaped approach

c) Travel cost approach

d) Developed approach
### TABLE 1  Multivariate Regression Results for the Three Approaches

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<thead>
<tr>
<th>Variable</th>
<th>Developed Approach</th>
<th></th>
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<th>Parabolic shaped approach</th>
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