Estimating Transit Accessibility with an Alternative Method

Evidence from Broward County, Florida

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Scientists have attempted to measure accessibility in several ways—the gravity-based measure being the most widely used. A typical gravity-based model estimates accessibility on a zonal basis as being a function of the sum of total opportunities weighted by the distance, time, and cost needed to travel from the origin zone to those dispersed opportunities. The model includes a parameter that represents the distance–decay relationship and takes an exponential form. Unfortunately, most scientists have arbitrarily chosen the value of the distance–decay parameter instead of estimating it from field survey data. Also, a typical model does not have any parameter attached to the socioeconomic variables. This study uses distance–decay parameters estimated with the use of survey data in Sacramento County, California, to estimate transit accessibility to jobs in Broward County, Florida. Assuming that transferability of distance–decay parameters is possible from one geographic area to another, it then explores such transferability of parameters from Sacramento County to Broward County by analyzing the spatial distribution of transit accessibility and compares the effectiveness of estimated transit accessibility with the traditional transit accessibility measure—proportion of a geographic unit covered by ¼-mi buffer from a transit route. Results indicate that accessibility indices estimated by using the method presented in this paper reflect what one would expect in reality—much better than what a simple ¼-mi transit buffer would produce. The paper explores the fact that the distance–decay parameters estimated in one geographic unit are transferable to another. It advances knowledge of the accessibility measuring method that would help solve long-standing debate on what parameters to use for distance–decay and socioeconomic variables going into the accessibility model. Future research needs to focus on validating such transferability of distance–decay parameters from one study area to another.

Accessibility is one of the most widely used terms in urban and regional planning, urban economics, geography, and transportation planning. Scientists of planning, economics, and geography have treated accessibility in different ways. Despite its importance and overwhelming use in local, regional, and national analysis of spatial patterns, the meaning of accessibility remains unclear because of the absence of a clear-cut definition (*1, 2*). Hanson defines accessibility as the "number of opportunities . . . available within a certain distance or travel time" (*3,* p. 4). It is the ease and convenience of access to spatially distributed opportunities with a choice of travel. Unfortunately, it is not easy to quantify the ease and convenience of access.

The objectives of this paper are threefold: (*a*) introduce an alternative method of estimating transit accessibility indices by using estimated distance–decay parameters, (*b*) explore the possibility of transferring distance–decay parameters from one geographic unit to another by analyzing the spatial distribution of transit accessibility, and (*c*) compare the effectiveness of estimated transit accessibility with the traditional transit accessibility measure—proportion of a geographic unit covered by ¼-mi buffer from a transit line. This paper uses distance–decay parameters calculated with the use of Sacramento County, California, data to estimate accessibility indices of traffic analysis zones (TAZs) in Broward County, Florida. It proposes a transit accessibility function that has a vector of empirically derived attraction variables and another vector of empirically derived transit impedance variables.

REPRESENTATIVE DEFINITIONS OF TRANSPORTATION ACCESSIBILITY

Accessibility is an indicator of potential spatial interaction. It is the ease with which spatially distributed opportunities may be reached from a specific place (hence, the origin) by means of a particular transportation system (*4–6*). This definition includes the place of origin, distribution of opportunities over space, and the means to reach those opportunities. Hansen defines accessibility as the potential of opportunities for interaction (*7*). He proposes that "the accessibility at point 1 to a particular type of activity (say employment) at area 2 is directly proportional to the size of the activity (number of jobs) at area 2 and inversely proportional to some function of the distance separating point 1 from area 2" (*7,* p. 73).

Accessibility can be of place or zone and person or individual. Accessibility of places/zones is defined as how easily certain places/zones can be reached; accessibility of people is defined as how easily a person or a group of people can reach activity sites. The zonal level definitions assume that all individuals inside a zone experience the same set of opportunities and that these definitions clearly neglect the distribution of activity sites in a zone. The zonal level definition of accessibility also neglects different levels of accessibility to transportation modes experienced by different individuals within a zone, which causes differing abilities of different people to reach the activity sites. In contrast, the individual-level accessibility measure makes it possible to generate measures of the traveler's accessibility to opportunities from home and the workplace (*8*).

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Accessibility has also been defined in regard to transportation options or other personal constraints. Mobility is a critical component of accessibility, and accessibility extends the concept of mobility a step further by incorporating information on the structure of networks and relative locations (*9, 10*). If two people are living in the same residential location, but one has an automobile and the other does not, it is likely that their accessibility to opportunities will be different.

Accessibility could be divided as relative accessibility between two points and integral or total accessibility at a point. Relative accessibility is the ease of accessing one point from another on the same surface, that is, the degree of interaction between two points on the same surface (*4*). However, the relative accessibility of two points in relation to each other on the same surface may not be equal in intensity. The integral accessibility of a place or point is defined as the degree of interaction with all other points on the same surface. It is, however, dependent on several relative accessibilities of a place, and it can be interpreted as an integration of the relative accessibilities over all places (*7, 11*).

Accessibility could also be categorized as trip-based accessibility (TBA) and activity-based accessibility (ABA). TBA considers one trip type at a time while ignoring scheduling and trip chaining. Trip type could include recreation trip, work trip, and shopping trip. ABA, in contrast, takes into account all activities a person is performing every day and the constraints to engage in those activities, scheduling, and chaining (*12*).

Apart from the above, a handful of scientists have dealt with the accessibility issue. Most use the established and early developed definitions of accessibility with some modifications for their research purpose as needed. The basic concept of accessibility, however, remains unchanged in those studies.

MEASURING TRANSPORTATION ACCESSIBILITY: A BRIEF OVERVIEW

Measuring accessibility has proved to be a daunting task. Transportation planners have approached this challenge in several different ways. Four major ways of measuring accessibility exist: (*a*) distance-based measure of accessibility (DBMA), (*b*) cumulative opportunities measure of accessibility (COMA), (*c*) utility-based measure of accessibility (UBMA), and (*d*) gravity-based measure of accessibility (GBMA). COMA is also known as isochronal measure of accessibility.

DBMA involves only the distance to and from an origin and destination of a trip or a transit station. Many transit planners, for instance, use a ¼-mi buffer around a transit stop, sometimes measured as the crow flies but occasionally refined to reflect true walking distance. They designate locations that lie within the buffer as having access to transit, and those outside as lacking transit access. In most metropolitan areas, this approach leaves very little territory outside the buffer. Gurmu, Ihlanfeldt, and Smith (*13*), Sanchez (*14*), and Sawicki and Moody (*15*) take this approach to measuring access to transit. DBMA also uses the average travel time to work from an origin zone (*16*). If travel time is greater, residents of the zone are disadvantaged in regard to access. But there is some difficulty interpreting this measure. A longer travel time could be a function of a large percentage of residents in the zone using transit, as opposed to jobs being located farther away (*17*).

In COMA an isochron is drawn around a zone, such as a line representing a 25- or 30-min travel time. Opportunities that lie inside the isochron are considered accessible and those lying outside are considered inaccessible (*18, 19*). A simple COMA can be expressed by Equation 1:

$$\text{COMA}_i = \sum_j X_j O_j \tag{1}$$

where

COMA_i = cumulative opportunities measure of accessibility index of zone i to be estimated,
O_j = opportunities such as employment in zone j,
X_j = 0 if $r_{ij} > r^*_{ij}$ and 1 otherwise,
r_{ij} = resistance or friction between zones i and j, and
r^*_{ij} = isochron radius such as 30-min search boundary within which the opportunities are enumerated.

It is easy to estimate the accessibility indices using a COMA approach, and it is easy to understand. However, the size of the job search radius sensitively affects the accessibility indices. The main part of the calibration of COMA is the choice of a cutoff travel distance or time (*20*). COMA represents a specific type of GBMA, with resistance function equal to zero if the opportunity is outside the job search radius, and one otherwise.

UBMA is grounded in random utility theory that explains that consumers (people) choose the best utility alternative, that is, the one attached to the highest utility (*21–23*). It is derived from the calibration of destination choice models. It is assumed that the probability of an individual making a particular choice depends on the utility of that choice relative to the utility of all choices (*20*). Based on the assumptions that travelers assign utility to each destination and mode choice on the basis of their preferences followed by choosing the best alternative that maximizes their utility, the UBMA approach defines the accessibility index as the logsum, that is, the denominator of the multinomial logit model shown in Equation 2 (*12, 24*):

$$\text{UBMA}_i = \ln\left\{\sum_{\forall \in C_i} \exp\left(A_{i(c)}\right)\right\} \tag{2}$$

where

UBMA_i = utility-based measure of accessibility index of an individual i,
$A_{i(c)}$ = observable alternative components of utility of choice c for person i, and
C_i = choice set for person i.

The strength of a UBMA approach shown by Equation 2 is that it includes a person's tastes or utilities according to her or his preferences (*2*), attributes or characteristics of travel destinations, and characteristics of travel resistance or friction to be overcome to reach the destination (*20*).

GBMA, however, provides a more realistic approach to measuring accessibility. Equation 3 presents a simple GBMA model:

$$\text{GBMA}_i = \sum_{j=1}^{n} \frac{O_j}{r_{ij}^b} \tag{3}$$

where

GBMA_i = gravity-based accessibility in zone i,
O_j = employment in zone j,
r_{ij} = travel time or distance or cost between zones i and j (there are n zones), and
b = parameter to be estimated.

This formulation calculates accessibility on a zonal basis, as being a function of the sum of total opportunities weighted by the distance or time needed to travel from the origin zone to those dispersed opportunities (*2, 25*). The formula includes a parameter that represents the distance–decay relationship. Hansen, the first scientist to introduce GBMA, explores on the basis of different empirical examinations that the distance function should be of exponential character, that is, the measurement of distance between different areas (points) should be raised to some power (*7*). Shen argues that there are limitations in the traditional Hansen-type gravity models because the nonuniform spatial distribution of demand is not taken into account by this model (*26*).

NATURE OF DISTANCE–DECAY PARAMETERS AND THEIR ESTIMATION

Typically, one of two approaches has been taken to estimate the parameter value for the travel impedance function in a gravity-based model, with the first approach being by far the most common. The first approach involves the assignment of an arbitrary value to the parameter. Sanchez (*14*), Shen and Sanchez (*27*), and Thompson (*28, 29*) take that approach. However, the approach is flawed because the parameter is not based on empirical data, but instead is arbitrarily defined by the researcher. The measure of accessibility changes as the value of the parameter changes—thus there is the potential for widely varying accessibility results depending on the parameter value selected. However, in the absence of other empirical data, this approach still yields more realistic results than three other approaches to measuring accessibility discussed earlier: DBMA, COMA, and UBMA.

The second approach is to estimate the parameter with the use of other survey data. Isard explores the fact that the distance–decay component of a gravity-based accessibility function is the same concept as the distance–decay component in a gravity-based demand model (*30*). Thus the distance–decay parameter of a direct demand model can be used as the distance–decay parameter of the gravity-based accessibility equation. Isard's direct demand model states that the number of trips made by travelers from an origin to a destination is a function of the number of travelers living in the origin subarea multiplied by the population in the destination subarea discounted by the friction factor between the origin and destination (*30*). The friction may be the time required to travel from the origin to destination, distance between the origin and destination, or cost of travel from the origin to the destination.

On the basis of this concept of Isard's (*30*), Thompson (*28, 31*) and Raphael (*32*) derive their gravity model parameters from direct-demand models estimated from onboard survey data of transit users. When the parameter is estimated from onboard survey data, it reflects how people actually perceive the friction associated with travel time or cost or distance and thereby removes the arbitrary nature of the parameter (*31*). Thompson's (*28, 31*) access measures are similar to Raphael's with a couple of key distinctions. First, Thompson's expression of the transit accessibility function was a linear combination of several different variables, including door-to-door transit travel time, door-to-door highway travel time, and physical distance between census tracts. A further refinement over Raphael (*32*) is that Thompson's (*28, 31*) attraction variable represents more than just employment, which is the standard approach. He includes a parameter that weights employment on the basis of how important it is to the user and also includes other variables that may be important to the transit user, including density and a dummy variable representing the central business district. Other scientists, however, have estimated the distance–decay parameter by using other methods as well, for example, the binomial count model derived from 1990 Census Transportation Planning Package commuting data (*33*).

Kawabata (*34*) and Sanchez, Shen, and Peng (*35*), drawing on Shen (*26, 36*), use a gravity formulation based on labor market theory. The attractions represent surplus jobs or job growth. These are the open jobs available to individuals who are seeking employment. However, their measure of accessibility is problematic. Their measure of zonal attraction, which is employment, has no parameter attached to it. Their measure of transit impedance is defined as transit time, but the type of transit travel time is not defined, nor is the method for estimating the parameter described. There are many types of transit time: line haul time, walking time, and door-to-door time, to name a few. Door-to-door time, in turn, is made up of several components, each of which is typically given a different weight. The Quick Response System of demand modeling provides recommendations for such weights (*37*).

ESTIMATION OF TRANSIT ACCESSIBILITY

The transit accessibility variable (TA_i) estimated and analyzed in this study is derived from a gravity model predicting transit patronage. The model shown by Equations 4 and 5, estimated from an onboard survey of bus riders in Sacramento, California, reflects transit user preferences, including the types of destinations that are important to them, the "attractions" that those destinations have to the riders, and the degree to which length of travel, measured in time and distance, works against that "attraction" (*25, 28, 32*). The general model, shown in Equation 4, predicts transit usage between two neighborhoods as a product of the variables producing transit trips in the origination neighborhood, variables attracting transit trips in the destination neighborhood (the ATTRACTION), and variables describing friction (the FRICTION) between two neighborhoods.

$$T_{ij} = \left(\mathrm{PDN}_i^p\right) * \left(\mathrm{ATN}_j^a\right) * \left(F_{ij}^f\right) \tag{4}$$

where

T_{ij} = transit trips between neighborhoods i and j,
PDN_i = vector of transit trip production variables and their estimated parameters in neighborhood i,
ATN_j = vector of transit trip attraction (the ATTRACTION) variables and their parameters in neighborhood j,
F_{ij} = vector of friction (the FRICTION) variables and their parameters that transit users encounter when traveling between i and j, and
p, a, and f = vectors of parameters to be estimated.

The accessibility index is created from Equation 4 by summing the equation over all n neighborhoods in the region. That is shown in Equation 5.

$$\sum_{j=1}^{n} T_{ij} = P_i = \left(\mathrm{PDN}_i^p\right) * \sum_{j=1}^{n}\left[\left(\mathrm{ATN}_j^a\right) * \left(F_{ij}^f\right)\right] \tag{5}$$

Equation 5 states that transit trips produced in neighborhood i (denoted as P_i) are the potential for neighborhood i to produce trips [denoted as (PDN_i^p)] multiplied by the transit accessibility of neighborhood i to all destinations in the region. That is shown as TA_{ij} in Equation 6.

$$TA_{ij} = \sum_{j=1}^{n} \left[\left(ATTRACTION_j^a \right) * \left(FRICTION_{ij}^f \right) \right] \quad (6)$$

Equation 6 is the specification of the accessibility index used in this paper. It has the general form of Equation 3 shown earlier. Each of the vectors of variables shown in Equation 6 corresponds to a variable in Equation 3. The parameter vector f in Equation 6 corresponds to the parameter b in Equation 3. Equation 3 has no parameter for the employment variable, but Equation 6 has a vector of parameters, a, to be estimated for the attraction variables. The a and f vector parameters were estimated with the use of origin–destination (O-D) survey data and Equation 5. The use of such estimated exponential parameters addresses the arbitrary selection of an exponential factor in the accessibility equation used by earlier studies.

The vectors of variables used to specify $ATTRACTION_j$ and $FRICTION_{ij}$ are shown in Table 1. These are variables that were used in an earlier study in Sacramento, California (*28*). Ideally, this study should have calculated all parameters associated with different variables used in the gravity-based accessibility model by using the onboard (O-D) survey of the study area. Unfortunately, Broward County does not have the recent record of the onboard survey that could be used for this study. Therefore, the study uses the calculated values of exponential distance–decay parameters of the Sacramento study by Thompson (*28*). By doing so, the study overcomes the weakness of Thompson (*29*) and Sanchez (*14, 18*) in that they used −2 as an arbitrary value of the distance–decay parameter of transit travel time.

Table 1 also shows the parameters that were estimated for each variable in that study. Each parameter reflects how important that variable is to transit users. Generally the table shows that transit friction between two zones is increased by greater distance between the zones (HDIS) and by longer door-to-door transit travel times between the zones (TTIM). However, with longer highway times (HTIM), because of, for example, the absence of freeways in paths connecting the zones, transit friction is reduced. The table also shows that the attractiveness of a zone for transit patrons is increased if it has more jobs, more job density, and more population density. If the zone lies in a central business district (CBD) or on the edge of a CBD, it also is more attractive than other zones, presumably because parking fees make auto use less attractive.

In the calculation of accessibility indices of different geographic areas, previous studies on this topic considered transit travel time as the only friction variable (*14, 18, 29*). In contrast, this paper introduces a more comprehensive way of calculating accessibility indices, incorporating transit travel time, highway travel time, and highway distance from each TAZ to all other TAZs as the friction variables. The source for the transport-related frictional variables was the output from the 2000 network of the Broward County Metropolitan Planning Organization urban transportation modeling database. Florida Standard Urban Transportation Modeling Systems Version 4 (FSUTMS v.4) Transportation Network Model with the year 2000 Alternative Data of Broward County was run to obtain the values of the above-mentioned variables.

However, FSUTMS v.4 model output does not provide transit travel time per se as the result. Rather, it produces data on door-to-bus-stop walk time in the origin zone, wait time at the bus stop, in-vehicle travel time, transfer time from one route to another, bus-stop-to-door walk time in the destination zone, HTIM, and HDIS. The first five variables were used to estimate TTIM. Components of TTIM were abstracted from the shortest transit path between each pair of TAZs and the applied default weights recommended for Quick Response System modeling (*37*). For paths in which transfers were involved, the paper used a penalty of 23 min, recommended for untimed transfers in Horowitz (*37*), because transfers are untimed in Broward County. However, FSUTMS does not produce any of these variables in organized or sorted form. So a computer program, consisting of several subprograms was written using C++ language to read the data, organize them, and calculate TTIM. This process yielded the TTIM between each pair of TAZs. The formula that was used to estimate TTIM is given by Equation 7 (*38*).

$$\begin{aligned} TTIM = {} & 1.3 * \text{walk time} + 0.95 * \text{wait time} \\ & + \text{8.4-min wait time penalty} + 0.8 * \text{transfer time} \\ & + \text{transfer penalty of 23 min for untimed transfer and} \\ & \text{12 min for timed transfer} + \text{in-vehicle travel time} \end{aligned} \quad (7)$$

Of 932 TAZs in Broward County, 40 are external. External TAZs are connected to the outside world. There is no household information for these TAZs. Therefore, they were excluded from the database.

TABLE 1 Variables Entering into Evaluation of Transit Accessibility Index for Zone *i*

Explanatory Variable	Description	Estimated Parameter	*t*-Statistic
Vector of Variables Entering into Transit Friction Between Zones *i* and *j*			
TTIM	Door-to-door transit time between zones *i* and *j*	−0.006067	−5.12
HTIM	Door-to-door highway time between zones *i* and *j*	0.122780	5.91
HDIS	Door-to-door highway distance between zones *i* and *j*	−0.250210	−7.05
Vector of Variables Entering into Attractiveness of Zone *j* for Transit Trips			
DPOP	Population of destination zone *j*	0.000008	2.88
DPOPDEN	Population density of destination zone	0.036496	0.91
DJOBS	Number of jobs in destination zone	0.000058	7.55
DJOBDEN	Job density in destination zone	0.036647	8.46
DSPLIT	Percentage of destination zone within ¼ mi of bus stop	0.013648	6.11
DDTN	Dummy variable indicating zone on edge of CBD, 1 = yes; 0 = no	0.324140	3.15
DCBD	Dummy variable indicating CBD zone, 1 = yes; 0 = no	0.372820	2.20

SOURCE: Adapted from Thompson (*28*), Table 4, Run 3.

Once TTIM was estimated, it was used as one of three transportation measures to calculate the accessibility indices of 892 internal county TAZs. In addition to transportation measures, the methodology for accessibility indices estimation of this research includes seven socioeconomic attributes of destination TAZs. It is unlike other existing studies that use the number of jobs in the destination zone as the sole socioeconomic attribute (*14, 18, 29*). The socioeconomic variables come from the ZDATA2 file of the Broward County Transportation Modeling Database; the data in the ZDATA2 table are abstracted from the Census 2000 database. As mentioned above, FSUTMS output produces raw data in fragmented matrices that are unusable in any statistical software package. The raw data are also not printable because they are huge. Therefore, similar to in the estimation of TTIM from its components, a computer program was written to read and tabulate the values of three frictional variables—TTIM, HTIM, and HDIS—from each TAZ to each of the other TAZs of the county, and another program was written to read the socioeconomic data from the ZDATA2 file. Last, the final program was written to estimate the accessibility indices of each TAZ. The program was written in such a way so that the transit accessibility indices (TA_{ij}) from each TAZ to each other TAZ were estimated first as shown by Equation 6. Then the accessibility indices from one specific TAZ i to all 892 TAZs were added to get its comprehensive accessibility index, TA_i, as shown by Equation 8. All computer programs used in this study were combined and run together at one time.

$$\mathrm{TA}_i = \sum_{j=1}^{n} \mathrm{TA}_{ij} \qquad (8)$$

where n equals 892 because there are 892 TAZs in Broward County, Florida.

TA_i estimation could be simplified by a small example. Say, there are only four TAZs in a county: TAZ 1, TAZ 2, TAZ 3, and TAZ 4. Their attributes are

$\mathrm{TTIM}_{11} = 0$, $\mathrm{TTIM}_{12} = 59.845$, $\mathrm{TTIM}_{13} = 63.665$, $\mathrm{TTIM}_{14} = 56.405$;
$\mathrm{HTIM}_{11} = 0$, $\mathrm{HTIM}_{12} = 2$, $\mathrm{HTIM}_{13} = 2$, $\mathrm{HTIM}_{14} = 2$;
$\mathrm{HDIS}_{11} = 0$, $\mathrm{HDIS}_{12} = 0.4$, $\mathrm{HDIS}_{13} = 0.7$, $\mathrm{HDIS}_{14} = 1$;
$\mathrm{POP}_1 = 1014$, $\mathrm{POP}_2 = 1712$, $\mathrm{POP}_3 = 0$, $\mathrm{POP}_4 = 1324$;
$\mathrm{POPDEN}_1 = 3.37$, $\mathrm{POPDEN}_2 = 3.05$, $\mathrm{POPDEN}_3 = 0$, $\mathrm{POPDEN}_4 = 3.32$;
$\mathrm{JOB}_1 = 424$, $\mathrm{JOB}_2 = 235$, $\mathrm{JOB}_3 = 6$, $\mathrm{JOB}_4 = 342$;
$\mathrm{JOBDEN}_1 = 1.41$, $\mathrm{JOBDEN}_2 = 0.42$, $\mathrm{JOBDEN}_3 = 0.02$, $\mathrm{JOBDEN}_4 = 0.86$;
$\mathrm{BUFFER}_1 = 61.81$, $\mathrm{BUFFER}_2 = 65.92$, $\mathrm{BUFFER}_3 = 47.29$, $\mathrm{BUFFER}_4 = 100$;
$\mathrm{CBD}_1 = 0$, $\mathrm{CBD}_2 = 0$, $\mathrm{CBD}_3 = 0$, $\mathrm{CBD}_4 = 0$; and
$\mathrm{DTN}_1 = 0$, $\mathrm{DTN}_2 = 0$, $\mathrm{DTN}_3 = 0$, and $\mathrm{DTN}_4 = 0$.

With these numbers plugged in Equation 6 and with the distance–decay parameters presented in Table 1, the transit accessibility to jobs of TAZ 1 over TAZ 4 could be estimated as shown below:

$$\mathrm{TA}_{14} = \left(\begin{array}{l} \left[\left(56.405^{-0.006067}\right) + \left(2^{0.122780}\right) + \left(1^{-0.250210}\right)\right] \\ \times \left[\left(1{,}324^{0.000008}\right) + \left(3.32^{0.036496}\right) + \left(342^{0.000058}\right)\right. \\ \left. + \left(0.86^{0.036647}\right) + \left(100^{0.013648}\right) + \left(0^{0.372820}\right) + \left(0^{0.324140}\right)\right] \end{array} \right)$$

$$\mathrm{TA}_{14} = 15.6436$$

Similarly, TA_{11}, TA_{12}, and TA_{13} are estimated as 0, 16.8407, and 9.2211. With the use of Equation 8, comprehensive transit accessibility to jobs (TA_i) of TAZ 1 over these four TAZs can be estimated as

$$\mathrm{TA}_1 = \sum_{j=1}^{4} \mathrm{TA}_{ij} = \sum_{j=1}^{4} \mathrm{TA}_{1j} = \mathrm{TA}_{11} + \mathrm{TA}_{12} + \mathrm{TA}_{13} + \mathrm{TA}_{14}$$
$$= 0 + 16.8407 + 9.2211 + 15.6436$$
$$\mathrm{TA}_1 = 41.7054$$

Originally, transit accessibility to service jobs, transit accessibility to commercial jobs, and transit accessibility to industrial jobs were estimated. However, paired correlation suggests the presence of multicollinearity among these three accessibility measures. Therefore, transit accessibility to service jobs was used as the proxy for the other two.

CASE STUDY: BROWARD COUNTY

Broward County, is bounded by West Palm Beach in the north, Miami–Dade County in the south, the Everglades in the west, and the Atlantic Ocean in the east. Following is a reflection on spatial setting and estimated transit accessibility to jobs in the study area.

Spatial Setting of Broward County

Figure 1 shows the locations of the CBD and downtown (DTN) TAZs and major transit routes in the study area. Ideally the CBD TAZs are contiguous and have the highest nonindustrial employment density in the region. They have high parking rates and little residential use. The downtowns are TAZs surrounding them. They also are contiguous and have lower employment density, but some of it might be industrial. Some downtown TAZs have a high population density. Parking is also expensive and/or restricted. However, for this research the CBDs and downtowns were selected in such a way that they reflect the impact of parking fees to a large extent. With the use of this rationale, any collections of TAZs with parking fees attached to them were considered as downtown TAZs, even if they are not contiguous to the CBDs. The CBD TAZs in Figure 1 are the hearts of the Fort Lauderdale metropolis. It is the place where the central terminal of Broward County is located and where more than 10 transit routes start/end. Figure 1 shows that all but three of the downtown TAZs are located in the eastern side of the county. Some of these surround the CBD TAZs, and others are in the north and south sides of the CBD. The figure further shows that there are no DTN or CBD TAZs in the southwest or middle-west sides of the county. The reason behind this is that the southwestern side as well as some parts of the midwestern side of the county and its adjacent counties are conservation areas.

Table 2 presents descriptive statistics of the independent variables (IVs) going into the accessibility index. It explores the fact that all the minimum values for all the IVs are zeros. The mean transit travel time (TTIM) from the centroid of a TAZ to another is nearly 1 h, and highway travel (HTIM) takes an average of only nearly 8 min. The average physical distance (HDIS) between the centroids is little more than 4.5 mi. The average of population density (DPOPDEN) and job density (DJOBDEN) is less than two per tenth hectare of

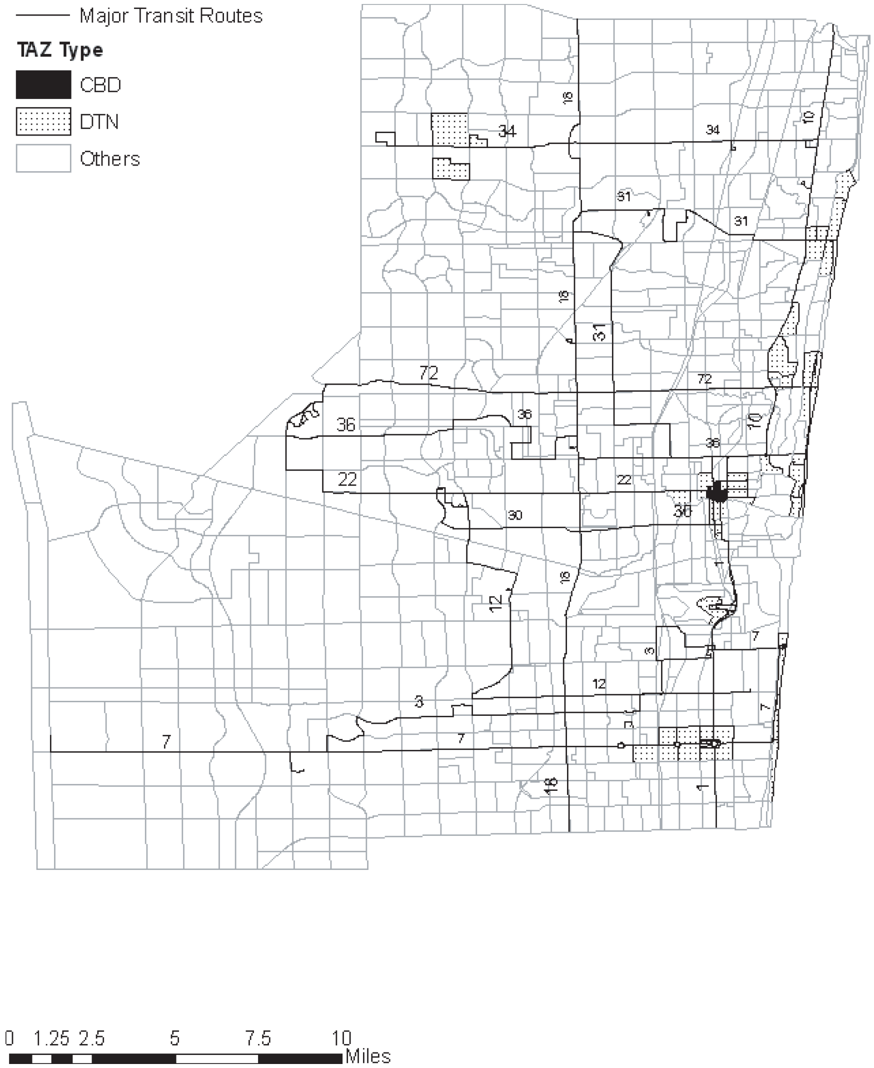

FIGURE 1 Spatial distribution of CBD, downtown, and major transit routes in Broward County.

TABLE 2 Descriptive Statistics of Independent Variables Going into Accessibility Indices

Variable	*N*	Range	Minimum	Maximum	Mean	SD
TTIM	892	132.225	0.000	132.225	51.388	50.110
HTIM	892	41.000	0.000	41.000	7.720	8.746
HDIS	892	28.100	0.000	28.100	4.583	5.498
DPOP	892	11,244.000	0.000	11,244.000	1,783.957	1,874.729
DPOPDEN	892	14.640	0.000	14.640	1.727	1.582
DJOBS	892	8,086.000	0.000	8,086.000	702.280	939.767
DJOBDEN	892	55.090	0.000	55.090	1.267	3.275
DSPLIT	892	100.000	0.000	100.000	65.177	33.912
DCBD	892	1.000	0.000	1.000	0.007	0.082
DDTN	892	1.000	0.000	1.000	0.059	0.237

NOTE: SD = standard deviation.

land. The mean transit coverage (DSPLIT) is more than 65%, indicating that most parts of the county are within the ¼-mi transit buffer. The variables DCBD and DDTN are dummy variables. The value of DCBD and DDTN is 1 when a TAZ is CBD or DTN; and 0 otherwise. The table shows that only 0.7% of the TAZs are categorized as CBDs and 5.9% as DDTN.

Spatial Pattern of Transit Accessibility to Jobs in Broward County

After the transit accessibility of each TAZ was estimated, the spatial distribution of transit accessibility was mapped and then the resulting pattern was compared with the transit route coverage, that is, the proportion of a TAZ covered by a ¼-mi buffer around a transit line. Figure 2 shows the spatial distribution of transit accessibility, as classified on the basis of "equal interval based on range" in the data. The figure shows that the areas with the highest transit accessibility are located in an east–west bulge in the center of the county and in north–south bands located several miles inland from the coast that run nearly the length of the county. The band with the highest levels of transit accessibility follows the approximate path of Broward County Transit Route 18. The minimum, maximum, mean, and standard deviation of transit accessibility to jobs are 0, 8507, 3063.02, and 2213.96, respectively.

Figure 2 also shows that the TAZs including and surrounding the CBDs have the highest accessibility indices. Some other TAZs through which a north–south and an east–west transit route pass also fall into this group. These routes provide transit services every 15 min and are highly efficient and effective. For example, the figure shows that the high-accessible TAZs make a sign like a cross (+) at the center of the county; that is, the result of the intersection of north–south Transit Route 18 with the east–west Transit Routes 22, 30, 36, and 72 at the center of the county. Transit Route 18 also intersects with east–west Routes 3, 7, and 12 in the south and with Routes 31 and 34 in the north of the county. The surrounding TAZs

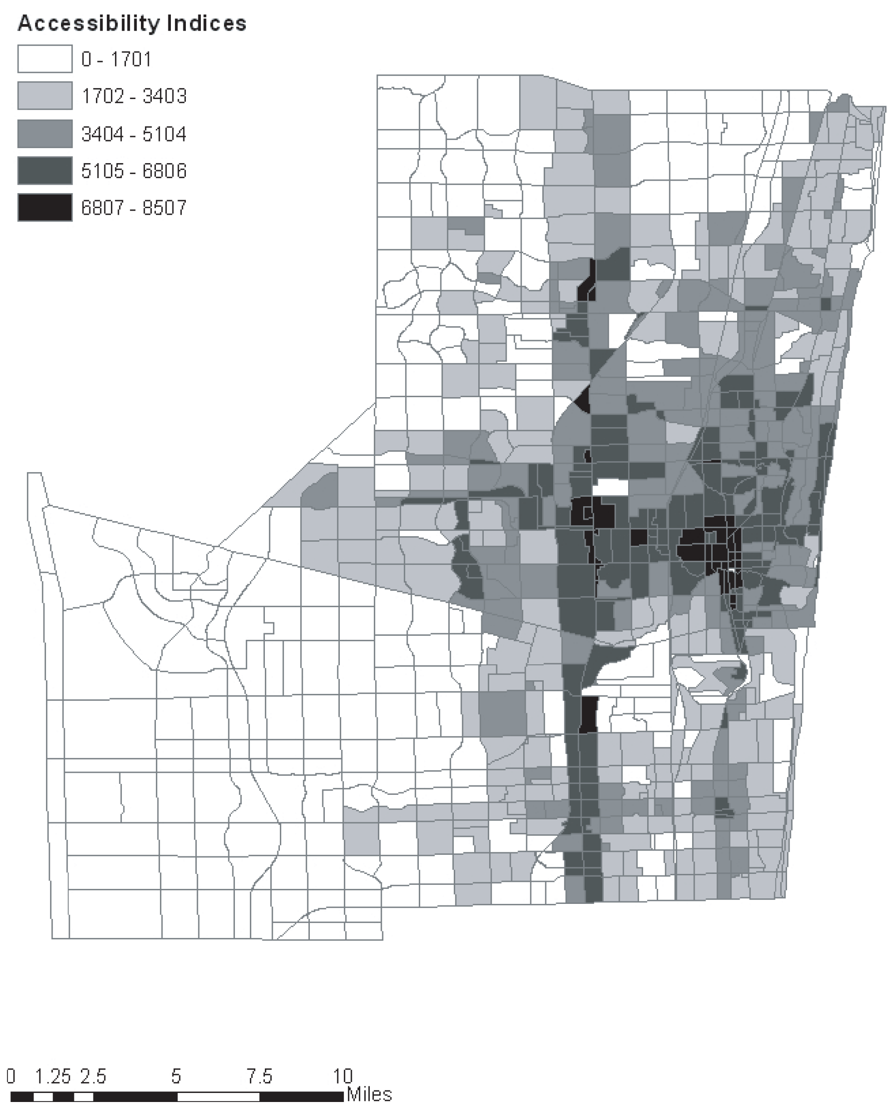

FIGURE 2 Transit accessibility to jobs in Broward County.

of the central TAZs have the second highest accessibility indices. North–south Routes 1 (in the southern part of Fort Lauderdale) and 10 (in the northern part of Fort Lauderdale) intersect with the above-mentioned east–west transit routes that help the respective TAZs to be associated with high transit accessibility.

Figure 2 explores the fact that the southwestern TAZs of the county have accessibility indices varying from 0 to 1,701, or the lowest of the five relative categories. The southwestern TAZs, which do not have transit route(s) passing through them, are associated with zero accessibility. Although it cannot be completely generalized, it can be assumed that to a large extent, the figure indicates that the accessibility indices decrease with the increase in distance from the CBD and downtown TAZs at the center. However, this hypothesis is not true for the middle and right side of the southern part of the county through which Routes 18 and 1 pass and which have high accessibility indices.

Figure 3 depicts the proportion of TAZs within ¼ mi of a surface street bus route, that is, the percentage of the total area of a TAZ that is covered by a ¼-mi buffer from the centerline of the transit routes. It is the traditional measure of transit accessibility (*13–15*). The figure shows that 85 (9.5%) TAZs have absolutely no transit coverage, 124 (13.9%) have less than 20% transit coverage, 391 (43.8%) have more than 80% transit coverage, and 177 (19.8%) have 100% transit coverage. It also reveals that 285 TAZs, equivalent to 31.9% of all TAZs, have less than 50% transit coverage. The figure further displays that the TAZs located in the middle-middle-eastern and southeastern parts have more transit coverage than the southwestern TAZs. Most of the southwestern TAZs do not have any transit coverage except those through which the transit routes run. The northwestern part of the county is also associated with no transit coverage at all; these TAZs do not have any transit routes as well. The smaller TAZs have more transit coverage than the bigger TAZs; ¼-mi distance from a transit route is more likely to cover a whole small TAZ but not a large one.

Because Figure 3 shows the transit accessibility indices estimated by the traditional ¼-mi buffer technique, it is important that

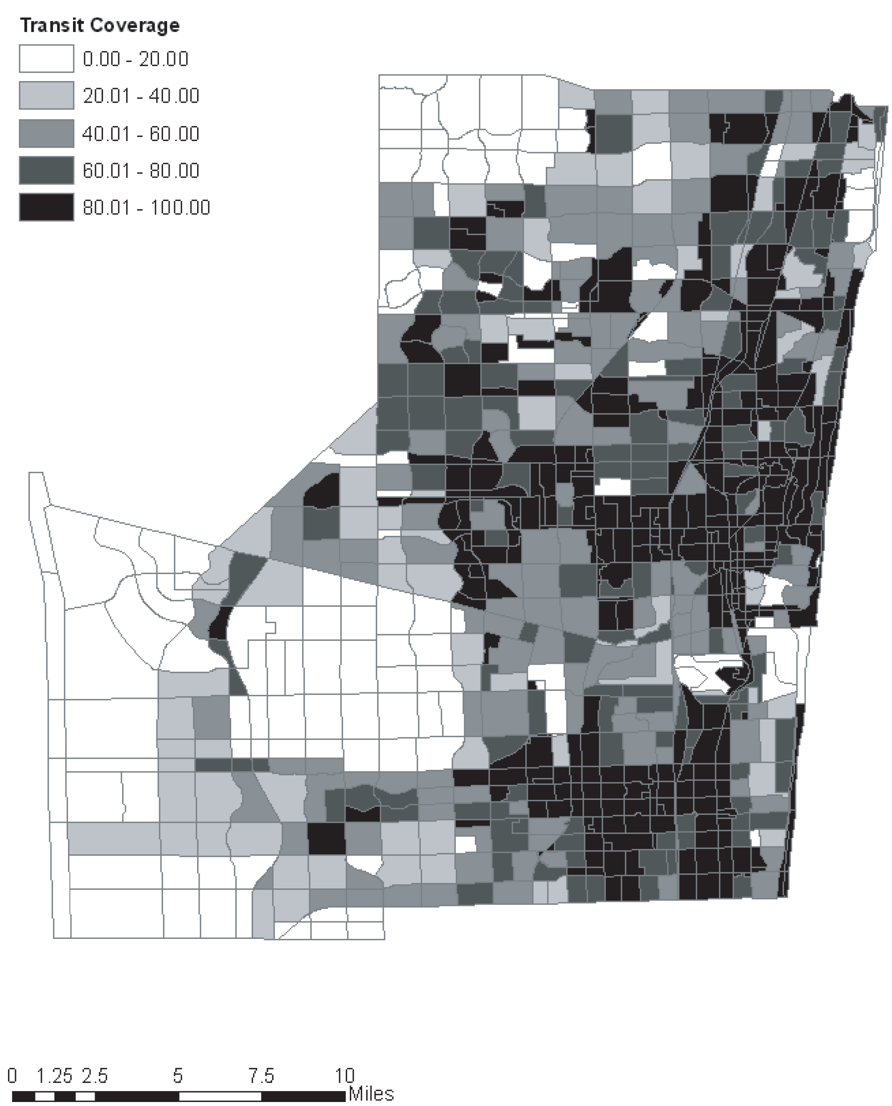

FIGURE 3 Transit route coverage in Broward County.

this figure be compared with Figure 2, which represents transit accessibility indices estimated by the approach presented in this paper. The areas shown to be highly transit accessible in Figure 2 differ considerably from the ¼-mi transit buffers shown in Figure 3. For example, many areas in the southeastern part of the county that lie within the transit buffer and would be considered accessible in Figure 3 are found to have very low levels of accessibility in Figure 2. Figure 3 shows that more TAZs are attached to very high transit accessibility indices than are shown by Figure 2. However, this depiction by Figure 3 is not correct because this figure is not prepared by using the attraction and friction variables needed to estimate transit accessibility indices. The pattern of accessibility in Figure 2 reflects the multidestination nature of the transit network. In a multidestination network, accessibility is dispersed, whereas in a radial network accessibility is concentrated at the center, where the routes converge.

A small TAZ may be fully covered by a ¼-mi transit buffer while not having any transit station in it or its neighboring TAZs. It may happen only because a transit line passes through the small TAZ. The TAZ may even have a transit station, but very long transit service frequency such as 1 or 2 h. Such a TAZ with high transit coverage but poor transit services is no better than a TAZ with low transit coverage but frequent/better transit service facilities. Transit coverage itself does not guarantee better transit service to its users. The comparison of Figures 2 and 3 establishes that physical coverage of a zone by transit route does not necessarily mean that it has a high accessibility index. Transit coverage is just one of the variables that play a role in the calculation of accessibility indices. If other variables going into the accessibility equation of a zone are not significant, the zone will not have high transit accessibility to jobs although it may be attached to high transit coverage. That is why a remarkable number of high transit coverage TAZs in Figure 3 do not have high transit accessibility to jobs indices depicted in Figure 2.

CONCLUSION

The use of GBMA is not easy despite its high level of popularity among planners, economists, and geographers. However, this paper presents an alternative GBMA that is based on the basic concept of the traditional gravity-based accessibility model (*7, 14, 18, 29*), yet takes into consideration other important factors ignored by traditional models. This method addresses the issue of arbitrarily assigning an exponential parameter value (−1 or −2) to a friction factor by means of estimated parameters from onboard travel survey data. It also assigns estimated parameters to socioeconomic variables, whereas traditional gravity-based models do not have parameters attached to such variables. The model presented in this paper includes three important variables related to friction between each of the TAZs and seven socioeconomic variables that typically attract people from an origin to a destination. The paper shows that accessibility indices calculated with the use of the presented model produce a better reflection of reality compared with traditional measures of accessibility—the proportion of TAZs covered by a ¼ mi of transit buffer, which is usually measured as the crow flies but occasionally represents true walking distance. One-fourth mile of transit coverage could cover 100% of a small TAZ, giving an impression that the TAZ has the highest level of transit accessibility. However, this notion is misleading because the transit service could be intermittent and it may not connect the TAZ to those variables attached to highly attractive job opportunities. The model presented in this paper addresses those issues. The paper explores the extent to which accessibility indices calculated by using the estimated parameters from onboard travel survey data produce what one would expect in a real-world scenario. It also explores the possibility of transferring estimated distance–decay parameters from one geographic unit to another, as in this case, Sacramento County, California, to Broward County, Florida. Future research needs to focus on validating such transferability of parameters.

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