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Measuring Service Gaps

Accessibility-Based Transit Need Index

Sha Al Mamun and Nicholas E. Lownes

The integration of transit needs into transit accessibility indexing is important for evaluating existing transportation systems and service gaps and for identifying priority areas for investments in transportation infrastructure. This study detailed an indexing model for accessibility of transit need and focused on the necessity of evaluating transit needs and transit accessibility simultaneously. A need index was developed to identify areas in high need of public transit services from economic and sociodemographic information, and a composite accessibility index was developed to identify levels of access to transit services and shortcomings in providing service. The need for transit service was then modeled as the lack of transit accessibility, and the model correlated different access indicators with their ability to predict transit service need. This model mapped areas with different levels of transit accessibility and transit needs by using a single score, which may be easily interpreted by planners who examine transit equity. The model was applied to the city of Meriden, Connecticut, and results were compared with a general approach for consistency and effectiveness. The usefulness of the model was also highlighted through a representative example of the model's application.

Public transportation has a great influence on regional development patterns, economic viability, and creation of livable communities. It provides travelers with greater opportunity, choice, and access to a variety of economic and social activities. Therefore, an accessible transit service remains an important social service and can be considered an essential part of livable communities. Accessibility, one of the most important aspects of studies of public transportation systems, measures people's ease and convenience in reaching public transit services (*1*). Measuring people's levels of access to transit services can help monitor how well the system is serving people, revealing where transit service is most intense and where it is lacking.

The rise in personal income, increase in household car ownership, and substantial public investment in construction of new streets and freeway systems have led to a reduction of transit ridership (*2*). Even with the prevalence of automobiles and auto-oriented infrastructure, many people with and without regular access to automobiles depend on public transit as their primary mode of transportation. For this portion of the population, continued availability of public transit is vital for access to jobs, medical care, and other necessities of social life. Hence, careful attention should be paid to provide investment in transit infrastructure, to improve accessibility for those with limited transport options.

Simultaneous recognition of transit needs and identification of spatial gaps in transit accessibility can help a region provide more equitable transit service. A combined transit needs and transit accessibility distribution can identify the areas most in need of transit service. Existing measures have been used to identify service supply level and needs level separately and to compare resulting scores to obtain the level of service gaps for different areas. Therefore, a single public transit service index that combines the unmet need of transit service and accessibility to the service would be an excellent measure for improving the existing accessibility models. This paper aims to develop a model for identifying the service gap with only one index value by integrating both the supply and need measures into one measure. This model intends to estimate the impact of service attributes on providing access to needy households within a given area.

The next section of this paper reviews existing transit accessibility measures, including those that evaluate service gaps. The methodology section describes development of transit accessibility and transit need indices, interaction between transit need and accessibility scores, basic technique of developing an accessibility-based need index regression model, and accessibility variables used in this model. The combined accessibility and need index is then presented. This paper concludes with a brief discussion of the applications, limitations, and future research questions related to this measure.

LITERATURE REVIEW

A variety of transit accessibility measures have been proposed and defined through of a wide range of concepts. Some methods measure accessibility level on the basis of access variables (e.g., spatial, temporal, comfort) but without reflecting the actual need for transit services. Rood developed the local index of transit availability (LITA), which measures the transit service accessibility in an area by integrating three aspects of transit service: route coverage, frequency, and capacity (*3*). The time-of-day-based transit accessibility analysis tool developed by Polzin et al. measures transit accessibility as the daily trip exposure, per capita, to the service (*4*). This tool uses the time-of-day distribution of travel demand to measure the relative value of transit services provided in each period of the day. The *Transit Capacity and Quality of Service Manual* (TCQSM) measures public transit accessibility of a system as the percentage of the transit-supportive area covered by the service coverage area (*5*). The transit-supportive area reflects the area with a minimum household density or an employment density capable of supporting hourly transit service (*5*).

Cheng and Agrawal described a time-based transit service area tool to map transit accessibility by measuring a transit service area

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based on users' door-to-door travel time (*6*). All components of travel time from a traveler's origin to destination (walk time, wait time, in-vehicle time, etc.) are included in the travel time calculations. This measure allows time-based transit service area tool users to adjust passengers' maximum acceptable walk time and total trip time.

Other researchers have approached the accessibility problem through examining service gaps by comparing transit access and needs indices. Currie and Wallis identified a method to assess the relative quality of public transport services with respect to transit needs (*7*). A single transport need index was developed with socio-economic and transport-need related indicators to quantify the distribution of needs. The transport supply index was calculated as the density of transit vehicle kilometers during daytime shopping periods on weekdays. Another approach called "needs gap" was developed by Currie to identify service gaps in the service coverage by comparing the distribution of supplied services with the spatial distribution of transport needs (*8*). The supply index was calculated with a transit network supply model, which measures the network supply costs for different time periods and trip purposes. This further refined the supply-side modeling used in previous applications of this approach, although the transit needs measure remained the same as in previous research (*7*).

A further adaptation of the needs gap approach was developed by Currie to quantify social gaps in providing public transit for socially disadvantaged people (*9*). This approach involved measuring public transport supply by service frequency (vehicle trips per week) combined with access distance. The measure for social need was developed by combining the Australian Bureau of Statistics Index of Relative Socio-Economic Advantage/Disadvantage and the earlier transport need index in Currie and Wallis (*7*).

Murray and Davis combined the public transit need with accessibility measure for evaluating the equity of this transit service provision (*10*). The need for public transport services was measured by a weighting approach combining average household income, unemployment rates, and average family size. Level of access to service of an area was measured as the percentage of area suitably covered by public transit (*10*).

Bhat et al. described a customer-oriented, utility-based transit accessibility measure to identify the inequality between provision of transit service and the level of transit need within a community (*11*). The transit accessibility measure index combined the transit accessibility index and transit dependence index. This measure identifies users who need the service most by comparing the level of service supply with the level of demand by the transit user.

Review of the aforementioned studies revealed that most of the research used a similar methodology to identify service gaps or mapping transit equity, which estimates both transit needs and transit access and then compares them to measure service gaps or identify transportation-disadvantaged areas. In this paper, this methodological approach is referred to as the general approach, and the studies (as reviewed earlier) that have been used in this general approach are listed as follows, for ease of identification:

- Currie and Wallis (*7*),
- Murray and Davis (*10*),
- Currie (*8*),
- Bhat et al. (*11*), and
- Currie (*9*).

This paper aims to detail a methodological alternative to the general approach that can measure the quantity and quality of transit service and represent the level of need with a single score. An accessibility-based need measure incorporating a transportation-disadvantaged population is proposed for examining equity in providing service.

OBJECTIVES AND ORGANIZATION

The purpose of this paper is to develop a single accessibility-based need measure that captures the overall need of an area for transit services and that can be used not only to describe levels of accessibility, but also to identify areas with a high need for transit services. In addition, an objective of this research is to map transit equity in providing service. A composite transit accessibility measure was developed by integrating three existing methods. Different classifications of transportation-disadvantaged workers were identified to determine public transport needs. It is shown that an accessibility index based on service characteristics and coverage has a strong linear relationship with the need index. Results of the linear regression model were compared and contrasted for consistency with the results obtained with the general approach. Finally, this paper examines the practical impact of the model by applying it as a decision support tool for improvements of transit systems.

METHODOLOGY

A series of research tasks had to be addressed in modeling of an accessibility-based transit need measure: (*a*) assessing public transit accessibility, (*b*) measuring transit needs, and (*c*) relating transit accessibility as a function of transit need. These research tasks are discussed before the description of the modeling methodology used in this research.

Assessing Public Transit Accessibility

A composite index of assessing accessibility of public transit was developed based on three less data-intensive methods (LITA, TCQSM, and time-of-day-based transit accessibility analysis tool). The method is described briefly here; greater detail is available in Mamun and Lownes (*12*). This approach used existing methods and their components to reflect public transit accessibility from differing perspectives (i.e., transit planner, transit operator, traveler, and property developer) and to characterize the three important transit accessibility coverage aspects (trip, spatial, and temporal) simultaneously.

The LITA measures the transit service intensity of an area using transit and census data (*3*). Transit data include transit stop locations, route maps, service schedules, and vehicle capacities. Census data provide information on total land area, resident population, and number of employees in each tract. The TCQSM uses a service coverage measure to assess transit accessibility (*5*). The service coverage area is calculated by a detailed geographic information system method that measures the percentage of area covered by a 0.25-mi buffer around bus stops. This method requires the same data sets (transit and census data) as the LITA does. The time-of-day-based transit accessibility analysis tool (*4*) was considered in developing the composite index, for it is the only tool to account for time-of-day distribution of travel demand and that reflects temporal coverage of transit accessibility. This tool gives the relative accessibility of transit services provided during a specific time period using time-of-day distribution of travel demand. It requires data on the temporal distribution of travel demand (hourly basis) in addition to the transit and census data required for the previously mentioned methods. Data on the time-of-day distribution of travel demand came from the 2001 National Household Travel Survey (*13*).

Table 1 shows the raw accessibility scores of the three methods as outlined. Each method uses different scale; therefore, the individual scores required modification before they could be integrated into a single, composite score. Hence, the raw scores for each method were standardized to represent the scores in terms of a relative scale. To get the standardized score (SS) for a tract in a method, first the difference between the raw score and the mean of scores was calculated, and then the difference was divided by the standard deviation of scores. Next, this approach applied weighting factors (WFs) to the individual methods to formulate a composite accessibility index. First, all the accessibility parameters used across all three methods were identified and assigned a unit WF to all the parameters. Then, to determine the WF of a method, all of the parameter WFs associated with that method were summed. Finally, the composite accessibility index for a tract was calculated according to the Equation 1. For ease of interpretation and mapping, this method outlines the composite index values as five letter grades, A through F (excluding E). Grade A represents a score of +1.5 or higher, indicating the highest level of accessibility; Grade F represents a score lower than –0.75, indicating the poorest level of accessibility (Table 1). The grade breaking points were determined on the basis of the standard deviations method. In this method, the mean value was identified first, and then the class breaks were placed above and below the mean at intervals of one-half standard deviations.

$$\text{composite accessibility index} = \frac{\left[\left(SS_{\text{time-of-day}} * WF_{\text{time-of-day}}\right) + \left(SS_{\text{TCQSM}} * WF_{\text{TCQSM}}\right) + \left(SS_{\text{LITA}} * WF_{\text{LITA}}\right)\right]}{WF_{\text{time-of-day}} + WF_{\text{TCQSM}} + WF_{\text{LITA}}} \quad (1)$$

Measurement of Transit Needs

Transit service is often considered a social service, and providing equitable transit service is essentially viewed as a basic right (*10*). An equitable transit service requires more concern given to serving those who most need the service. Therefore, it is necessary to identify those people who do not have sufficient opportunities for public transport service but have significant need. To do this, a transit need index was developed on the basis of information about people who are transportation disadvantaged.

Hine and Mitchell defined transportation-disadvantaged people as those whose needs are not met by public transit services (*14, 15*). Included are people with disabilities, elderly people, children, unemployed people, and low-paid people. In another paper, Hine and Grieco defined transportation-disadvantaged people as those with low income, women, elderly, disabled, and children (*16*). Currie et al. identified transportation-disadvantaged people according to car availability in households (*17*). This approach included an assessment of forced car ownership and zero car ownership households. Forced car ownership was defined as low-income households who own three or more cars, and zero car ownership was defined as low-income households that do not own a car.

For this paper, five classifications of transportation disadvantage were considered; all data were from the Census Transportation Planning Package 2000 Database (*18*). These classifications are based on the number of workers belonging to the transportation-disadvantaged classes, as in the following sections.

Forced Car Ownership

This group consists of workers living in low-income households with annual incomes below $30,000 who own three or more cars. This classification hypothetically represents households that must own a

TABLE 1 Composite Accessibility Index and Scores

	Raw Score			Standardized Score			Composite Index	
Census Tract	Time-of-Day Tool	LITA	TCQSM	Time-of-Day Tool	LITA	TCQSM	Score (using weighted scheme)	Grade
1701	0.0273	12.97	76.89	1.976	7.973	1.144	4.2916	A
1702	0.0229	5.46	62.36	1.44	0.465	0.668	0.9728	B
1703	0.0119	3.99	40.94	0.88	–1.001	–0.032	0.0364	C
1704	0.0028	3.45	5.23	–1.03	–1.545	–1.201	–1.2531	F
1705	0.0025	4.25	11.39	–1.072	–0.742	–0.999	–0.9327	F
1706	0.0062	4.83	21.37	–0.614	–0.161	–0.673	–0.4387	D
1707	0.0125	4.85	50.65	0.162	–0.146	0.285	0.0511	C
1708	0.0097	5.25	29.21	–0.182	0.25	–0.416	–0.0326	D
1709	0.0196	7.69	83.09	1.036	2.694	1.347	1.7303	A
1710	0.022	4.72	69.63	1.327	–0.272	0.906	0.6453	C
1711	0.0065	4.20	17.10	–0.581	–0.792	–0.812	–0.6885	D
1712	0.0041	3.71	13.42	–0.876	–1.286	–0.933	–1.0457	F
1713	0.0086	4.80	39.53	–0.316	–0.194	–0.078	–0.2434	D
1714	0.017	8.16	91.28	0.712	3.164	1.615	1.7831	A
1715	0.0133	5.42	83.51	0.2586	0.42	1.361	0.4334	C
1716	0.0028	4.50	14.24	–1.03	–0.492	–0.906	–0.8024	F
1717	0.0007	1.97	2.91	–1.298	–3.023	–1.277	–1.9859	F

large number of vehicles to meet their mobility needs because transit service is lacking.

Zero Car Ownership

This group includes workers in low-income households that do not own a private car. People in these low-income households may not be able to afford a car because they would have to spend a significant portion of their total household income to operate a car (*17*).

Low-Income Earners

Low-income earners are workers in households with annual incomes less than \$25,000. This constraint of low income makes it difficult for them to have a high budget for their daily transport expense. This group is assumed to rely on low-cost public transit services more than do those in higher-income households.

People Older Than 65

This group includes elderly people, who out of need or desire, often change their driving habits toward suitable transit services. As people grow older, they shorten their trips, seek easier parking spaces to enter and exit, and look for less congested and lower speed roadways. Also, they eventually stop driving (*19*).

Disabled Individuals

This group identifies workers with any kind of disabilities (physical, mental, and other serious health impairments). This classification is considered because people generally depend on transit services that are disabled friendly, for access to jobs and other social services.

The transit needs index uses only the workers. Because the index was limited to workers, two classes of transportation-disadvantaged people (i.e., elderly people and people with disabilities) were undercovered in the need index. The researcher recognized the limitation but continued to use these data to maintain consistency in unit of measure, with other data classes. Another important consideration in the need index is the possible double counting of workers in different transportation-disadvantaged classes. For example, many workers in the low-income class were also in the zero car ownership class and thus double counted. Therefore, the actual need index of a census tract may be lower than represented in the calculation. To prevent this situation, group data were collected and sorted as carefully as possible on the basis of cross-data between classes. Common data on different combinations of classes were collected and subtracted from the classes to avoid overcounting (e.g., data on elderly or disabled workers who use a car as their mode of travel and data on workers who are both elderly and disabled). Then the common data were halved and subtracted from both classifications.

Transit Accessibility as Function of Unmet Transit Need

The primary objective of this paper was to develop an accessibility-based need measure to reflect unmet transit needs in an area as well as the level of accessibility to public transit. Thus, a composite accessibility index and a transit need index were estimated. The access index relies heavily on service and coverage characteristics of a transit service, whereas the need index focuses on demographics. The transit need index was measured as the percentage of transportation-disadvantaged workers in a census tract who use private cars as their mode of travel. Although the authors defined the transit need index on the basis of car ownership indicators, they did not consider travelers' mode choice or lifestyle preference to own a private car, which might be worth considering. Therefore, it is not presumed that all transportation-disadvantaged workers would use a transit service, even if they had access to the service. The intention is only to investigate the relationship between unmet transit needs and accessibility measures as a means to look at the relationship between need for service and the characteristics of service. A linear regression model was estimated for the composite accessibility scores and the need scores.

A histogram (Figure 1*a*) shows that the need index data (Table 2) are normally distributed; therefore, these data can be used for developing further statistical models. The distribution shows some skewness to the right, but it is expected, for the majority of tracts of these small sample data have relatively high need index values. A regression line (Figure 1*b*) over the actual data points, with the transit need index on the *x*-axis and the composite transit accessibility index on the *y*-axis, is plotted for evaluating the correlation among them. Because the transit need index reflects the percentage of transportation-disadvantaged workers who use cars, it is reasonable to expect some negative correlation between the need index and the transit accessibility index. In this case, the transit need index has a negative coefficient, suggesting that the percentage of auto usage decreases as transit accessibility increases. The R^2 value is .676, indicating that 67.6% of variance can be accounted for by the entire regression. Most

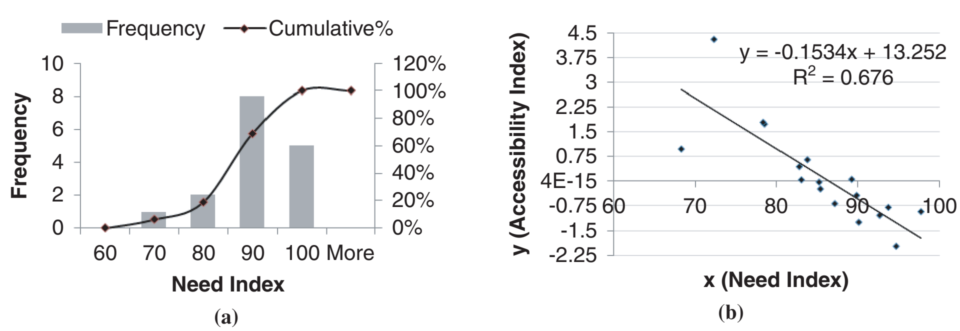

FIGURE 1 Estimation of linear function between transit accessibility and needs: (*a*) histogram of need index and (*b*) scatter plot to examine relationship.

TABLE 2 Comparison of Results for Combined Transit Accessibility and Transit Needs

	General Approach					Model-Based Approach	
Census Tract	Accessibility Index	Level of Accessibility[a]	Need Index	Level of Unmet Transit Need[b]	Combined Accessibility and Need Level (double grade)	Fitted Accessibility–Based Need Index	Combined Accessibility and Need Level (single grade)
1701	4.29	A	72.3	A	A-A	69.0	A
1702	0.97	B	68.3	A	B-A	73.7	B
1703	0.04	C	83.0	C	C-C	87.8	D
1704	−1.25	F	90.1	F	F-F	93.0	F
1705	−0.93	F	97.7	F	F-F	91.5	F
1706	−0.44	D	89.8	D	D-D	90.6	F
1707	0.05	C	89.2	D	C-D	86.4	D
1708	−0.03	D	85.2	C	D-C	88.5	D
1709	1.73	A	78.5	C	A-C	80.3	C
1710	0.65	C	83.8	C	C-C	83.3	C
1711	−0.69	D	87.1	D	D-D	90.4	F
1712	−1.05	F	92.7	F	F-F	90.0	F
1713	−0.24	D	85.4	C	D-C	87.1	D
1714	1.78	A	78.4	B	A-B	76.0	B
1715	0.43	C	82.8	C	C-C	81.2	C
1716	−0.80	F	96.7	F	F-F	90.2	F
1717	−1.99	F	94.7	F	F-F	93.7	F

[a]A = very high; B = high; C = average; D = low; F = very low.
[b]A = very low; B = low; C = average; D = high; F = very high.

of the data points are clustered toward the lower right corner of the plot, indicating that most of the tracts have high transit need and low level of accessibility. Ordinary least square assumptions were verified for this linear model. The linear relationship indicates that higher percentage of auto use by the transportation-disadvantaged workers is correlated to poor accessibility to transit service. This serves to validate the supposition that transit service need is strongly correlated to the lack of accessibility.

Modeling Accessibility-Based Need Index

This section describes the development of a model of transit need as a function of service characteristics. Previous sections support the idea that transit need (as defined in this paper) is correlated with lack of service accessibility. The models as described give a simple way to estimate the impact that service improvements might have on addressing the need for transit service. The independent access variables were selected to represent both spatial and temporal aspects of transit accessibility. Computational simplicity and data source availability were also taken considered. Independent variables were examined by investigating summary statistics, frequency distributions, raw data scatter plots, and a measure of collinearity, the variance inflation factor (VIF) for agreement with model assumptions. Following is a brief description of these variables, with an explanation of methods used to compile the required data.

Percentage of Service Area

This variable (%service_area) is the percentage of a census tract served by the transit system. It is calculated by dividing the tract area covered by 0.25-mi buffers around transit stops by the total tract area. This variable reflects spatial accessibility to transit service.

Compiled Route Miles per Square Mile of Area

For this variable (bus_route_den), the total length of transit routes running through each census tract was estimated by using ArcGIS area per length calculation feature. Routes running along the edge of a tract were halved between the bordering tracts to avoid overcounting the actual route length. Total tract route length (mile) is then divided by the tract area (square mile).

Average Daily Bus Runs per Stop

For this variable (daily_bus), the total number of stops in each tract was first determined. Bus stops falling on a tract boundary were allocated proportionally to bordering tracts. The number of bus runs for all stops was summed to obtain the daily total buses run for each tract. A bus stop with multiple routes expands the summation over all the routes serving the stop. Finally, the total daily bus runs from each bus stop within a tract were averaged to obtain that tract's average daily bus runs per stop. Calculation of this variable requires a schedule of bus services to determine the daily vehicle runs per bus stop and a service map to obtain the exact location of bus stops.

Daily Seat Miles per Capita

This access variable (seat_mile/capita) was calculated on the basis of three data items: total daily available seats, total route miles, and total

TABLE 3 Regression Models for Estimating Transit Needs Using Accessibility Variables

Model	Model R^2	F-Statistic	Independent Variable	Coefficient	t-Statistic	P-Value	VIF
1	.8232	32.59	%service_area	−0.14751	−4.58	.0004	1.23
			seat_mile/capita	−2.96682	−4.01	.0013	1.23
2	.8417	37.23	%service_area	−0.07091	−1.75	.1026	2.18
			bus_route_den	−1.79409	−4.43	.0006	2.18
3	.7396	19.87	%service_area	−0.17540	−4.75	.0003	1.09
			daily_bus	−0.47412	−2.53	.0239	1.09

population for each census tract. Daily available seats per capita was calculated by multiplying the total daily bus runs within a tract by bus capacity and total route miles, and then dividing by the total tract population.

To find the best approximation of the relationship between the transit need index and the independent access variables, three models were identified (Table 3). The three models were evaluated on the basis of their overall utility. Model 1 and Model 2 proved to be better models than Model 3, as shown by the coefficient of determination (R^2) and the F-statistic values. In Model 1, variable %service_area has a stronger significant coefficient (higher t-value) than it does in Model 2. Furthermore, Model 2 has a higher P-value for the %service_area variable than Model 1 does, meaning it is less useful for predicting the response variable. This is likely owing to increased correlation between service area and the second independent variable, a hypothesis supported by the higher VIF. Thus, it would be reasonable to conclude that, overall, Model 1 is the best for estimating transit need with access indicators. The functional form for Model 1 is as follows:

$$\text{accessibility-based need index} = 94.2442 - 0.14752 * \%\text{service\_area} - 2.96682 * \text{seat\_}\frac{\text{mile}}{\text{capita}}$$

The model indicates that the percentage of transportation-disadvantaged workers who use cars to travel might be well served by transit service, with the increase in service coverage and daily available seat mile per capita of a transit service. In addition, this model states that if transportation-disadvantaged populations can be located within accessible distance to transit services, then reliance on private autos seems lower, and public transit service will become a more feasible option.

All models were checked for normality, linearity, homoscedasticity (constant variance), and multicollinearity between independent variables. Details of these checks for Model 1 are shown in Figure 2. A histogram of residuals was plotted to test for normality (Figure 2*a*). This plot showed some departures from normality, which might be caused by the small sample size. To further test normality, a normal probability plot was created (Figure 2*b*). The points on this plot formed an approximately straight line. Therefore, the residuals can safely be assumed to be normally distributed. The plot of residuals versus fitted values is considered the single best diagnostic for checking assumptions in multiple regression (*20*). This plot, in Figure 2*c*, shows that the residuals are reasonably evenly distributed about zero, suggesting that the residuals have zero mean, and the correlation between the residuals and the fitted values is approaching zero. However, this plot displays some curvature, and vertical spread varies to some extent, so for a more thorough check of constant variance, White's general test for heteroscedasticity was performed (*21*). No evidence of heteroscedasticity was found. The VIF was calculated to identify the multicollinearity of the explanatory variables (Table 3). Depending on the source, upper thresholds of acceptable VIF can vary, with common boundaries being a VIF of 5 or VIF of 10 (*22, 23*). Against these thresholds, all three models have an acceptable level of multicollinearity, with the preferred model, Model 1, having a VIF of 1.23. As with any model, results are far from certain; they are estimates and need careful interpretation.

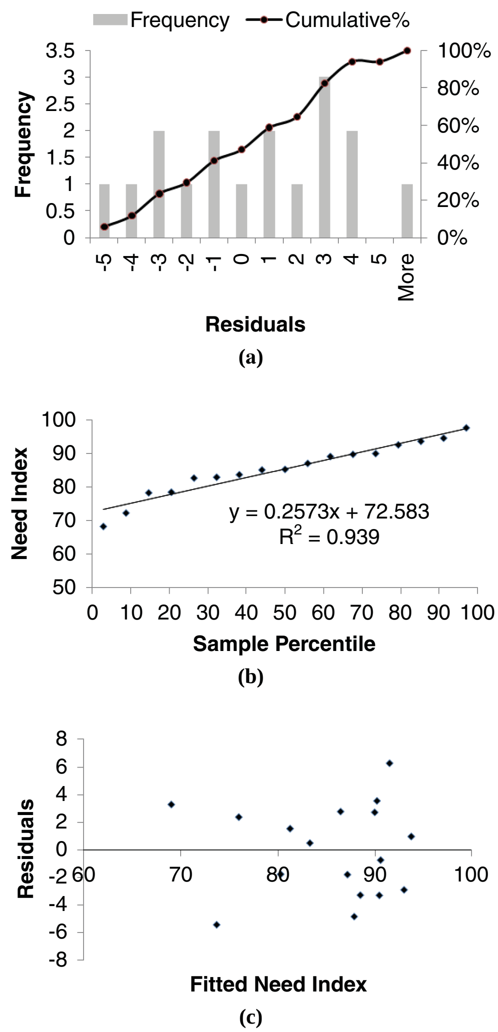

FIGURE 2 Verification of regression model assumptions: (*a*) histogram of residuals, (*b*) plot of normal probability, and (*c*) plot of residuals versus values of fitted need index.

RESULTS

Analysis was conducted on the 17 census tracts of Meriden, Connecticut. Accessibility calculations were carried out for three public bus routes that service the city (A, B, and C). This paper developed a model-based approach that can identify service gaps in providing transit service with a single accessibility-based need measure. This approach does not require calculation of separate transit accessibility and need scores; it uses only accessibility variables, which are less data intensive. Results of the single measure were compared with results obtained from the general approach to justify consistency and completeness of the new results. For the general approach, both the accessibility index and the need index results were grouped into five categories (very high, high, average, low, and very low). Also, five grades were assigned (A through F, excluding E), as shown in Table 2. The accessibility-based need index was also grouped into five categories, A through F excluding E. Grade A characterizes an area having a very high level of accessibility to transit service and very low levels of unmet transit need; Grade F represents very low level of accessibility with very high level of unmet transit need.

One limitation of this model is associated with the small sample size. A large sample size could provide more meaningful results, which might be useful to conduct some other statistical diagnostic tests to justify that the correlation between transit needs and transit accessibility did not just happen by chance alone.

Table 2 shows that the need index obtained from the model-based approach was consistent with those from the general approach. For most of the census tracts (tracts 1701, 1704, 1705, 1710, 1712, 1715, 1716, and 1717), the service gap results are consistent. For some tracts (1702, 1708, and 1713), the model-based approach showed results of higher unmet transit needs to some extent but did not alter the accessibility scores. For example, tract 1702 shows high accessibility and very low unmet transit need in the general approach; however, it shows high accessibility and low unmet transit need in the model-based approach. Other tracts (1707, 1709, and 1714) showed lower accessibility scores with the model-based method. For tracts 1703, 1706, and 1711, both the transit accessibility and unmet transit need scores experienced lower results in the model-based method. Therefore, it can be said that the new model-based approach tends to rate tract accessibility as lower than the general approach does.

Transportation-Disadvantaged Areas and Assessing Service Gaps

Figure 3 shows the spatial distribution of the combined transit accessibility and transit need scores for the census tracts; darker shades are areas with higher accessibility and lower unmet transit needs, and lighter shades indicate lower accessibility with higher unmet needs. Using this single index for each tract, one can easily identify the transport-disadvantaged areas. The low level of public transportation and consistently high unmet transit need for transit services areas suggest that significant expenditure on public transportation services and infrastructure should be prioritized for this region. These areas should be of great interest to transit providers because they contain the neediest transit users. This should be a concern to increase the efficiency of the service; it would help transit planners in government agencies ensure an equitable use of public resources.

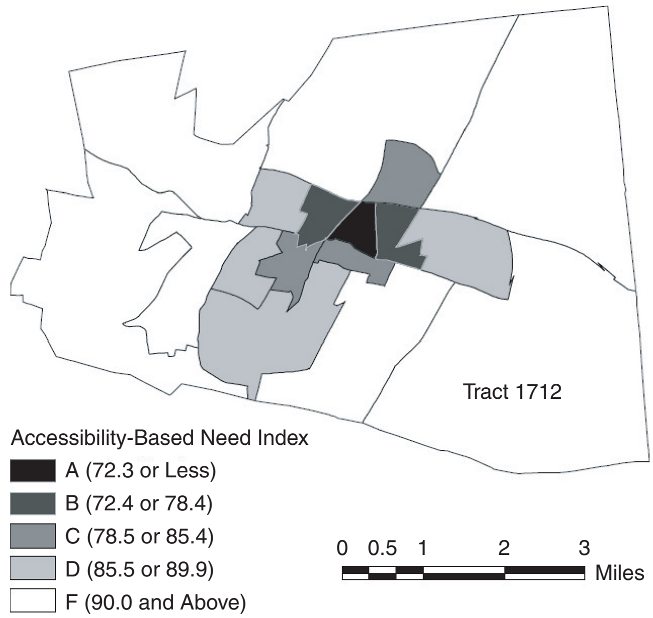

FIGURE 3 Levels of combined transit accessibility and transit needs.

Determining Service Improvement Options

This paper developed a model that can be used to examine service changes and their estimated impact on unmet transit need. This model requires relatively little data. Yet it is designed to assist transit providers in identifying best possible new facilities or reallocating schemes to optimally use resources from the perspective of transit accessibility and need. Following is a brief example of how such a method could be applied.

Transportation-disadvantaged areas can be analyzed to determine potential locations for new and expanded facilities or services. An assessment of options for service improvement was done for census tract 1712. Figure 3 shows that tract 1712 is a transportation-disadvantaged area with a very high need for service, but it experienced a very low accessibility level for transit.

Figure 4*a* shows the existing locations of bus stops and route alignment in census tract 1712. This tract had a population of 7,565 in 2000 and a land area of 5.034 sq mi (*24*). Forty vehicle runs are made at these four bus stops daily. The average service span for this route is 11 hours (from 6:30 a.m. to 5:30 p.m.), and the average headway for each stop is approximately 1 h. This low frequency bus service results in poor accessibility, and according to the model developed in this paper, it represents the highest transit need for this tract. Two hypothetical options for service improvement for this census tract are considered.

In Option 1, the bus service frequency and the service span were increased for the existing bus stops and route alignments (Figure 2*a*). The service span was increased from 11 h to 13 h, and service frequency was changed to 40 min, which caused changes to only one of the independent variables, seat_mile/capita. With use of the model equation, this option improved the accessibility-based need grade from F to D (i.e., from very high need with very low accessibility to high need with low accessibility).

In Option 2, two new transit stops are built within this tract (Figure 4*b*). Locations of these stops were chosen so that the 0.25-mi buffers around the stops would not overlap, increasing service

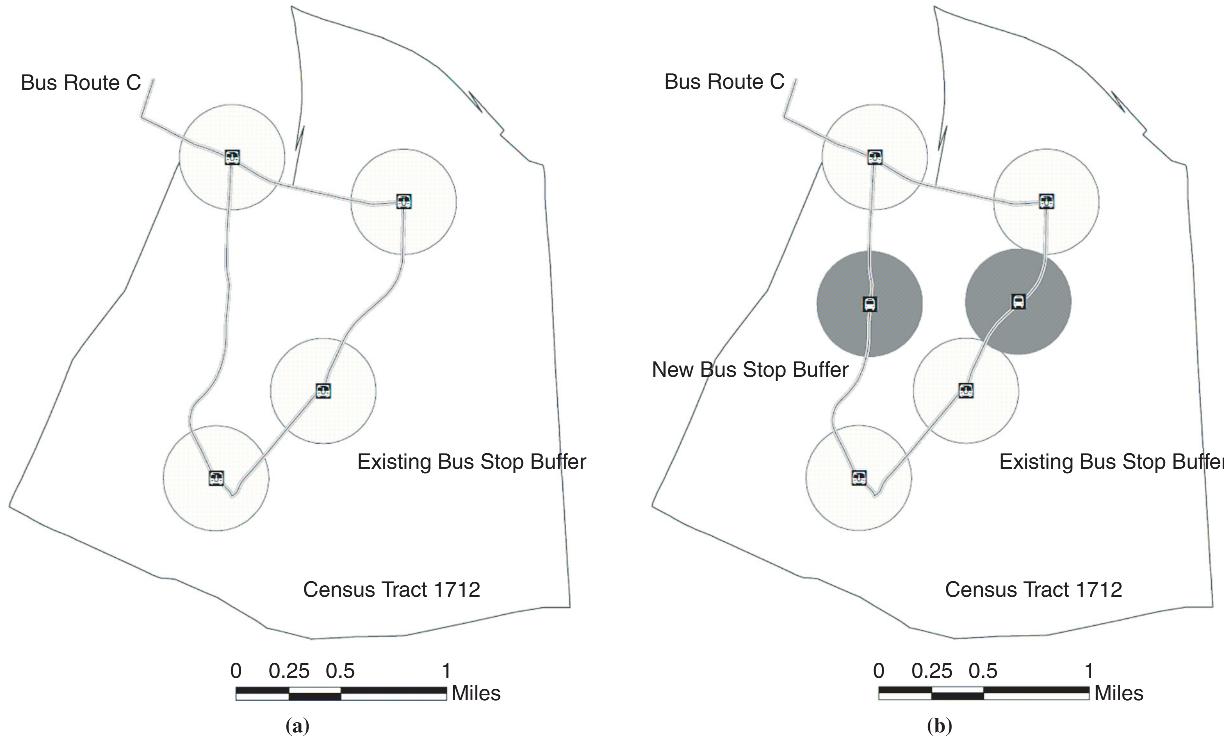

FIGURE 4 Assessing options for improving accessibility for Tract 1712: (*a*) Option 1, existing locations of bus stops and route alignment, and (*b*) Option 2, proposed new bus stops.

coverage. Also assumed was that the number of bus run from the new stops is the same as for buses running from the adjacent stops. The addition of these two stops affected both of the independent accessibility variables (%service_area and seat_mile/capita). Little improvement was offered in the accessibility-based need index (from Grade F to Grade D).

Changes in level of unmet transit need with provision of transportation service attributes may be predicted using results of this model, by calculating changes in the percentage of transportation-disadvantaged workers using cars as their mode of travel (i.e., the need index). Results show that the accessibility-based transit need index value decreases from 90.0 to 88.3 in Option 1 and to 87.4 for Option 2, meaning that more transportation-disadvantaged workers may possibly be covered by the transit service if there are frequent bus stops rather than increased service span or more frequent bus service. Intuitively, the cost for building two new transit stops may be much less than the cost for increasing service span by 2 h and increasing the service frequency of transit service. A detailed benefit–cost analysis would be needed for final determination; however, the derived accessibility-based need improvements clearly favor Option 2.

CONCLUSIONS

This research addresses the unmet need for a better measure of accessibility that is responsive to the transit needs of the transportation-disadvantaged population. The method for evaluating transport need, as presented in this paper, is intended to aggregate the volume of transportation-disadvantaged workers who might face limited mobility options in their community. To evaluate the existing service supply and proximity of transit users to the service, a composite transit accessibility measure was developed. This relatively robust measure integrated several different aspects of transit service, including spatial and temporal. The lack of transit service is highly correlated with large transportation-disadvantaged populations, suggesting that a relationship exists between these services and demographic characteristics. A regression model was then estimated for the transit need index, based on simple service characteristics. This model was found to account for a significant amount of variability in the relatively small data set, and it provided useful insight into the relationship between transit need and service provision.

This paper examined the consistency of results of the model with results of the general approach used to identify transportation-disadvantaged areas. The comparison showed that the model was able to identify service gaps in transit service provision in a reliable and defendable quantitative manner. Furthermore, the model is computationally straightforward and relatively easy to apply to the mapping of well-served and poorly served areas. Results should therefore be a solid basis for identifying shortcomings in service coverage and examining equity in providing transit service. This paper presented a scenario with two options for increasing transit accessibility. It also predicted effects of those options on reducing service need by using the model, demonstrating how this model can provide a basis for priorities in service improvements. Making equitable allocation of investments in transit service can increase access to community events for all people, particularly those who have limited transportation options.

The model needs to be expanded to deal with more accessibility indicators, such as travel time, pedestrian network connectivity, and service reliability. Further modification of the transit need index, considering total transportation-disadvantaged populations (i.e., not only workers) would be useful in identifying the neediest population with mobility problems. An important consideration is that this model was developed based on very small sample data sets. Future research will validate and improve this model through application in larger metropolitan areas and statewide intercity travel.

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