Using GIS to Measure the Effect of Overlapping Service Areas on Passenger Boardings at Bus Stops

Thomas J. Kimpel, Kenneth J. Dueker, and Ahmed M. El-Geneidy

Abstract: *This study examines the effects of overlapping walking service areas of bus stops on the demand for bus transit. This requires controlling for variation in potential transit demand as measured by the number of dwelling units and their locations. A model of passenger boardings for the morning peak hour of service is estimated. Boardings are modeled as a function of potential transit demand at the level of the individual bus stop. To address overlapping bus stop service areas, a geographic information system is used to measure the accessibility of each parcel to each bus stop relative to other accessible stops. A distance decay function is empirically estimated and used to calculate walking accessibility from dwelling units to bus stops. This stop-level boarding model is an improvement over methods in which ridership is typically related to potential transit demand using one-quarter-mile service areas under the assumption of uniform density of demand, often with little or no consideration given to double counting.*

INTRODUCTION

This study examines the effects of overlapping bus stop service areas on the demand for transit at the bus stop level. Potential transit demand is measured at the most disaggregate level, in terms of the number of dwelling units per parcel of land. Transit supply is measured spatially at the individual bus stop, and temporally for the morning peak hour of service. A GIS-based approach is used to measure accessibility of dwellings at the parcel level to the nearest bus stop. The distance decay parameters of the accessibility function are empirically derived by varying intercept and slope values systematically using ordinary least-squares regression. Demand at the bus stop level, as measured by average morning peak hour boardings, is related by regression to a measure of accessibility-weighted dwelling units that controls for competing bus stops.

This examination of walking distance to bus stops focuses on potential transit demand from a residential standpoint using a measure of integral accessibility (Makri and Folkesson 1999, Song 1996). The study focuses on inbound radial routes in the morning peak time period serving close-in urban neighborhoods—a route type, service direction, and time period in which demand is primarily associated with residential boardings.

A one-quarter-mile walking distance is a well-known rule of thumb in transit service planning. In most instances, bus stops are spaced closer than a quarter mile, creating overlapping bus stop service areas on the same route. In many areas, parallel bus routes are spaced at distances less than one-half mile, creating overlapping service areas between routes that often operate at different service frequencies. To control for these overlapping service areas, a geographic information system (GIS) is used to measure the accessibility of each parcel to bus stops within walking distance and the integral accessibility of each bus stop to dwelling units within walking distance to the stop. Deriving and including distance decay parameters in the accessibility measure is an improvement over traditional methods in which ridership is related to potential transit demand by 1) intersecting census block groups with bus stop buffers and using areal interpolation to calculate population or 2) counting the number of housing units within stop buffers. These methods are based on the questionable assumption of uniform density of demand to allocate population or housing units to transit service areas. The approach used in this study disaggregates potential transit demand to the stop level and relates it to actual morning peak hour bus boardings at each bus stop although the data are aggregated to average boardings per trip in the morning peak hour.

BACKGROUND

A review of the existing literature shows that stop-level transit demand is modeled from a spatial standpoint. Miller and Shaw (2003) stress the need for understanding the underlying spatial assumptions as they relate to GIS transportation analysis. A number of researchers have empirically analyzed walking distance to transit stops (Neilson and Fowler 1972, Levinson and Brown-West 1984, Hsiao et al. 1997, Zhao et al. 2003) based on information derived from passenger surveys. These studies found that the relationship between transit demand and walking distance is expressed as a negative exponential distance decay function. The findings from these studies suggest 1) that passenger demand decreases with respect to walking distance to stops and 2) that a one-quarter-mile bus stop service area will not capture all potential transit users while a larger service area will result in an overestimation of the number of potential riders if distance decay is not explicitly addressed.

GIS techniques have been used to relax the assumption of uniform density to prorate potential transit demand to transit service area buffers (Peng and Dueker 1998). Instead of uniform density, O'Neill et al. (1992) used street density, while Zhao (1998) used dwelling units from a parcel database as the basis for assignment. Also, Zhao addressed barriers to walking and used network distance rather than straight-line distance to define transit service areas around bus stops. While these GIS approaches serve to more accurately measure potential transit demand, they are not related to actual transit ridership.

Rather than using ridership data based on passenger surveys, econometric models typically use a sampling of actual passenger boardings. Most previous studies seeking to explain the determinants of transit demand have been conducted at either the route (Kemp 1981, Horowitz 1984, Azar and Ferreira 1994, Hartgen and Horner 1997) or route-segment (Peng and Dueker 1995, Kimpel 2001) levels. Stop-level transit demand has been discussed in the literature as being the most appropriate level of analysis (Peng and Dueker 1995, Kimpel 2001, Furth et al. 2003), and implemented in T-BEST (Chu, 2004). The use of automatic passenger counters at transit agencies increasingly supports this type of modeling because an abundance of high- quality ridership data can be collected at relatively low cost. (see Furth et al. [2003] for a discussion of transit data collection technologies).

Bus stops are typically located and spaced according to a transit agency's service standards. Ammons (2001) looked at bus stop spacing standards for a number of transit properties and found that stop spacing typically ranges from 656 to 1,968 feet in urban areas. Such small distances between stops leads to overlapping bus stop service areas on the same route as well as with stops on adjacent routes serving similar destinations. In prior research, competition for choice riders was addressed at the route-segment level by Peng and Dueker (1995) and Kimpel (2001) through different means. In the former study, competition was addressed in the modeling stage using an explanatory variable based on the percent area of a buffer subject to overlap. In the latter study, competition was addressed during the data-processing stage by proportionally assigning potential demand in overlapping service areas using secondary information derived from disaggregate data (tax parcel value) as the basis for allocation. One of the primary reasons that stop-level demand models are lacking is because of the exceedingly complex difficulties associated with allocating potential transit demand in overlapping transit service areas to specific stops. Although the use of a GIS to solve problems related to transit accessibility is now fairly common, only a few researchers have adequately addressed overlapping service areas in a manner consistent with theory and only at spatial levels higher than the level of the bus stop. Also notable is that none of the econometric studies have addressed the issue of distance decay but instead have relied on the assumption of a uniform density of demand within transit service areas. In the present analysis, rather than using an arbitrary one-quarter-mile service area buffer, we use an initial distance of one-third mile and then apply a distance decay function that is presented in more detail later. We utilize a network-based method for determining transit service areas using a GIS and undertake an analysis that addresses overlapping service areas through measurement of integral accessibility at the tax parcel level.

Accessibility is a measure of potential opportunities for interaction (Hansen 1959). While accessibility can be calculated in various ways, the gravity-based measure of accessibility is the most widely used measure in planning studies (Handy and Niemeier 1997). The relative accessibility to transit service using a gravity-based measure is obtained by weighting opportunities of attraction for transit users (e.g., service frequency) and discounting this attraction by a negative exponential or a Gaussian impedance measure based on distance. In this analysis, we use integral accessibility to transit to address the overlap in service areas. Integral accessibility is the sum of relative accessibility over all possible destinations divided by the total attraction of the bus stop being studied (Song 1996).

In addition to issues of overlapping service areas and distance decay in stop-level demand modeling, a third issue concerns service quantity. Besides spatial proximity to bus stops, passengers are also concerned with the availability of service across the temporal dimension (Kittelson and Associates 2003) because it influences wait times at transit stops. A measure of service quantity such as the number of buses per hour passing a given location is needed to capture any variation in the level of service between stops on the same route as well as between stops on competing routes. In the former case, certain bus stops will have higher service levels compared to others because of varying service patterns (e.g., regular, limited, and express service). In the case of overlapping bus stop service areas on different routes serving the same destination, choice riders would most likely walk to the bus stop associated with the greater service frequency *certis paribus*. The review of the literature shows the strength of GIS-based methods, the need for a distance decay-weighted measure of potential transit demand at the bus stop level, and the need to relate demand to automatic passenger counter–generated passenger boardings. This research builds on these developments and estimates a descriptive model at the disaggregate level—passenger boardings at bus stops averaged over all trips in the morning peak hour. This is similar to planning models such as T-BEST, which is a stop-level model that also aggregates trips to time periods and identifies potential demand using a buffering technique, but does not address distance decay. Our parcel-based accessibility measure incorporates the size effect (number of housing units), the likelihood of waiting at a bus stop (scheduled headway), and a distance decay function.

STUDY DESCRIPTION

The study uses data from three sources. TriMet, the regional transit provider for the Portland metropolitan region has automatic vehicle location (AVL) and automatic passenger counter (APC) technologies on most of the fixed-route bus fleet collecting boarding and alighting information as well as service reliability information at each bus stop. Metro, the regional transportation and land-use planning organization, distributes GIS data for bus stops, bus routes, and tax parcels on a quarterly basis as part of the Regional Land Information System. The Multnomah County tax assessment database was used to obtain information on the number of units associated with multifamily parcels.

Boardings associated with the morning peak hour of service (7:30 A.M. to 8:30 A.M.) for two routes for 69 stops were obtained from TriMet. The routes of interest are the 14 Hawthorne and the 15 Belmont, two radial routes connecting southeast

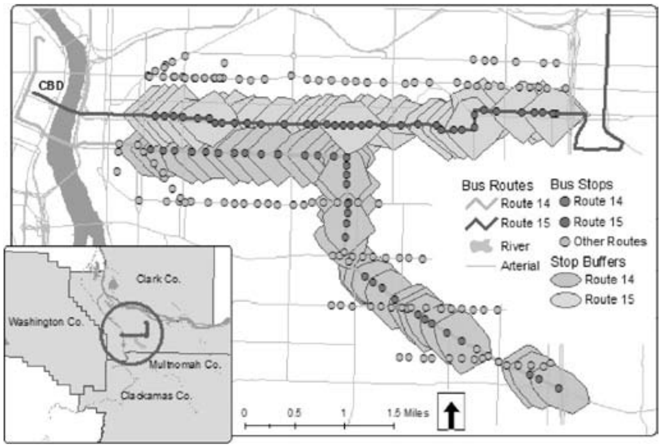

Figure 1. Study area

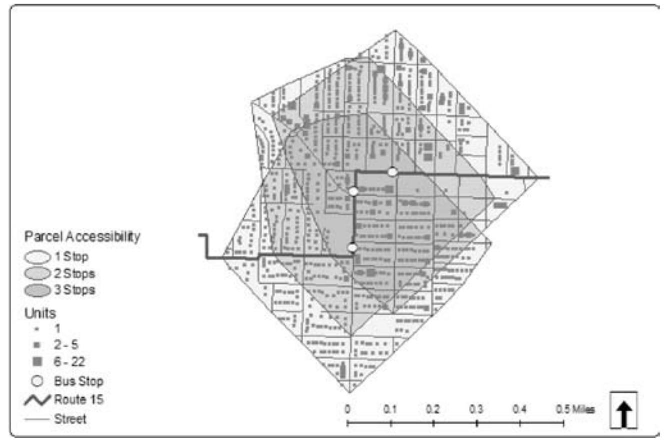

Figure 2. Overlapping bus stop service areas

Portland with the Central Business District. The study area encompasses an inner-city area that is well served by bus transit that is well patronized. Nine months of data associated with weekday service yielded approximately 126,000 data points. The study stops were limited to those located between I-205 and S.E. 12th Avenue. Stops that could attract patronage from other sources such as transfer and park-and-ride locations rather than the surrounding neighborhoods were eliminated from consideration.

The study area and the bus stop service areas within one-third-mile walking distance along the street network are presented in Figure 1. Note the prevalence of overlapping bus stop service areas on the same route as well as between routes. The distribution of dwelling units associated with parcels in relation to three bus stops is presented in Figure 2. The different colored areas represent locations where parcels have access to one or more stops.

DISTANCE DECAY FUNCTION

Zhao et al. (2003) fit a negative exponential function to survey data of walking distance to transit stops. Others use an arbitrary one-quarter-mile service area buffer, in which the probability of demand falls from one to zero at exactly a one-quarter-mile distance. Similar to Vuchic (2005), we posit something in between—that a negative logistic function of the form $\exp(a - bd_{ij})/(1+\exp(a - bd_{ij}))$ is better suited for distance decay of transit demand to reflect a more gradual decline in transit demand at short distances, a steeper decline as distance approaches one-quarter mile, and a more gradual tail. We estimated the distance decay function by empirically analyzing multiple sets of intercept (*a*) and slope (*b*) parameters in a series of ordinary least-squares regression models of transit demand allowing us to identify the parameter set that maximizes goodness of fit. The estimation of the distance decay function utilized distance to the nearest stop and does not include accessibility to more than one stop. The following model specification was used to empirically derive the parameters:

$$ONSX_j = f\{DWDU_j\} \quad (1)$$

where:

$ONSX_j$ = average passenger boardings per trip at stop j in the morning peak hour over all days;

$DWDU_j = \sum_i (\exp(a - bd_{ij})/(1+\exp(a - bd_{ij})) * DU_i)$ = the sum of distance-weighted dwelling units associated with stop j expressed as a probability using a negative logistic distance decay function;

where:

d_{ij} = on-street distance in miles from parcel i to stop j; and

DU_i = dwelling units at parcel i.

The estimated probabilities for several of the logistic functions $\exp(a - bd)$, Zhao et al.'s exponential function exp(-6.864d), and the uniform density of demand assumption (UDD) where p = 1 for d <= 0.25 miles and p = 0 for d > 0.25 miles are shown in Table 1. Figure 3 shows this information graphically.

Parameters $a = 2$ and $b = 15$ were selected as the best representation of distance decay using the negative logistic function since this particular model provided the best fit of the data. This parameter set depicts a steep distance decay prior to one-quarter mile. At short distances the probability of taking the bus is high, while at distances approaching one-quarter mile the probability is low.

Our approach to estimating the walking distance decay function is indirect. The direct approach requires information about where each transit rider lives and which particular stop he or she accesses. This knowledge is often gained by means of an onboard survey of transit riders; however, this technique normally yields sample sizes that are too small for subsystem analyses (e.g., stop, corridor, or route level). Instead, our indirect approach involves

Table 1. Estimated Probabilities for Various Distance Decay Functions

Parameters/ Distance	Negative Logistic					Negative Exponential	Uniform Density
	5-23d	4-21d	3-22d	2-22d	2-15d	-6.864d	UDD
d = 0.10 mile	0.9370	0.8699	0.6900	0.4502	0.6225	0.5034	1.0000
d = 0.20 mile	0.5987	0.4502	0.1978	0.0832	0.2689	0.2534	1.0000
d = 0.25 mile	0.3208	0.2227	0.0759	0.0293	0.1480	0.1798	1.0000
d = 0.30 mile	0.1301	0.0911	0.0266	0.0100	0.0759	0.1276	0.0000
d = 0.40 mile	0.0148	0.0121	0.0030	0.0011	0.0180	0.0642	0.0000

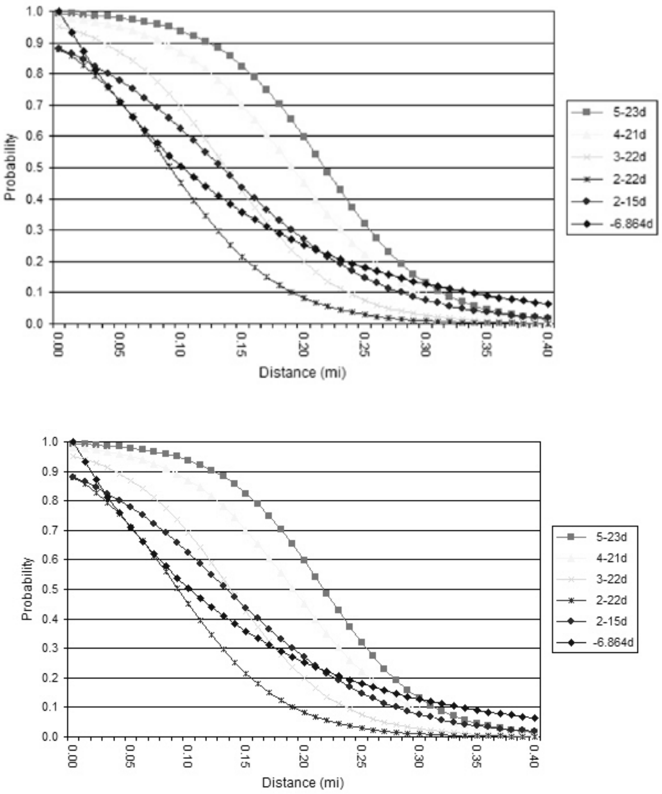

Figure 3. Estimated demand probabilities

estimating the distance decay function parameters by relating actual boardings to distance-weighted dwelling units by means of an iterative fitting process using ordinary least-squares regression.

While the model with the exponential function had the highest R^2, the results across the models did not vary that much with values ranging from 0.285 to 0.315. The parameters $a = 2$ and $b = 15$ yielded the best R^2 value of all the negative logistic functions; however, the low intercept value of $a = 2$ makes our function similar to the exponential function estimated by Zhao et al. Ridership is quite sensitive to distance, but the various measures of distance-weighted dwelling units were nearly indistinguishable, perhaps because of the simplifying assumption of distance to nearest stop. Nevertheless, our "best" distance-decay function is consistent with prior research that shows distance decay that starts close, is steep, and has a long tail. Similarly, our estimation does not support the use of a quarter-mile buffer that is commonly used in GIS-based analysis of transit demand. Although people can walk that distance, most transit riders do not. Thus, a quarter-mile transit buffer overestimates the population thought to be served by transit and lends support for bus stop spacing standards that call for relatively short distances between stops.

ACCESSIBILITY-WEIGHTED DEMAND MODEL

With the empirically estimated parameters for distance decay, another demand model is estimated for the case of overlapping bus stop service areas using a measure of integral accessibility. The average number of passenger boardings per trip per bus stop during the morning peak hour is modeled as a function of potential transit demand at the level of the individual bus stop controlling for overlapping bus stop service areas. Our model controls for variation in potential transit demand as measured by the number of dwelling units and their location (by distance from all bus stops within walking access) as well as the amount of scheduled service provided at stops. The following specification was used for the model:

$$ONSX_j = f\{AWDU_j\} \quad (2)$$

where:

$ONSX_j$ = average passenger boardings per trip at stop j in the morning peak hour over all days;

$AWDU_j = \sum_i ((A_{ij} / \sum_j A_{ij}) * \exp(a - bd_{ij})/(1+\exp(a - bd_{ij})) * DU_i$ = accessibility-weighted dwelling units around stop j;

where:

$A_{ij} / \sum_j A_{ij}$ = integral accessibility or proportion of accessibility at parcel i attributable to stop j;

where:

A_{ij} = accessibility of parcel i to bus stop j = $\exp(a - bd_{ij})/(1+\exp(a - bd_{ij})) * BUSHR_j * DU_i$;

where:

$\exp(a - bd_{ij})/(1+\exp(a - bd_{ij}))$ = probability of taking transit based on the negative logistic distance decay function using the parameters $a = 2$ and $b = 15$;

where:
d_{ij} = on-street distance in miles from parcel i to stop j;

$BUSHR_j$ = scheduled service measured by buses per hour at stop j;

DU_i = dwelling units at parcel i; and

$\sum_j A_{ij}$ = accessibility of parcel i to all stops j within 1/3 mile of parcel i.

The integral accessibility ($A_{ij} / \sum_j A_{ij}$) of parcel i to stop j is a key concept in this research. It measures the share of parcel i demand that is allocated to bus stop j, where the denominator ($\sum_j A_{ij}$) measures the accessibility of parcel i to all stops within walking distance. The accessibility of parcels to all walking accessible stops is shown for parcels associated with bus stop 2606 in the first panel of Figure 4. The second panel shows walking accessibility to stop number 2606 without considering overlap. More intense colors indicate a combination of nearness and density. The third panel of Figure 4 takes overlapping bus stop service areas into consideration. The third panel shows the effect of applying integral accessibility ($A_{ij} / \sum_j A_{ij}$) of stop 2606 times the accessibility (A_{ij}) of stop 2606, the result of which we call accessibility-weighted dwelling units at parcel i attributable to bus stop j ($AWDU_{ij}$).

The number of distance-weighted dwelling units for the 69 study stops according to the uniform density of demand assumption, the negative exponential function derived by Zhao et al. (2003), the negative logistic function using the parameters *a* = 2 and *b* = 15, and the same negative logistic function controlling for integral accessibility are shown in Table 2. By incorporating distance decay, potential transit demand is shown to decrease by a factor of approximately 2x using the negative exponential function and the two negative logistic functions relative to the traditional one-quarter-mile buffer method. Potential demand is higher relative to the negative exponential decay function for the negative logistic function using nearest stop criterion and lower based on the notion of integral accessibility. These results are aggregated over all 69 study stops so considerable variation in potential demand at any given stop may exist, depending on which particular distance decay function is used.

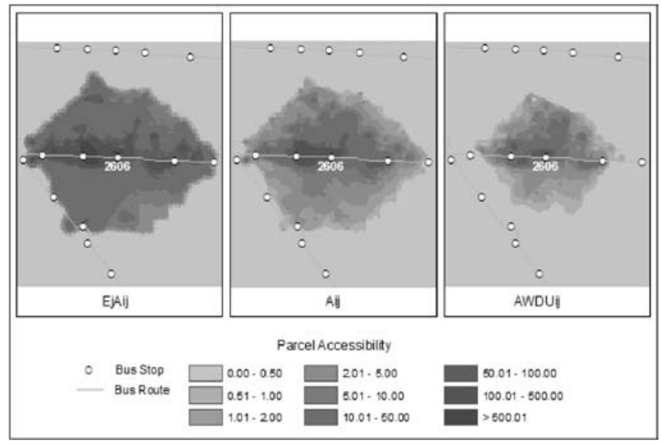

Figure 4. Measures of parcel accessibility

Table 3 contains the descriptive statistics for the variables used in the accessibility-weighted dwelling unit model and the other comparative models. Table 4 contains the results of the regressions.

The results in Table 4 show that the accessibility-weighted dwelling unit (AWDU) model performs better than do the comparison models.

The parameter for the number of dwelling units, controlling for integral accessibility, 0.0147 boardings per accessibility-weighted dwelling unit, is used to estimate morning peak hour boardings at stops on a per-trip basis for counts of accessibility-weighted dwelling units. The results of this simulation are shown in Table 5.

CONCLUSIONS

The research examined the determinants of transit boardings, taking advantage of automatically collected passenger data at bus stops. A tax parcel layer database was used as the basis for calculating potential transit demand at each stop using the

Table 2. Distance-Weighted Dwelling Units

Decay Function	Assumption	Distance (feet)	Units
UDD	Nearest stop	1,320	10,854
DWDU (Neg. Exponential)	Nearest stop	1,760	4,937
DWDU (Neg. Logistic)	Nearest stop	1,760	5,601
AWDU (Neg. Logistic)	Integral accessibility	1,760	4,266

Table 3. Descriptive Statistics for Accessibility-Weighted Dwelling Unit (AWDU) Model and Comparison Models

Name	Mean	Std. Dev.	Var.	Min.	Max
ONSX	0.92	0.68	0.46	0.02	2.76
UDD	157.36	85.87	7374.40	17.00	391.00
DWDU (Neg. Exponential)	71.55	38.92	1515.00	10.19	194.53
DWDU (Neg. Logistic)	81.18	44.38	1969.10	11.33	210.36
AWDU (Neg. Logistic)	61.83	28.24	797.30	16.86	150.16

Table 4. Model Results for Accessibility-Weighted Dwelling Unit (AWDU) Model and Comparison Models

	Coef.	Std. Err.	T-ratio	Adj. R2	Constant
UDD	0.0044	0.0008	5.5714	0.3064	0.2167
DWDU (Neg. Exponential)	0.0099	0.0018	5.6833	0.3152	0.2049
DWDU (Neg. Logistic)	0.0086	0.0015	5.5939	0.3082	0.2159
AWDU (Neg. Logistic)	0.0147	0.0069	6.3350	0.3652	0.0069

Table 5. Simulation of Stop-Level Boardings Using Accessibility-Weighted Dwelling Units

Accessibility-Weighted Dwelling Units Per Stop	Estimated Stop-Level Boardings Per Trip During Morning Peak Hour
25	0.368
75	1.104
100	1.472
150	2.207

measure of integral accessibility that takes into consideration distance-weighted accessibility and competing stops. The analysis was confined to the morning peak hour, when transit demand is most directly related to dwelling units.

Data preparation required the use of a GIS, which consisted of snapping dwelling units from parcel centroids to abutting streets, computing distance on the street network to all bus stops within one-third-mile distance, computing integral accessibility of dwelling units to those stops, and summing the integral accessibility of dwellings for each bus stop.

Distance decay parameters of the accessibility function were empirically derived from ordinary least-squares regression models by varying intercept and slope values. These parameters were then used to estimate a stop-level bus boarding model using accessibility-weighted dwelling units. The number of accessibility-weighted dwelling units is positively related to the number of boarding passengers. The parameter on this variable can be used to estimate morning peak hour transit ridership at the bus stop level.

This research illustrates the power of analysis using detailed disaggregate data, boardings at the bus stop level, and for parcel-level counts of dwelling units. A GIS analysis was needed to relate dwelling units to the street network and to calculate distances to bus stops. A distance decay function was derived and used to compute an accessibility measure to account for overlapping bus stop service areas for an improved estimation of stop-level transit demand.

It is important to note that distance decay parameters may not be constant; they may vary by trip purpose and access mode. In the future, it is recommended that more reliable distance decay parameters be estimated from passenger intercept surveys conducted at bus stops. These surveys can ask transit users about their point of origin, trip purpose, destination, access mode, and whether they will undertake a transfer. It is expected that decay curve parameters will vary based on these factors. Accordingly, a better transit demand model can be generated.

About The Authors

Thomas J. Kimpel is a research associate in the Center for Urban Studies, Portland State University, where he has been employed since 1996. His areas of interest include GIS analysis, transportation and land-use planning, and bus transit performance monitoring.

Corresponding Address:
Thomas J. Kimpel
Center for Urban Studies
Portland State University
506 S.W. Mill Street, Room 350
Portland, OR 97201
Phone: (503) 725-8207, Fax: (503) 725-8480
E-mail: kimpelt@pdx.edu

Kenneth J. Dueker, Professor Emeritus of Urban Studies and Planning, Portland State University, is an experienced educator and researcher in transportation. He directed the Center for Urban Studies at PSU from 1979 to 1998. His areas of interest include transportation and land-use interactions, travel and parking behavior, and GIS transportation.

Corresponding Address:
Kenneth J. Dueker
Center for Urban Studies
Portland State University
506 S.W. Mill Street, Room 350
Portland, OR 97201
Phone: (503) 725-4040, Fax: (503) 725-8480
E-mail: duekerk@pdx.edu

Ahmed M. El-Geneidy is a postdoctoral research fellow in the Department of Civil Engineering and the Humphrey Institute of Public Affairs, University of Minnesota. He formerly worked under the auspices of the Center for Urban Studies as a graduate research assistant. His areas of interest include GIS analysis in transportation planning and bus transit performance monitoring.

Corresponding Address:
Ahmed M. El-Geneidy
Department of Civil Engineering and
Humphrey Institute of Public Affairs
University of Minnesota
500 Pillsbury Drive S.E.
Minneapolis, MN 55455
E-mail: geneidy@umn.edu

References

Ammons, D. N. 2001. Municipal benchmarks: assessing local performance and establishing community standards. Thousand Oaks, CA: Sage Publications.

Azar, K. T., and J. F. Ferreira. 1994. Integrating geographic information systems into transit ridership forecast models. Journal of Advanced Transportation 29(3): 263-79.

Chu, X. 2004. Ridership models at the stop level. Tampa, FL: Center for Urban Transportation Research, University of South Florida, Report No. BC137-31.

Furth, P. G., B. Hemily, T. H. Mueller, and J. G. Strathman. 2003. Uses of archived AVL-APC data to improve transit performance and management: review and potential. Washington, D.C.: Transportation Research Board. TRCP Report No. 23 (Project H-28), http://gulliver.trb.org/publications/tcrp/tcrp_webdoc_23.pdf.

Handy, S. L., and D. A. Niemeier. 1997. Measuring accessibility: An exploration of issues and alternatives. Environment and Planning A 29(7): 1,175-94.

Hansen, W. 1959. How accessibility shapes land use. Journal of the American Institute of Planners 25(2): 73-76.

Hartgen, D., and M. W. Horner. 1997. A route-level transit ridership forecasting model for lane transit district: Eugene, Oregon. Charlotte, NC: Center for Interdisciplinary Transportation Studies, Report No. 170.

Horowitz, A. J. 1984. Simplifications for single-route transit ridership forecasts. Transportation 12: 261-75.

Hsiao, S., J. Lu, J. Sterling, and M. Weatherford. 1997. Use of geographic information system for analysis of transit pedestrian access. Transportation Research Record 1604: 50-59.

Kemp, M. A. 1981. A simultaneous equations analysis of route demand and supply, and its application to the San Diego bus system. Washington, D.C.: UMTA, Report DTUM-60-80-71001.

Kimpel, T. J. 2001. Time point-level analysis of transit service reliability and passenger demand. Portland, OR: Unpublished Doctor of Philosophy in Urban Studies, Portland State University.

Kittelson and Associates. 2003. Transit capacity and quality of service manual. Washington, D.C.: U.S. Department of Transportation.

Levinson, H. S., and O. Brown-West. 1984. Estimating bus ridership. Transportation Research Record 994: 8-12.

Makri, M., and C. Folkesson. 1999. Accessibility measures for analyses of land-use and travelling with geographical information systems. Department of Technology and Society, Lund Institute of Technology, Sweden, 1-17.

Miller, H., and S. Shaw. 2001. Geographic information systems for transportation: principles and applications. New York: Oxford University Press.

Neilson, G., and W. Fowler. 1972. Relation between transit ridership and walking distances in a low-density Florida retirement area. Highway Research Record 403: 26-34.

O'Neill, W. A., R. D. Ramsey, and J. Chou. 1992. Analysis of transit service areas using geographic information systems. Transportation Research Record 1364: 131-38.

Peng, Z., and K. J. Dueker. 1995. Spatial data integration in route-level transit demand modeling. URISA Journal 7: 26-37.

Song, S. 1996. Some tests of alternative accessibility measures: A population density approach. Land Economics 72(4): 474-82.

Vuchic, V. 2005. Urban transit: operations, planning and economics. Hoboken, NJ: John Wiley and Sons, Inc.

Zhao, F. 1998. GIS analysis of the impact of community design on transit accessibility. Proceedings of the ASCE South Florida Section 1998 Annual Meeting, Sanibel Island, Florida, 1-12.

Zhao, F., L. Chow, M. Li, I. Ubaka, and A. Gan. 2003. Forecasting transit walk accessibility: regression model alternative to buffer method. Transportation Research Record 1835: 34-41.