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# Public Transit Accessibility and Need Indices: Approaches for Measuring Service Gap

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# Public Transit Accessibility and Need Indices: Approaches for Measuring Service Gap

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B.S., Bangladesh University of Engineering and Technology, 2006.

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

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**APPROVAL PAGE**

Master of Science Thesis

**Public Transit Accessibility and Need Indices: Approaches for Measuring  
Service Gap**

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## CHAPTER 1: INTRODUCTION

### BACKGROUND

The vast majority of travelers in the United States are primarily dependent on privately owned cars as their mode of travel. The higher car ownership, rising household income, and increasing investment in urban street and highway systems have resulted the excessive automobile travel (1). However, many people without access to a car, or another means of personal transport, are dependent on some form of publicly available transport for making trips. One study reveals that nearly 9 in 10 Americans claim to own a car which agrees with the U.S. Census (2000) statistic that only 10.29% of households in the USA have no car and fully depend on public transit or walking for travel (2). This excessive use of private cars contributes to traffic congestion, air pollution, traffic accidents, and high operating and maintenance cost to car users. Rapidly increasing fuel prices continue to prompt increased interest in and usage of alternate transportation systems over the use of private cars.

The public transit system has been considered as an important means of sustainable and social transportation alternative in creating livable and sustainable cities. Public transportation assures long term sustainability in terms of resource consumption by relieving highway congestion and provides a very efficient means of moving large numbers of people with considerable flexibility to meet demand throughout an area (3). It improves systemic mobility without placing the economic and environmental burden of increased auto ownership on the traveling population and provides mobility to those who do not have access to a car (Transit Disadvantaged). Therefore, public transit service is



widely deemed as a means for ensuring all travelers can make use of transportation service and has been considered as a social service now-a-days (4).

In order to reduce people's reliance on private autos and to provide mobility option to transit disadvantaged people, there is an urgency to increase investment in and expansion of public transportation system. However, the provision of public transport service and infrastructure will not in itself fulfill public transportation's potential. Transit service is unlikely to be utilized as a mode of travel if there is lack of access to the service and the system is not available to potential transit riders. Therefore, access to transit service is an important measure in the study of transportation system. Generally, accessibility is defined as a measure of ease with which people can reach their opportunities or services (4).

Therefore, the transit system must be properly accessible and available to the community who need this service most. As a result, there is need to assess and quantify public transportation access to travelers and to identify the under-connected and under-served areas within a community or region. By recognizing mobility needs and identifying available resources, an accessibility-based need measures might aid transit operators and local authorities as a basis for justifying and making choices in public transit investment.

### **TRANSIT PLANNER/PROVIDER SURVEY**

A Transit Planner/Provider survey was conducted to collect provider's current service information, methods used to collect transit data, and their different coordination activities with other transit agencies in the state of Connecticut. This survey was designed to understand the relative importance of different accessibility measures used to measure

transit accessibility for a service area and to identify the most critical gaps/unmet needs in existing transit services and the barriers/challenges to accomplish the unmet needs in transit services. The survey questionnaire is provided in the Appendix and Table A.1 provides relative importance of accessibility measures and Table A.2 provides a list of unmet transportation needs obtained from responses to the survey. ‘More frequent service and better service span’ was found as the most important measure for assessing transit accessibility and ‘more parking availability’ was found as the least important accessibility measure. Most transit providers agreed that adequate transit route connection to the job centers and sufficient access between developments and transit services is the most significant unmet transit need in Connecticut. Respondents recommended that identification of classifications of people that potentially need public transit services is important and providing service to those who need this service can increase access to community events using transit service.

## **OBJECTIVES AND THESIS STRUCTURE**

The objectives of this research effort are: 1) Investigate the current state of the practice of quantifying public transportation access, 2) Develop a method for quantifying public transit access that combines existing public transit accessibility indices, 3) Develop a transit need measure to identify areas in high need of public transit services, 4) Develop an accessibility-based need measure to identify service gaps, and 5) Apply this accessibility-based service gap measuring approach to a selected Connecticut public transportation corridor as a pilot study.

This thesis has five chapters including this first introductory chapter. The second chapter is devoted to the development of a composite accessibility measure. A paper

titled “A Composite index of Public Transit Accessibility” accepted for publication in the *Journal of Public Transportation* represents this chapter. This paper provides a review of the literature on previous and current methods for measuring transit service accessibility and develops a composite measure considering three important accessibility aspects for assessing transit services.

The research methodology for measuring service gaps using transit accessibility and transit needs is presented in Chapter 3. This chapter consist of a paper titled “Measuring Service Gaps: An Accessibility-Based Transit Need Index” accepted for publication in *Transportation Research Record: Journal of the Transportation Research Board*. This paper details an accessibility-based transit need indexing model for measuring service gaps. This model maps areas with different levels of transit accessibility and transit needs using a single score, which may be easily interpreted by planners to support service planning decisions. This paper also highlights the implication of service gap results in order to prioritize the type of service improvement option.

Both the composite transit accessibility calculation (Chapter 2) and the accessibility-based transit need indexing model (Chapter 3) have been applied to the public transit system of Meriden, CT. Chapter 4 applies the accessibility-based service gap measuring approach to a larger metropolitan area, New Haven, CT. This chapter is devoted to the validation of this approach.

Conclusions and future research are presented in the final chapter. A brief review of results and the potential applications of developed measure to a variety of transit users are described. A wide variety of future research questions and suggestions for further refinement of the accessibility-based service gap measuring tool are identified.

*\*This paper is being published in the **Journal of Public Transportation***

## **CHAPTER 2: A COMPOSITE INDEX OF PUBLIC TRANSIT ACCESSIBILITY**

### **ABSTRACT**

Measuring ease of access to transit services is important in evaluating existing services, predicting travel demands, allocating transportation investments and making decisions on land development. A composite index to assessing accessibility of public transit is described. It involves use of readily available methods and represents a more holistic measure of transit accessibility integrating developer, planner and operator perspectives. The paper reviews previous and current methods of measuring accessibility and selects three methods for application in a case study in Meriden, CT. Inconsistencies are noted across the methods, and a consistent grading scale is presented to standardize scores. Finally, this paper proposes weighting factors for individual methods to formulate a composite measure based on individual accessibility component measures. The approach aims to provide a robust and uniformly applicable measure that can easily be interpreted by planners to identify shortcomings in service coverage and promote equity in transit accessibility in the community.

## INTRODUCTION

Public transit is a key component of a sustainable transportation system that improves systemic mobility and can serve to mitigate the economic and environmental burdens that increased auto ownership can impose on the traveling population. Provision of public transit and infrastructure will not in itself fulfill public transit's potential. The system must be accessible and available to the community and its activity centers and connected with the rest of the transportation system. In this paper, we consider accessibility to have three primary components: *trip coverage* - travelers would consider public transit accessible when it is available to and from their trip origins/destinations, *spatial coverage* - travelers would consider public transit accessible when it is within reasonable physical proximity to their home/destination, *temporal coverage* - a service is accessible when service is available at times that one wants to travel. Another key aspect of public transit service is comfort - which addresses the question: "Is sufficient space available on the public transit at the desired time?" (5). Hence, there is need to assess and quantify public transit access considering the three aspects of public transit accessibility - trip, spatial and temporal coverage, along with comfort.

Accessibility measures aid public transit operators and local authorities in the development of appropriate transit service expansion plans and policies by recognizing mobility needs and identifying service gaps. For the purpose of assessing public transit accessibility in a region and the comparison of results with the existing methods, consistent grading scale across the methods is warranted. Measures with consistent grading scales can facilitate the assessment of the distribution and quality of public transit

service provided within an area and a composite measure (properly weighted) can provide a single, representative measure.

This paper proceeds with a literature review of existing transit accessibility measures, highlighting their scale of analysis and the measures used in their calculation. The methodology section focuses on the three methods used in the development of the composite measure, which is then applied in a case study. This section also provides a standardized scaling option for comparison of the results. The results section presents output of the comparative analysis and composite measure. The final section concludes the paper with a summary of major findings and some discussion of future adoption of the examined method to improve the performance of accessibility measures.

## **LITERATURE REVIEW**

A number of means of measuring accessibility have been developed in several studies since the 1950s and continues to receive growing attention in the transit sector (6).

Different measures have been designed to reflect differing points of view. Some of the measures of public transit accessibility focused on local accessibility and considered both spatial and temporal coverage. The Time-of-Day-Based Transit Accessibility Analysis Tool (Hereafter referred to as *Time-of-Day Tool*) developed by Polzin et al. (7) is one measure that considers both spatial and temporal coverage at trip ends. In addition to the inclusion of supply side temporal coverage, this tool explicitly recognizes and considers the demand side of temporal coverage by incorporating the travel demand time-of-day distribution on an hourly basis.

The Transit Capacity and Quality of Service Manual (5) provides a systematic approach to assessing transit quality of service from both spatial and temporal dimensions. This procedure measures temporal accessibility at the stops by using various temporal measures (Table 1). Assessing spatial public transit accessibility throughout the system is carried out by measuring the percentage of service coverage area and incorporating the Transit Supportive Area (TSA) concept. The calculation of service coverage area using the buffer area calculation (available in GIS software) is presented as an option.

The transit level-of-service (TLOS) indicator developed by Ryus et al. (8) provides an accessibility measure that uniquely considers the existence and eminence of pedestrian route connected to stops. It also combines population and job density with different spatial and temporal features (Table 1) to measure transit accessibility. Revealing the association of safety and comfort of the pedestrian route to stops makes this method distinctive in the evaluation of public transit accessibility. Another measure that considers the space and time dimensions of local transit accessibility is the public transport accessibility level (PTAL) index developed in 1992 by London Borough of Hammersmith and Fulham (9, 10). This index measures density of the public transit network at a particular point (origin), using walk access time and service frequency and integrating the accessibility index (AI) for all available modes of transport from that point.

Fu et al. (11) proposed an O-D based approach called Transit Service Indicator (TSI) to evaluate transit network accessibility by combining the various temporal attributes (Table 1) into one composite measure. To develop the Transit Service Indicator

(TSI) for a single O-D pair, they used ratio of the weighted door-to-door travel time by auto (WTA) to the weighted door-to-door travel time by transit (WTT). Schoon et al. (6) formulated another set of Accessibility Indices (travel time AI and travel cost AI) for different modes between an O-D pair. Travel Time AIs for a particular mode were calculated by using ratio of the travel time of a particular mode to the average travel time across all modes. Cost AIs were calculated in much the same way. The different methods, their coverage of analysis, the incorporated measures, and the most important features of the methods are summarized in Table 1.

Hillman and Pool (12) described a measure to examine how a database and public transit planning software (ACCMAP) can be implemented to measure accessibility for Local Authorities and Operators. This software measured local accessibility as the Public Transport Accessibility Level Index (PTAL) using the combination of walk time to a stop and the average waiting time for service at that stop. Network accessibility was measured between an origin and destination including walk time from origin to transit stop, wait time at stop, in-vehicle travel time, wait time at interchanges, and time spent walking to destination.

There were few studies that paid attention to the comfort and convenience aspect of transit service. The Local Index of Transit Availability (LITA), developed by Rood (13), measures the transit service intensity, or transit accessibility in an area by integrating three aspects of transit service: route coverage (spatial availability), frequency (temporal availability), and capacity (comfort and convenience). Incorporation of comfort and convenience aspect makes this tool distinctive from the passengers' perspective.



**TABLE 1 Summary of Previous Transit Accessibility Measures**

| Study/<br>Paper         | Type of<br>Measure        | Reflecting Local<br>Accessibility |                      | Reflecting<br>Network<br>Accessibility | Incorporated Accessibility<br>Measure(s)  | Important<br>Feature                       | Computational<br>Complexity | Intended Users  |
|-------------------------|---------------------------|-----------------------------------|----------------------|--|---|--|-----------------------------|---|
|                         |                           | Spatial<br>Coverage               | Temporal<br>Coverage |  |   |  |                             |   |
| Polzin et al. (2002)    | Time-of-Day tool (Index)  | Yes                               | Yes                  | No                                     | Service Coverage, Time-of-Day, Waiting Time, Service Frequency, Demographic data.   | Time-of-Day Trip Distribution              | Transportation Specialist   | Transit Planner   |
| Rood (1998)             | LITA (Grade)              | Yes                               | Yes                  | Yes                                    | Service Frequency, Vehicle Capacity, Route Coverage.  | Comfort and Convenience                    | Little Technical Skill      | Property Developer  |
| Schoon et al. (1999)    | AI (Index)                | No                                | No                   | Yes                                    | Travel Time, Travel Cost  | Travel Cost                                | Little Technical Skill      | Transit Planner<br>Transit User                           |
| TCQSM (2003)            | LOS                       | Yes                               | Yes                  | No                                     | Service Frequency, Hours of Service, Service Coverage, Demographic data.  | LOS Concept                                | Some Technical Skill        | Transit Operator<br>Transit User                          |
| Hillman and Pool (1997) | PTAL (Index)              | Yes                               | Yes                  | Yes                                    | Service Frequency, Service Coverage   | Agg. Travel Time between O-D pairs         | Transportation Specialist   | Transit Planner<br>Transit Operator                       |
| Fu et al. (2005)        | TSI (Index)               | Yes                               | Yes                  | Yes                                    | Service Frequency, Hours of Service, Route Coverage, Travel time components   | Weighted Travel Time                       | Some Technical Skill        | Transit Operator  |
| Ryus et al. (2000)      | TLOS                      | Yes                               | Yes                  | No                                     | Service Frequency, Hours of Service, Service Coverage, Walking Route, Demographic data  | Availability & quality of Pedestrian Route | Transportation Specialist   | Transit Planner<br>Transit Operator                       |
| Currie et al. (2004)    | Supply Index & Need Index | Yes                               | Yes                  | Yes                                    | Service Frequency, Service Coverage, Travel time, Car Ownership, Demographic data.  | Transport Needs Measure                    | Some Technical Skill        | Transit Planner<br>Transit Operator<br>Property Developer |
| Bhat et al. (2006)      | TAI & TDI (Index)         | Yes                               | Yes                  | Yes                                    | Access distance, Travel time, Comfort & parking, Network Connectivity, Service Frequency, Hours of Service, Vehicle Capacity. | Transit Dependency Measure                 | Transportation Specialist   | Transit Planner<br>Transit Operator<br>Transit User       |

Bhat et al. (14) described the development of a customer-oriented, utility-based Transit Accessibility Measure (TAM) for use by TxDOT and other transportation agencies. Two types of indices were included in this manual to identify patterns of inequality between transit service provision and the level of need within a population: transit accessibility indices (TAI) and the transit dependence index (TDI). The TAI reveals level of transit service supply and considers various elements of the utility measures in transit service. The transit dependence index (TDI) measures the level of need for transit service as a function of socio-demographic characteristics of potential transit users.

A new approach to identify the geographical gaps in the quality of public transit service was developed by Graham Currie (15). This 'Needs Gap' approach assesses the service of public transit by comparing the distribution of service supply with the spatial distribution of transit needs. Another study by Currie et al. (16) quantifies the associations between shortage of transit service and social exclusion and uniquely links these factors to social and psychological concept of subjective well-being. This paper investigates the equity of transit service by identifying the transport disadvantaged groups and evaluating their travel and activity patterns.

A customer demand-oriented methodology incorporating all categories of accessibility measures is best for measuring the quantity and quality of service. Such a method should not view transit as a last-resort option, but as a service that should be available for heavily traveled corridors because it is a good option for travelers. Any method identifying service quality must consider the populations being served, meaning that one must consider the equity aspects of service configuration. The method should be

easily understandable to public transit operators and contain fundamental information about the system and the community it serves.

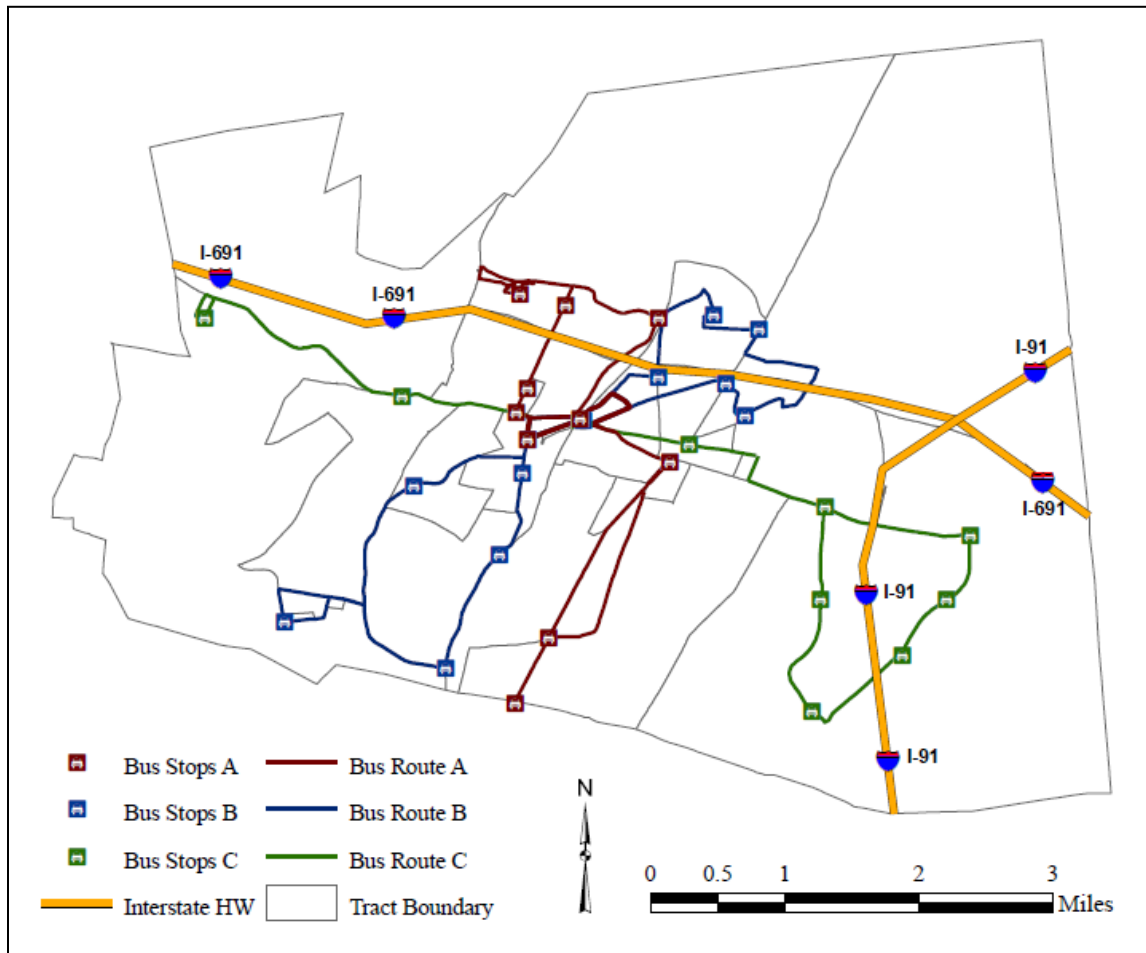
## **OBJECTIVES AND ORGANIZATION**

The objective of this paper is to describe a method for quantifying public transit access that combines existing public transit accessibility indices to harness the positive features of each. For the development of a performance/accessibility measure, TCRP Report 88 (17) identified eight categories of performance measures based on underlying goals and objectives of different transit users. The categories are overlapped in some extent and hence require some distinct broad categorization (14). Three methods have been selected to assure that three primary accessibility measures are being considered. The three methods, individually and in combined, are applied to Meriden, CT as a case study. The results are compared and contrasted for consistency, completeness, and clarity. Finally, this paper evaluates weighting schemes for individual factors for their inclusion in the composite index.

## **METHODOLOGY**

The method presented seeks to leverage less data-intensive methods for measuring public transit accessibility into a single, composite index. For simplicity in calculation, more sophisticated probabilistic modeling methods are not incorporated – the composite index presented requires only straightforward calculations and use of some basic GIS software commands. Selection of methods also considers the intended user of this product and limitation of data sources. This paper selected existing measures which can address public transit accessibility from differing perspectives (i.e. transit planner, transit

operator, the traveler and the property developer). On this basis, three methods: LITA, TCQSM and Time-of-Day tool, were picked to characterize the three transit accessibility coverage aspects.



**FIGURE 1 Three Local Bus Routes and Stop Locations of Meriden, Connecticut.**

Analysis was conducted on the 17 census tracts of the city of Meriden.

Accessibility calculations were carried out for three (A, B and C) public bus routes throughout the city provided by CTtransit. The local bus route network and stop locations are shown in Figure 1. The three methods, their data sources, reasons for selection of these particular methods, the intended users, and scales of analysis are explained below.

### **Method 1: The Time-of-Day Tool**

The Time-of-Day tool (7) measures transit service accessibility using time-of-day travel demand distribution and provides the relative value of transit service provided for each specific time period. This tool requires data on temporal distribution of travel demand on an hourly basis in addition to the transit and census data required for the previous two methods. The time-of-day distribution of travel demand data and a daily trip rate of 4.09 trips per person were adopted from the 2001 National Household Travel Survey (18). Tolerable wait time was defined as 10 minutes in accordance with NHTS data. The fractional distribution for each tract that falls within the 0.25 mile buffered transit route was calculated using GIS software.

The Time-of-Day tool considers the time-of-day distribution of travel demand and reflects the temporal coverage of transit accessibility. The calculation and interpretation of data from several different sources makes this tool more difficult to use and requires some transportation expertise. This measure plays an important role to the public transit planners in determining the importance of transit service provided in each time period of the day.

### **Method 2: The Local Index of Transit Availability (LITA)**

LITA (13) measures the transit service intensity of an area and two basic types of data are required: transit data and census data. Transit data includes full route maps and schedules of all transit lines serving the study area, locations of transit stops, and transit vehicle capacities. Census data encompasses total land area, resident population, and number of employees in each tract. All transit data was collected from the transit provider and census data from U.S. Census (2000).

This method considers the comfort and convenience facet of transit service by appending the vehicle capacity measure in calculation. LITA scores are intended to be useful to property developers by revealing where transit service is most intense and aid the development of land use plans and policies for areas with different levels of transit accessibility.

### **Method 3: The Transit Capacity and Quality of Service Manual (TCQSM)**

The Transit Capacity and Quality of Service Manual (5) incorporates service coverage measure to assess transit accessibility and requires the same datasets (transit and census data) as LITA. Two methods are used to calculate the service coverage: GIS method and the Manual (Graphical) method. For this research, detailed GIS method was used. To identify the spatial service coverage area, a 0.25 mile radius buffer area is applied around transit stops. This method was selected for this research to account for spatial coverage in public transit accessibility assessment.

### **Scaling**

One purpose of this paper is to examine how consistently the three methods rated transit accessibility for each tract of study area. To do this, accessibility grades from each method were compared for each census tract. This presented some problems, as the results were given on three different scales.

LITA was scored to five grades (as shown in Table 2), A through F (excluding E). Grade “A” corresponded to a LITA+5 rating of 6.5 or higher, indicating the highest level of accessibility. TCQSM adopted the level-of-service (LOS) concept, introduced in the Highway Capacity Manual (HCM), for measuring quality of transit service. Scores were grouped in six LOS, A through F (including E). The Time-of-Day-based transit

accessibility analysis tool measures transit accessibility with regard to the number of daily trips per capita (in each Census Tract) that is provided by the transit service. For a more consistent comparison of accessibility results, the calculated scores for each method were standardized across all the census tracts for relative accessibility scores. The scores were standardized by finding the difference between a specific score and the mean of scores and then dividing that difference by the standard deviation of scores for all tracts. For ease of interpretation, this paper develops a common grading scale (as shown in Table 2) with five grades A through F (excluding E). Grade “A” represents a score of +1.5 or higher, indicating the highest level of accessibility, and grade “F” represents a score lower than -0.75, indicating poor level of accessibility.

**TABLE 2: Existing Scaling of Three Methods and the Developed Consistent Grading Scale**

| <i>Grading Scale of Three Methods</i> |   |                                      | <i>New Consistent Grading Scale</i>                               |              |                               |
|---------------------------------------|---|--------------------------------------|---|--------------|-------------------------------|
| <b>Time-of-Day Tool</b>               | <b>LITA+5 Score Scale Range (Grade)</b> | <b>TCQSM Score Scale Range (LOS)</b> | <b>Scale Range</b>  | <b>Grade</b> | <b>Level of Accessibility</b> |
| No Grading Scale                      | $\geq 6.5$ (A)                          | 90.0 – 100.0% (A)                    | $(\mu + \frac{3}{2}\sigma) \geq$                                  | A            | Very High                     |
|                                       | 5.5 – 6.5 (B)                           | 80.0 – 89.9% (B)                     | $(\mu + \frac{1}{2}\sigma) \text{ to } (\mu + \frac{3}{2}\sigma)$ | B            | High                          |
|                                       | 4.5 – 5.5 (C)                           | 70.0 – 79.9% (C)                     | $\mu \text{ to } (\mu + \frac{1}{2}\sigma)$                       | C            | Average                       |
|                                       | 3.5 – 4.5 (D)                           | 60.0 – 69.9% (D)                     | $(\mu - \frac{1}{2}\sigma) \text{ to } \mu$                       | D            | Low                           |
|                                       | $< 3.5$ (F)                             | 50.0 – 59.9% (E)                     | $\leq (\mu - \frac{1}{2}\sigma)$                                  | F            | Very Low                      |
|                                       |   | $< 50.0\%$ (F)                       |   |              |                               |

The development of the composite index on the basis of the three selected methods comprises several steps. First, the raw scores were standardized for each method, as mentioned earlier. Next, the accessibility metrics used for calculations across the three methods were identified (Table 3). Individual weighting factors (WF) were then

assigned to each of the individual measures. The summation of all weighting factors for the individual measures was assigned as the final weighting factor for each method.

Three weighting schemes were considered to assign weighting factors to the measures. In Scheme # 1, WF were allotted according to the occurrence of a measure in the methods (i.e. if a measure is common in all the three methods then its weighting factor was assigned as 3). Scheme # 2 assigns a WF of one to all measures and Scheme # 3 assigns the WF such that the weights for common measures sum to one and unique measures simply receive a weight of one. The weighting factors of individual elemental measures and the total weighting factors for the three methods are shown in Table 3.

**TABLE 3 Development of Weighting Factors (WF)**

| Method           | Accessibility Metric | Scheme # 1    |               | Scheme # 2    |               | Scheme # 3    |               |
|------------------|----------------------|---------------|---------------|---------------|---------------|---------------|---------------|
|                  |                      | Metric Weight | Method Weight | Metric Weight | Method Weight | Metric Weight | Method Weight |
| Time-of-Day Tool | Service Coverage     | 3             | 9             | 1             | 5             | $\frac{1}{3}$ | 10/3          |
|                  | Service Frequency    | 2             |               | 1             |               | $\frac{1}{2}$ |               |
|                  | Demographics         | 2             |               | 1             |               | $\frac{1}{2}$ |               |
|                  | Travel Demand        | 1             |               | 1             |               | 1             |               |
|                  | Waiting Time         | 1             |               | 1             |               | 1             |               |
| LITA             | Service Coverage     | 3             | 8             | 1             | 4             | $\frac{1}{3}$ | 7/3           |
|                  | Service Frequency    | 2             |               | 1             |               | $\frac{1}{2}$ |               |
|                  | Demographics         | 2             |               | 1             |               | $\frac{1}{2}$ |               |
|                  | Capacity             | 1             |               | 1             |               | 1             |               |
| TCQSM            | Service Coverage     | 3             | 3             | 1             | 1             | $\frac{1}{3}$ | 1/3           |

## RESULTS

Table 4 depicts the accessibility results for all census tracts in original scales for each method. With the actual scales for individual method, one can interpret the accessibility results according to that method's grading system. Table 4 shows that the obtained results vary greatly across the methods. To get a comparable picture of accessibility using the



results of these methods, the results must be interpreted in terms of the applicable scale. Furthermore, the accessibility results of the Time-of-Day tool cannot be compared with the other methods because this tool does not provide any grading or scaling system by which one can easily interpret or compare the accessibility results. Thus, for a meaningful comparison of transit accessibility between the tracts that can be easily understood, this paper standardizes the results, providing a picture of the relative difference in accessibility between methods. The results of the standardized scores shown in Table 4 provide less variable results across methods.

**TABLE 4 Comparison of Results in the Raw Scores and Standardized Scores for the Three Methods**

| Census Tract | Raw Score   |  |   |  |   | Standardized Score            |   |                   |   |                    |   |
|--------------|---|--|---|--|---|-------------------------------|---|-------------------|---|--------------------|---|
|              | Time-of-Day Tool Score(Daily exposure per capita) | LITA Score (Rescaled overall score, Grade) |   | TCQSM Score(% of service area served, LOS) |   | Time-of-Day Tool Score, Grade |   | LITA Score, Grade |   | TCQSM Score, Grade |   |
| 1701         | 0.027   | 12.97                                      | A | 76.89                                      | C | 1.97                          | A | 7.97              | A | 1.14               | B |
| 1702         | 0.023   | 5.46                                       | C | 62.36                                      | D | 1.44                          | B | 0.46              | C | 0.67               | C |
| 1703         | 0.012   | 3.99                                       | D | 40.94                                      | F | 0.88                          | C | -1.00             | F | -0.03              | D |
| 1704         | 0.003   | 3.45                                       | F | 5.23                                       | F | -1.03                         | F | -1.54             | F | -1.20              | F |
| 1705         | 0.002   | 4.25                                       | D | 11.39                                      | F | -1.07                         | F | -0.74             | D | -0.99              | F |
| 1706         | 0.006   | 4.83                                       | C | 21.37                                      | F | -0.61                         | D | -0.16             | D | -0.67              | D |
| 1707         | 0.012   | 4.85                                       | C | 50.65                                      | E | 0.16                          | C | -0.15             | D | 0.28               | C |
| 1708         | 0.009   | 5.25                                       | C | 29.21                                      | F | -0.18                         | D | 0.25              | C | -0.42              | D |
| 1709         | 0.019   | 7.69                                       | A | 83.09                                      | B | 1.04                          | B | 2.69              | A | 1.35               | B |
| 1710         | 0.022   | 4.72                                       | C | 69.63                                      | D | 1.33                          | B | -0.27             | D | 0.91               | B |
| 1711         | 0.006   | 4.20                                       | D | 17.10                                      | F | -0.58                         | D | -0.79             | F | -0.81              | F |
| 1712         | 0.004   | 3.71                                       | D | 13.42                                      | F | -0.88                         | F | -1.29             | F | -0.93              | F |
| 1713         | 0.009   | 4.80                                       | C | 39.53                                      | F | -0.32                         | D | -0.19             | D | -0.08              | D |
| 1714         | 0.017   | 8.16                                       | A | 91.28                                      | A | 0.71                          | C | 3.16              | A | 1.61               | A |
| 1715         | 0.013   | 5.42                                       | C | 83.51                                      | B | 0.26                          | C | 0.42              | C | 1.36               | B |
| 1716         | 0.003   | 4.50                                       | C | 14.24                                      | F | -1.03                         | F | -0.49             | D | -0.91              | F |
| 1717         | 0.001   | 1.97                                       | F | 2.91                                       | F | -1.30                         | F | -3.02             | F | -1.28              | F |

The standardized scores shown in Table 4 do still show some variation across the methods (e.g. census tracts 1703, 1710, and 1714). Table 5 presents the grades for the standardized scores using three weighting schemes from Table 3. The results show that the composite scores are consistent across the schemes and the only difference is that Scheme #1 provided composite grade as ‘D’ rather than ‘C’ in Scheme # 2 and 3 for tract 1703. In Scheme #2, each individual measure is treated equally and the presence of a particular measure in all methods gives it additional weight in the combination process. Scheme #1 evaluates transit accessibility addressing the spatial aspects (i.e. service coverage) extensively and Scheme #3 reflects emphasis on the temporal dimension of accessibility measures. In Scheme #3, temporal distribution of travel demand and service frequency are used to calculate the transit accessibility more heavily weighted than the spatial data. Therefore, three (spatial, temporal, and both spatial & temporal) combinations of accessibility measures were considered in different schemes.

**TABLE 5 Comparison of Composite Accessibility Grades for Three Schemes**

| Census Tract | Composite Grade |            |            |
|--------------|-----------------|------------|------------|
|              | Scheme#1        | Scheme # 2 | Scheme # 3 |
| 1701         | A               | A          | A          |
| 1702         | B               | B          | B          |
| 1703         | D               | C          | C          |
| 1704         | F               | F          | F          |
| 1705         | F               | F          | F          |
| 1706         | D               | D          | D          |
| 1707         | C               | C          | C          |
| 1708         | D               | D          | D          |
| 1709         | A               | A          | A          |
| 1710         | C               | C          | C          |
| 1711         | D               | D          | D          |
| 1712         | F               | F          | F          |
| 1713         | D               | D          | D          |
| 1714         | A               | A          | A          |
| 1715         | C               | C          | C          |
| 1716         | F               | F          | F          |
| 1717         | F               | F          | F          |

### **Spatial Distribution of Accessibility Results**

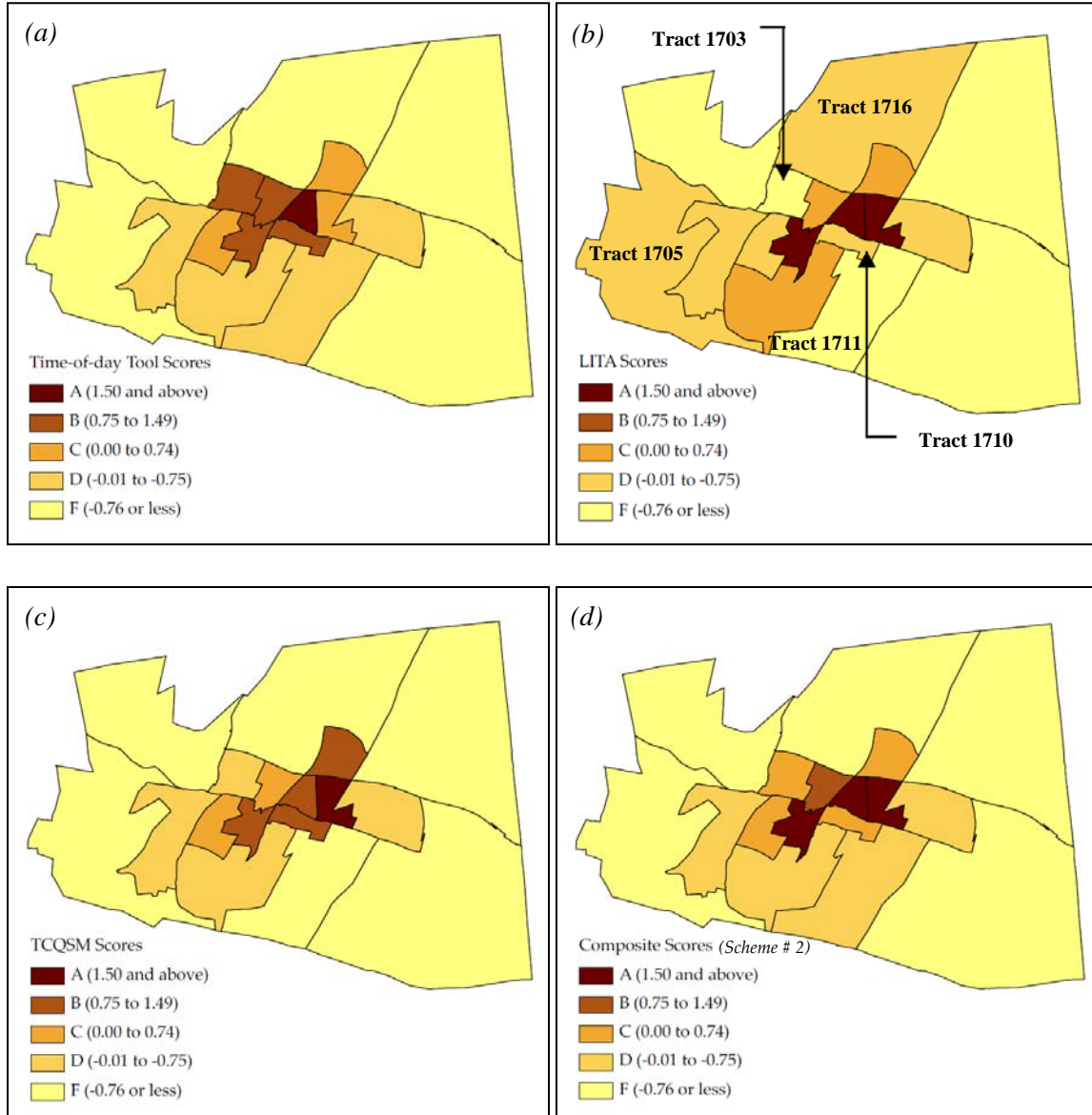
TCQSM considers a much smaller coverage area than the other two methods. While there is broad agreement that the best coverage is concentrated in a relatively small area (which is expected, given the service map in Figure 1), there is disagreement on that extent for the middle of the accessibility spectrum (Figure 2). LITA considers a much larger area to have moderate accessibility, but this may be due in part to its target audience: developers. LITA is designed to broadly identify good investment possibilities near transit, leaving more detailed analysis to those regions a developer may want to target. TCQSM is concerned with spatial coverage only and therefore follows the layout of lines and stops closely. The Time-of-Day tool considers measures of demand which reflect that some tracts that are not well covered spatially may in fact serve high demand populations. It is important to remember that these scaled versions are comparing a particular tract against the average measure for the entire system. These values are not absolute.

### **Comparative Example**

Figure 2 maps the grades of accessibility scores across methods and illustrates the grading scale of the accessibility scores. This graphical view shows relative accessibility intensity which is helpful for the comparison of accessibility between different tracts.

Three census tracts (e.g. census tracts 1703, 1710 and 1711) chosen to represent difference in accessibility intensity across the methods are indicated in Figure 2. LITA represents lower scores for tracts 1703 and 1710 than the other methods. This method provides relative lower score to the dense populated smaller area (i.e. already developed area) and gives a moderate accessibility result to the larger areas (e.g. census tracts 1705 and 1716, Figure 2). This is primarily due to the intended users' viewpoint of this

method. Higher LITA score for a census tract indicates that this tract has more potential for future transit oriented development or redevelopment.



**FIGURE 2 Accessibility Scores for Different Methods: (a) Time-of-Day Tool; (b) LITA; (c) TCQSM; (d) Composite, Scheme # 2.**

The TCQSM method provides higher accessibility scores than the LITA method for the census tracts 1703 and 1710. TCQSM is intended to characterize transit

accessibility generally by the existence of transit stops and transit lines in the service area and counts for the percentage of 0.25 mile radius buffer area around the bus stops.

Therefore census tract 1703 results in a higher accessibility score in TCQSM than in LITA.

The Time-of-Day tool considered time-of-day travel demand distribution for an area and did not consider the spatial distribution of transit routes as in TCQSM. Census tract 1711 appears as a moderate accessible tract in the time-of-day tool but this tract has poor accessibility in TCQSM and LITA method. This reveals that some tracts that have poor spatial coverage of transit may have considerable temporal coverage to serve the high demand population for this tract.

The composite scores mapped in Figure 2 provide a single accessibility score for tracts that show variability between methods. This score represents three stakeholder perspectives and if a single metric is to be used, may be a more robust measure than one of the individual methods.

## **CONCLUSIONS**

This paper examined the benefit of a consistent grading scale across different stakeholder groups and formulated a composite accessibility measure. The individual accessibility results were calculated to examine consistency in the results as well as in the grading scales across methods. The composite accessibility measure was developed by integrating three methods, which may be useful as a reliable and defensible measure for stakeholders and policy officials as it encompasses several user perspectives. This paper standardized individual raw scores and adopted a common grade scale. Several

permutations of combined weighting scheme were tested. This paper helps planners select a set of accessibility measures and presents a method of combining them to produce a more defensible and robust accessibility result for their customers. The result of composite measure can be taken as a basis for adjusting the priorities of public transport services and to address lack of service in public transport provision. The composite index provides a relative accessibility measure of the degree to which transit is reasonably available at the origin of a trip. This information is important for zonal service equity analysis and understanding transit supply provision in the community.

Further development and refinement of the measure would be useful in several areas. In addition to those accessibility measures in this study, a needs gap (*14, 15*) assessment in transit service would address the transportation disadvantaged population and its relationship to systemic spatial coverage.

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### **CHAPTER 3: MEASURING SERVICE GAPS: AN ACCESSIBILITY-BASED TRANSIT NEED INDEX**

#### **ABSTRACT**

The integration of transit needs into transit accessibility indexing is important for the evaluation of existing transportation systems and, service gaps, and for the identification of priority areas for future investments in transportation infrastructure. This paper details an accessibility-based transit need indexing model that focuses on the necessity of evaluating transit needs and transit accessibility simultaneously. A need index is developed to identify areas in high need of public transit services using economic and socio-demographic information and a composite accessibility index is developed to identify levels of access to transit services and shortcomings in service provision. The need for transit service is then modeled as the lack of transit accessibility and correlates different access indicators with their ability to predict transit service need. This model maps areas with different levels of transit accessibility and transit needs using a single score, which may be easily interpreted by planners examining transit equity. The model has been applied to the city of Meriden, CT and results have been compared with a general approach for consistency and effectiveness. The paper also highlights the model's usefulness through a representative example of its application.

## INTRODUCTION

Public transportation has a large influence on regional development patterns, economic viability, and the 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 continues to be an important social service and can be considered an essential part of livable communities. Accessibility, one of the most important aspects of public transportation system studies, measures people's ease and convenience of 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.

Some might assume that the increased levels of access to transit services would lead to better transit ridership. However, the rise in personal income, increase in household car ownership, and substantial public investment in the construction of new streets and freeway systems have resulted in reduction in demand for public transit (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, the 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 transit infrastructure investment to improve accessibility for those who have limited transport options.

The 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 that do not have it in required level. Existing measures have been used to identify service supply level and needs level separately and compare those 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 the 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 quantify the impact of service attributes on providing access to needy households within an area.

The next section of this paper reviews existing transit accessibility measures and the different accessibility variables used in their calculations, including those that evaluate service gaps or transit disadvantaged areas. The methodology section describes the development of transit accessibility and transit need indices, the interaction between transit need and accessibility scores, the basic technique of developing an accessibility-based need index regression model, and the 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 have been defined on the basis of a wide range of concepts. Some methods measure accessibility level on the basis of access variables (e.g., spatial, temporal, comfort, etc.) but without reflecting the actual need for transit services. Rood (3) 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. The Time-of-Day based transit accessibility analysis tool developed by Polzin *et al.* (4) measures transit accessibility as the daily trips exposure per capita to the service. This tool uses the time-of-day distribution of travel demand to measure the relative value of transit services provided in each time period of the day. It also integrates buffer-extracted zonal demographic data to identify potential transit riders. The Transit Capacity and Quality of Service Manual (TCQSM) (5) measures public transit accessibility of a system as the percentage of the transit-supportive area (TSA) covered by the service coverage area. TSA reflects the area with either a minimum household density or employment density that capable of supporting hourly transit service (5). Therefore, TSA identifies areas that need transit service based on minimum density criteria.

Cheng and Agrawal (6) described a Time-Based Transit Service Area Tool (TTSAT) to map transit accessibility by measuring transit service area on the basis of users' door-to-door travel time. All components of travel time from traveler's origin to destination (i.e., walk time, wait time, in-vehicle time, etc.), are included in the travel time calculations. This measure allows TTSAT users to adjust passengers' maximum acceptable walk time and total trip time.

Other researchers have approached the accessibility problem by examining service gaps in transit service provision and they compared the transit access and transit need indices to evaluate service gaps in an area. Currie and Wallis (7) identified a method to assess the relative quality of public transport services with respect to transit needs. A single transport need index was developed using socio-economic and transport-need

related indicators to quantify the distribution of needs in the community. The transport supply index, measuring the availability of transport to the transport disadvantaged, was calculated as the density of transit vehicle-kilometers during daytime shopping periods on weekdays. Another approach for identifying geographical gaps in the service coverage was developed by Currie (8). He developed a 'Needs Gap' approach to assess public transport services by comparing the distribution of the supplied services with the spatial distribution of transport needs. The supply index was calculated using a transit network supply model, which measures the network supply costs for different time periods and trip purposes. This provided a further refinement of the supply side modeling used in previous applications of this approach, though the transit needs measure remained same as noted in previous research (7).

Another adaptation of the 'Needs Gap' approach was developed by Currie (9) to quantify social gaps in public transit provision for socially disadvantaged peoples. This approach involved measuring public transport supply with combined service frequency (vehicle trips per week) and access distance. The measure for social need was developed by combining the Australian Bureau of Statistics Index of Relative Socio-Economic Advantage/Disadvantage (IRSAD) and the earlier transport need index mentioned in (7).

Murray and Davis (10) combined public transit need with accessibility measure for evaluating the equity of this transit service provisions. An index was developed in order to evaluate the relative public transport needs for each zone within the study area. They used a weighting approach to combine average household income, unemployment rates, and average family size. The level of access to service of an area was measured as the percentage of area suitably covered by public transit (10).

Hine and Mitchell (11) assessed transit need and transit related social exclusion. For this purpose, they conducted a household survey to collect basic household data, socio-economic information, travel behavior, and particulars on private car ownership. This information was used by the researchers to identify transport disadvantaged peoples.

Bhat *et al.* (12) described a customer-oriented, utility-based Transit Accessibility Measure (TAM) to identify the inequality between transit service provision and the level of transit need within a community. The TAM index combined the transit accessibility index (TAI) with the transit dependence index (TDI). This measure identifies the users who need the service most by comparing the level of service supply with the level of demand by the transit user.

The review of the above mentioned studies revealed that most of the research used a similar methodology to identify service gaps or to map transit equity, which estimates both transit needs and transit access, then compares them to measure service gaps or identify transit disadvantaged areas. This methodological approach is referred further in this paper as *General Approach* and the studies (as reviewed earlier) that have been used this general approach are listed as follows for ease of identification:

- Currie and Wallis (7)
- Murray and Davis (10)
- Currie (8)
- Bhat *et al.* (12)
- 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 transport disadvantaged population is proposed for examining equity in service provision.

## **OBJECTIVES AND ORGANIZATION**

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

## **METHODOLOGY**

A series of research tasks needed to be addressed in the 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 below prior to 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 (i.e., LITA, TCQSM, and Time-of-Day based transit accessibility analysis tool). The method is described briefly here; the reader is directed to Mamun and Lownes (13) for greater detail. This approach used existing methods and their components to reflect public transit accessibility from differing perspectives (i.e., transit planner, transit operator, the traveler and property developer) and characterize the three important transit accessibility coverage aspects (trip, spatial, and temporal coverage) simultaneously.

LITA (3) measures the transit service intensity of an area and requires both transit and census data. Transit data includes locations of transit stops, full route maps, and schedules of all transit lines serving the study area, and transit vehicle capacities. Census data provides information on total land area, resident population, and the number of employees in each tract. TCQSM (5) uses a service coverage measure to assess transit accessibility. The service coverage area is calculated by a detailed GIS method that measures the percentage of area covered by a 0.25 mile buffer around bus stops. This method requires the same datasets (transit and census data) as LITA. The Time-of-Day based transit accessibility analysis tool (4) was considered to develop the composite index as it is the only tool to account for time-of-day distribution of travel demand and which reflect the temporal coverage of transit accessibility. This tool provides the relative accessibility of transit services provided during a specific time period using time-of-day travel demand distribution. It requires data on the temporal distribution of travel demand (on an hourly basis) in addition to the transit and census data required for the previously

mentioned methods. The time-of-day distribution of travel demand data was adopted from the 2001 National Household Travel Survey (NHTS) (14).

**TABLE 1 Composite Accessibility Index: Raw, Standardized and Composite Scores**

| Census Tract | Raw Score              |            |             | Standardized Score (SS) |            |             | Composite Index                  |       |
|--------------|------------------------|------------|-------------|-------------------------|------------|-------------|----------------------------------|-------|
|              | Time-of-Day Tool Score | LITA Score | TCQSM Score | Time-of-Day Tool Score  | LITA Score | TCQSM Score | Scores (using Weighted Scheme#2) | 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     |

Table 1 shows the raw accessibility scores of the three methods outlined above.

Each method uses a different scale and therefore, the individual scores required adjustment before they could be integrated into a single, composite score. Hence, the raw scores for each method were normalized 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 for this tract and the mean of scores for all tracts was calculated

and then the difference was divided by the standard deviation of scores for all tracts. Next, this approach applied weighting factors (WF) 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. To determine a method's WF, all of the parameter WFs associated with that method were summed together. 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); the reader is directed to Table 2 in Chapter 2 for greater details about scaling. Grade 'A' represents a score of +1.5 or higher, indicating the highest level of accessibility, while grade 'F' represents a score lower than -0.75, indicating the poorest level of accessibility (Table 1). The grade breaking points were determined based on the standard deviations method. In this method the mean value was identified firstly and then the class breaks were placed above and below the mean at intervals of ½ standard deviations.

$$\begin{aligned} &\text{Composite Accessibility Index} \\ &= \frac{(SS_{\text{Time-of-Day}} * WF_{\text{Time-of-Day}}) + (SS_{\text{TCQSM}} * WF_{\text{TCQSM}}) + (SS_{\text{LITA}} * WF_{\text{LITA}})}{WF_{\text{Time-of-Day}} + WF_{\text{TCQSM}} + WF_{\text{LITA}}} \end{aligned} \quad (1)$$

### **Transit Needs Measurement**

Transit service is often considered a social service in urban areas and the provision of equitable transit service is essentially viewed as a basic right by transit planners (10). An equitable transit service requires more concern given to serving those who need the service most. Therefore, there is a necessity to identify those people who do not have

sufficient public transport service opportunities but have significant need. To do this, a transit need index was developed based on the workers who are transport disadvantaged.

Hine and Mitchell (15) defined transport disadvantaged people as people whose needs are not met by public transit services. These include people with disabilities, elderly people, children, the unemployed and low-paid individuals. In another paper, Hine and Grieco (16) defined the transport disadvantaged as people with low income, women, the elderly, disabled people, and children. Currie *et al.* (17) identified transport disadvantaged people on the basis of car availability in households. This approach included an assessment of ‘forced car ownership’ (FCO) and ‘zero car ownership’ (ZCO) households. FCO was defined as low income households who own 3+ cars and ZCO was defined as low income households that do not own a car.

Five different transport disadvantaged classifications were considered with all data were from the Census Transportation Planning Package (CTPP) 2000 Database (18). The transport disadvantaged classifications are based on the number of workers belonging to the transport disadvantaged classes and are as follows:

#### *Forced Car Ownership (FCO)*

This group is comprised of workers living in low income households (annual incomes below \$30,000) who own 3 or more cars. The terminology ‘forced’ car ownership has been used for low-income households in remote rural areas those ‘forced’ to own and operate cars (17). It is hypothesized that this classification represents households that must own a large number of vehicles to meet their mobility needs because transit service is lacking.

### *Zero Car Ownership (ZCO)*

This group includes workers in low income households that do not own a private car.

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 low income constraint makes it difficult for them to have a high budget for their daily transport expense. It is assumed that this group relies on low cost public transit services more than higher income households.

### *People over 65 years old*

This group includes elderly people, who out of need or desire often change their driving behaviors and likely to use transit services for their mobility needs. As people grow older, they shorten their trips, and look for less congested and lower speed roadways and eventually stop driving (19).

### *Disabled Individuals*

This group identifies workers with any kind of disabilities (i.e., physical disability, mental illness, and other serious health impairments). This classification is considered because they generally depend on accessible and wheelchair friendly transit services for getting access to jobs and other social services.

The transit needs index uses only the disadvantaged workers. While limiting the index to workers, the need index under-represents two classes of transit disadvantaged people (i.e., elderly people and people with disabilities). This research recognizes the limitation of this data but continues to use these data to maintain consistency in unit of

measure with other data classes. Another important consideration in the development of a need index is the possible double counting of people in different transit disadvantaged groups. For example, many people in the low income group were also in the zero car ownership group, meaning they were double counted in the calculations. Therefore, the actual need index of a census tract may be lower than represented in the calculation. To prevent this, the group data was collected and sorted out as carefully as possible on the basis of cross data availability between groups<sup>1</sup>.

### **Transit Accessibility as a Function of Unmet Transit Need**

The primary objective of this paper was to develop an accessibility-based need measure to reflect an area's unmet transit needs as well as its level of public transit accessibility. For this purpose, a composite accessibility index and a transit need index were estimated in the earlier sections. The access index relies heavily on service and coverage characteristics of a transit service, while the need index focuses on demographics. The unmet transit need index was measured as the *percentage of transit disadvantaged workers in a census tract who used private car as their mode of travel*. While defining the unmet transit need index based on car ownership indicators, this research does not consider the travelers' mode choice or lifestyle preference to own private car, which might be worth considering. Therefore, we do not presume to say that all transit disadvantaged workers would take transit service even if they have access to the service. We only intend to investigate the relationship between these unmet transit needs and accessibility measures as a means to look at the relationship between need for service and

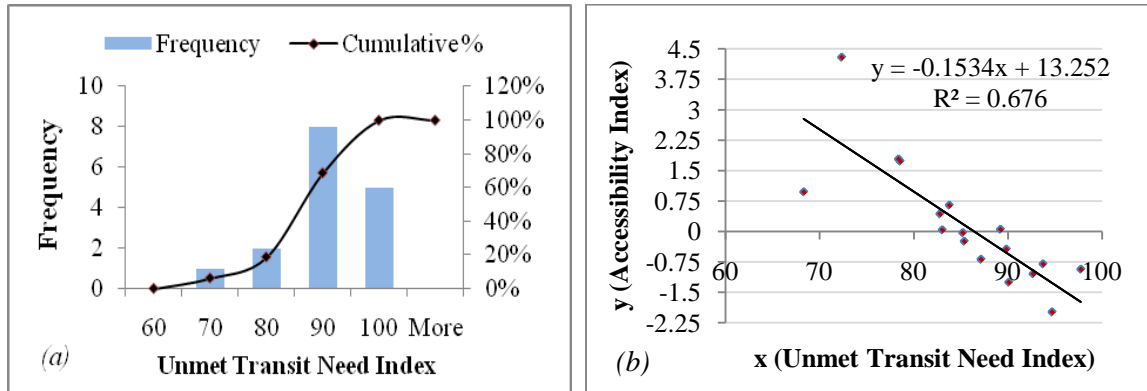
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<sup>1</sup> Common data on different combinations of classes were collected and subtracted from the classes to avoid over counting. For example, workers who use auto as their mode of travel for elderly people and disable individuals, and the workers who are both elderly and disable were collected. Then the common data were halved and subtracted from both classes.

the service characteristics. A linear regression model was estimated for the composite accessibility scores and the unmet transit need scores, with unmet transit need index on the x-axis and composite transit accessibility index on the y-axis.

The histogram shows (Figure 1(a)) that the unmet transit need index data (Table 3) is normally distributed and therefore, this data can be used for developing further statistical models. The distribution shows some skewness to the right, but it is expected as the majority of tracts of this small sample data have relatively high need index values. A regression line (shown in Figure 1(b)) over the actual data points is plotted for evaluating the correlation among composite accessibility index and unmet transit need index. A hypothesis test (*t-test* at 5% significance level) was conducted to determine whether there is significant relationship between unmet transit need and composite accessibility scores and it was found that the slope of the regression line (shown in Figure 1(b)) differs significantly from zero. Since unmet transit need index reflects the percentage of transit disadvantaged workers that use auto, it is reasonable to expect that there is some negative correlation between the unmet transit need index and composite transit accessibility index. In this case unmet transit need index has a negative coefficient suggesting that the percentage of auto usage decreases as transit accessibility increases. The  $R^2$  value indicates that 67.6% of variance can be accounted for by the entire regression. Most of the data points are clustered towards the lower right corner of the plot, indicating most of the tracts have high transit need and low level of accessibility and will temper any extrapolations outside of the observed data range. Ordinary Least Square (OLS) assumptions were verified for this linear model. The linear relationship indicates that higher unmet transit need (*measured as the percentage of auto use by the transport*

*disadvantaged workers*) is correlated to poor transit service accessibility. This serves as a means of validating the supposition that transit service need is strongly correlated to the lack of accessibility.



**FIGURE 1 Estimation of Linear Function between Transit Accessibility and Needs: (a) Histogram of Unmet Transit Need Index, and (b) Scatter Plot to Examine Relationship.**

### Modeling Accessibility-Based Need Index

This section describes the development of service gap model as a function of service characteristics. Previous sections support the idea that unmet transit need (as measured by transit disadvantaged workers) is correlated with the lack of service accessibility as measured by service characteristics. The models described below intend to provide a simple way to estimate the impact service improvements might have on addressing the need for transit service. Furthermore, the goal of this modeling approach is to estimate service gap using only service characteristics. The response variable in the models is named as ‘Accessibility-based Need Index’ which estimates the unmet transit need index/service gap. The independent variables were selected to represent both spatial and temporal aspects of transit accessibility. Computational simplicity and data source availability were also taken into consideration during the selection of access variables.



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. Below is a brief description of these variables, an explanation of the required data, and an outline of the methods used to compile the data:

*Percent of Service Area (%SERVICE\_AREA)*

Percent of 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 mile buffers around transit stops by the total area of the tract. This variable reflects spatial accessibility to transit service.

*Compiled Route-Miles per Square Mile of Area (BUS\_ROUTE\_DEN)*

The total length of transit routes running through each census tract was estimated by using ArcGIS area/length calculation feature. Routes running along the edge of a tract were halved between the bordering tracts to avoid over counting the actual route length. Total tract route length (miles) is then divided by the tract area (square miles).

*Average Daily Bus Runs per Stop (DAILY\_BUS)*

Total number of bus stops in each tract was first determined. Bus stops falling on a tract boundary were halved between the bordering tracts. The number of bus runs for all stops were summed to get total number of daily bus runs for each census 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. The calculation of this variable requires a schedule of bus services to determine the daily vehicle runs per bus stop and a service map to get the exact location of the bus stops.

*Daily Seat-Miles per Capita (SEAT\_MILE/CAPITA)*

This access variable was calculated based on three data: total daily available seats, total route-miles and total 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 population of the tract.

**TABLE 2 Regression Models for Estimating Transit Needs Using Accessibility Variables**

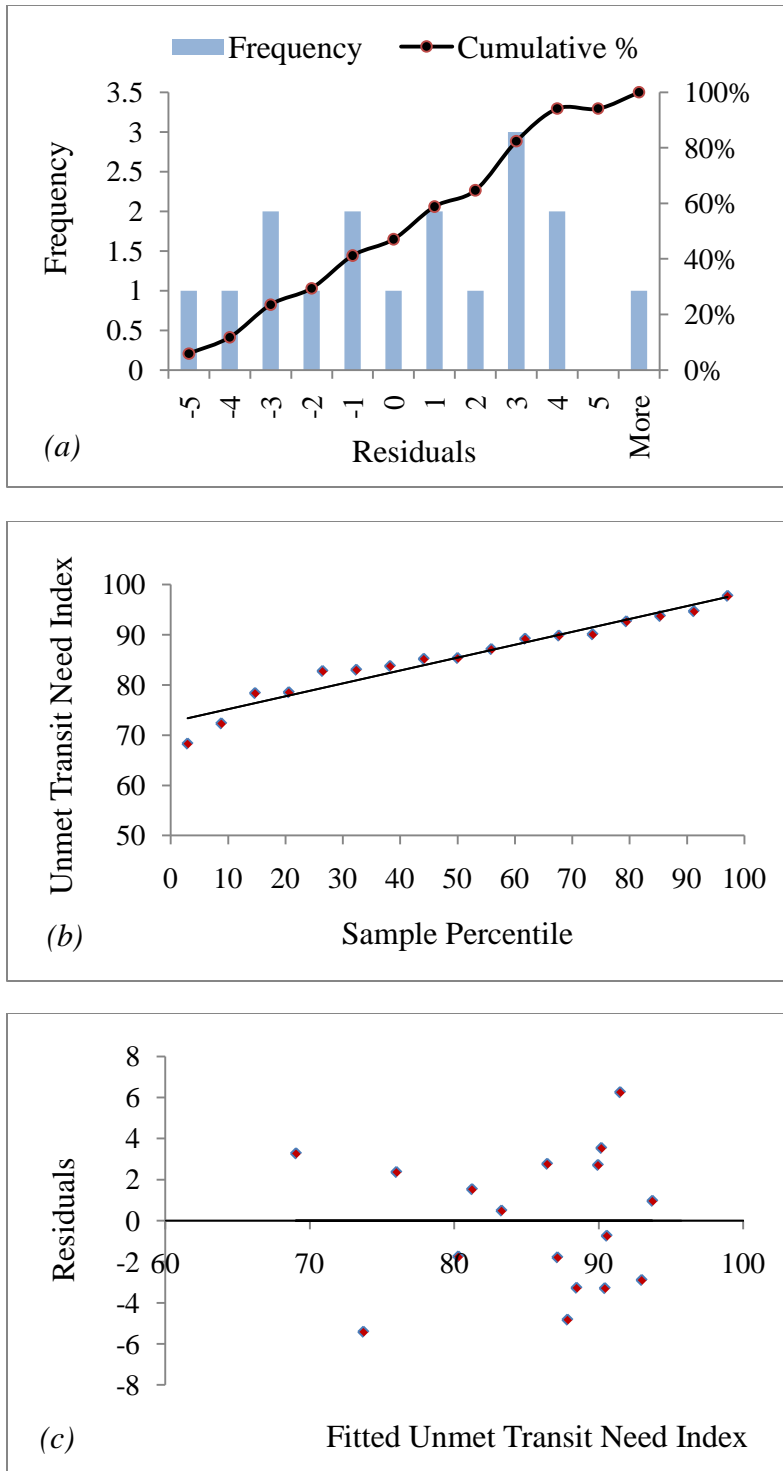
| Model   | Model R <sup>2</sup> | F-value | AIC    | Intercept, Independent Variable | Coefficient | t-statistic | P-value | VIF  |
|---------|----------------------|---------|--------|---------------------------------|-------------|-------------|---------|------|
| Model 1 | 0.8232               | 32.59   | 8.4583 | Intercept                       | 94.2442     | 63.19       | 0.0000  | -    |
|         |                      |         |        | %SERVICE_AREA                   | -0.14751    | -4.58       | 0.0004  | 1.23 |
|         |                      |         |        | SEAT_MILE/CAPITA                | -2.96682    | -4.01       | 0.0013  | 1.23 |
| Model 2 | 0.8417               | 37.23   | 8.5333 | Intercept                       | 93.9822     | 66.67       | 0.0000  | -    |
|         |                      |         |        | %SERVICE_AREA                   | -0.07091    | -1.75       | 0.1026  | 2.18 |
|         |                      |         |        | BUS_ROUTE_DEN                   | -1.79409    | -4.43       | 0.0006  | 2.18 |
| Model 3 | 0.7396               | 19.87   | 9.3333 | Intercept                       | 100.0435    | 33.32       | 0.0000  | -    |
|         |                      |         |        | %SERVICE_AREA                   | -0.17540    | -4.75       | 0.0003  | 1.09 |
|         |                      |         |        | DAILY_BUS                       | -0.47412    | -2.53       | 0.0239  | 1.09 |

To find the best approximation of the relationship between the unmet transit need index (*measured as the percentage of transit disadvantaged workers in a census tract who used private car as their mode of travel*) and the independent access variables, three different models (shown in Table 2) were identified using backward elimination technique.. In this technique, the model begins by including all variables and then the variables with the largest *p*-value removed from the model. With this backward elimination technique, Model 1 was found as the best model to predict the unmet transit

need/service gap. In addition, two extra models were identified by substituting one predictor from each model. The resulting three models were evaluated based on 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  $F$ - values. In *Model 1*, variable *%SERVICE\_AREA* has a stronger significant coefficient (higher  $t$ -value) than in *Model 2*. Furthermore, *Model 2* has a higher  $P$ -value for the *%SERVICE\_AREA* variable than *Model 1*, meaning it is less useful for predicting the response variable – this is likely due to increased correlation between service area and the second independent variable, a hypothesis supported by the higher Variance Inflation Factor (VIF) values. The variance inflation factor (VIF) was calculated (shown in Table 2) to identify the multicollinearity of the explanatory variables. Depending on the source, upper thresholds of acceptable VIF can vary with common boundaries being a VIF of 5 or VIF of 10 (20, 21). Against these thresholds, all three models have an acceptable level of multicollinearity, with the preferred model, *Model 1*, having a VIF of 1.23. Furthermore, the Akaike Information Criteria (AIC) values (as shown in Table 2) were calculated to measure the relative goodness of fit of those non-nested competing models (22). This comparison approach favors *Model 1* among them with the smallest AIC value. Thus, it would be reasonable to conclude that overall *Model 1* is the best of the three models for estimating transit need using access indicators. The functional form for *Model 1* is as follows:

#### **Accessibility-Based Need Index**

$$= 94.2442 - 0.14752 * \%SERVICE\_AREA - 2.96682 * SEAT\_MILE/CAPITA$$



**FIGURE 2** Verification of Regression Model Assumptions: (a) Histogram of Residuals, (b) Normal Probability Plot, and (c) Plot of Residuals Versus Fitted Unmet Transit Need Index Values.

The model (Model 1) indicates that the accessibility-based need index reduces with the increase in service coverage and daily available seat-mile per capita of a transit service. Therefore, it states that the percentage of transit disadvantaged workers who use auto as their mode of travel reduces with the transit service improvements. The negative relationship between transit need index and the service variables suggests that an improved accessibility to transit service can reduce people's reliance on private autos. In addition, this model states that if transit disadvantaged populations can be located within accessible distance to transit services then car ownership appears to 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. The details of these checks for *Model 1* are shown in Figure 2. A histogram of residuals was plotted (Figure 2(a)) to test for normality. This plot showed some departures from normality and which might be due to the small sample size. To further test normality, a normal probability plot was created (Figure 2 (b)) and it was found that 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 as the single best diagnostic for checking assumptions in multiple regression (23). This plot (shown in Figure 2(c)) shows that the residuals are reasonably evenly distributed about zero, suggesting the residuals have zero mean and the correlation between the residuals and the fitted values is approaching zero. However, this plot does display some curvature and vertical spread does vary to some extent, so for a more thorough check of constant

variance, *White's General Test for Heteroskedasticity* (24) was performed and it was found that there is no evidence of heteroscedasticity.

## RESULTS

Analysis was conducted on the 17 census tracts of Meriden, CT<sup>2</sup>. Accessibility calculations were carried out for three (A, B and C) public bus routes that service the city. All of the previously mentioned studies (i.e., General Approach) measured transit accessibility and the need for transit services separately and then compared them to quantify service gaps and identify transport disadvantaged areas. This paper developed a model-based approach which can identify service gaps in transit service provisions with a single accessibility-based need measure. This approach does not require the calculation of separate transit accessibility and need scores and only uses accessibility variables, which are less data intensive. The single measure's results were compared with the results obtained from General Approach to justify the 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), and five grades (A through F, excluding E) were assigned as shown in Table 3. The accessibility-based need index was also grouped into five categories, A through F excluding E. Grade 'A' characterizes an area having 'very high level of accessibility to transit service and very low levels of unmet transit need' and grade 'F' represents 'very low level of accessibility with very high level of unmet transit need'.

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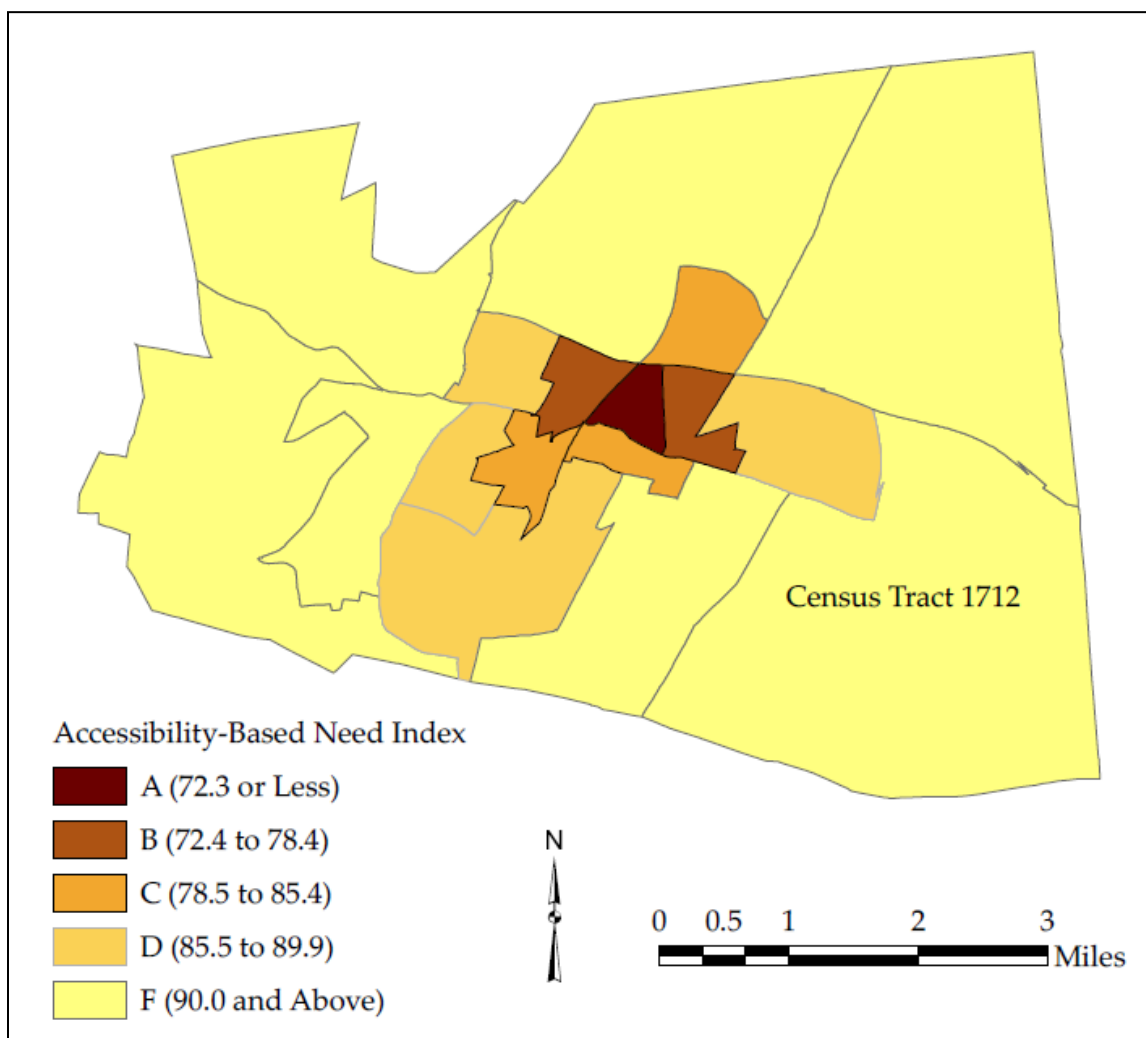
<sup>2</sup> One of the limitations of this model is associated with the small sample size. A large sample size could provide more meaningful results, and which might be useful to conduct some other statistical diagnostic tests to justify that the correlation between transit needs and transit accessibility did not just happened by chance alone.

**TABLE 3 Comparison of Combined Transit Accessibility and Transit Need Results Obtained Form General Approach and Model-Based Approach**

| Census Tract | General Approach     |                        |            |                       |                                    | Model-Based Approach                   |                                    |
|--------------|----------------------|------------------------|------------|-----------------------|------------------------------------|--|------------------------------------|
|              | Access-ibility Index | Level of Accessibility | Need Index | Level of Transit Need | Service Gap Measure (Double Grade) | Fitted Accessibility –Based Need Index | Service Gap Measure (Single Grade) |
| 1701         | 4.29                 | A-(Very High)          | 72.3       | A-(Very Low)          | A-A                                | 69.0                                   | A                                  |
| 1702         | 0.97                 | B-(High)               | 68.3       | A-(Very Low)          | B-A                                | 73.7                                   | B                                  |
| 1703         | 0.04                 | C-(Average)            | 83.0       | C-(Average)           | C-C                                | 87.8                                   | D                                  |
| 1704         | -1.25                | F-(Very Low)           | 90.1       | F-(Very High)         | F-F                                | 93.0                                   | F                                  |
| 1705         | -0.93                | F-(Very Low)           | 97.7       | F-(Very High)         | F-F                                | 91.5                                   | F                                  |
| 1706         | -0.44                | D-(Low)                | 89.8       | D-(High)              | D-D                                | 90.6                                   | F                                  |
| 1707         | 0.05                 | C-(Average)            | 89.2       | D-(High)              | C-D                                | 86.4                                   | D                                  |
| 1708         | -0.03                | D-(Low)                | 85.2       | C-(Average)           | D-C                                | 88.5                                   | D                                  |
| 1709         | 1.73                 | A-(Very high)          | 78.5       | C-(Average)           | A-C                                | 80.3                                   | C                                  |
| 1710         | 0.65                 | C-(Average)            | 83.8       | C-(Average)           | C-C                                | 83.3                                   | C                                  |
| 1711         | -0.69                | D-(Low)                | 87.1       | D-(High)              | D-D                                | 90.4                                   | F                                  |
| 1712         | -1.05                | F-(Very Low)           | 92.7       | F-(Very High)         | F-F                                | 90.0                                   | F                                  |
| 1713         | -0.24                | D-(Low)                | 85.4       | C-(Average)           | D-C                                | 87.1                                   | D                                  |
| 1714         | 1.78                 | A-(Very High)          | 78.4       | B-(Low)               | A-B                                | 76.0                                   | B                                  |
| 1715         | 0.43                 | C-(Average)            | 82.8       | C-(Average)           | C-C                                | 81.2                                   | C                                  |
| 1716         | -0.80                | F-(Very Low)           | 96.7       | F-(Very High)         | F-F                                | 90.2                                   | F                                  |
| 1717         | -1.99                | F-(Very Low)           | 94.7       | F-(Very High)         | F-F                                | 93.7                                   | F                                  |

Table 3 shows that the need index obtained from the model-based approach were consistent with those from the general approach. For most of the census tracts (e.g., tracts 1701, 1704, 1705, 1710, 1712, 1715, 1716, and 1717) the service gap results are consistent. For some tracts (e.g., 1702, 1708, and 1713), the model-based approach showed higher unmet transit needs results 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 (e.g., 1707, 1709, and 1714) showed lower accessibility score using 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.



**FIGURE 3 Levels of Combined Transit Accessibility and Transit Needs.**



### **Assessing Service Gaps/Transit Disadvantaged Areas**

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 the 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 transport and consistently high unmet transit need for transit services areas suggests that significant expenditure on public transport services and infrastructure should be prioritized for this region. These areas should be of great interest to transit providers because they contain the most needy transit users, which should be a concern to increase the efficiency of this service and it will help transit planners in government agencies ensure an equitable use of public resources.

### **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 provides a basis for assessing various policies to ameliorate the lack of transit accessibility. This model requires relatively little data and yet is designed to assist transit providers to identify best possible new facilities or re-allocation schemes in order to optimally utilize resources from a transit accessibility and need perspective. Following is a brief example of how such a method could be applied.

Transit disadvantaged areas can be analyzed to determine potential locations for new and expanded facilities or services. An assessment of service improvement options were investigated for census tract 1712. Figure 3 shows that tract 1712 is a transit

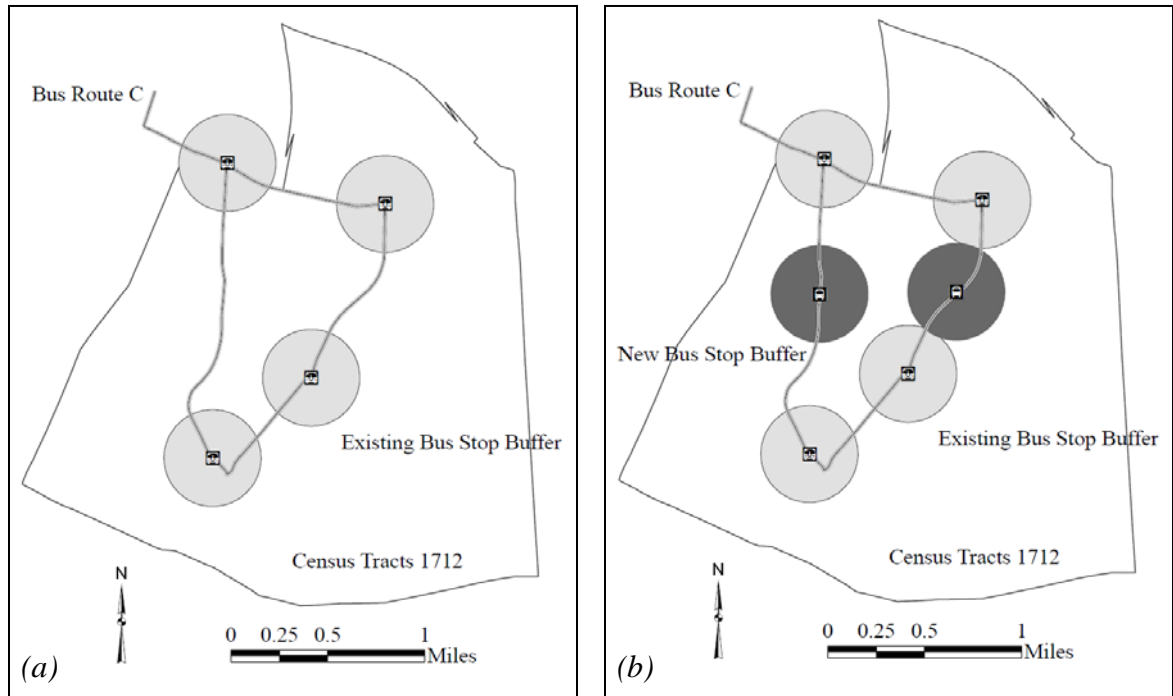
disadvantaged area with a very high need for service but a very low transit accessibility level.

Figure 4(a) shows the existing locations of bus stops and route alignment in census tract 1712. Connecticut transit (CTtransit) provides bus service to this tract with bus route C. This tract had a population of 7,565 in the year 2000 and a land area of 5.034 square miles (US Census). A total of 40 vehicles runs are made at these four bus stops daily. The average service span for this route is eleven hours (from 6:30 am to 5:30 pm) and the average headway for each stop is approximately one hour. This low frequency bus service results in poor accessibility and according to the model developed in this paper, represents highest transit need for this tract. With this simple model, improvement policies can be inspected to measure the changes in transit need resulting from of service improvements. Two hypothetical options for this census tract are considered in this paper.

In Option 1, the bus service frequency and the hours of service were increased for the existing bus stops and route alignments (Figure 2(a)). The service span was increased to 13 hours from 11 hours and the bus service frequency was changed to 40 minutes, which only caused changes to one of the independent variables, SEAT\_MILE/CAPITA. Using the model equation, this option improves 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’).

The second option considers the placing of two new transit stops (Figure 4(b)) within this tract. Locations of these stops were chosen so that the 0.25 mile buffer areas around the transit stops would not overlap, increasing service coverage. It was also assumed that the number of buses run from the new stops is the same as the 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) which also found to offer little improvement (from grade F to grade D) in the accessibility-based need index.



**FIGURE 4 Assessing Accessibility Improvement Options for Tract 1712: (a) #1 Existing Locations of Bus Stops and Route Alignment, and (b) #2 Proposed New Bus Stops.**

Changes in level of unmet transit need with the provision of transit service attributes may be predicted using this model result by calculating the changes in the percentage of transit disadvantaged workers using auto as their mode of travel (i.e., the need index). Results show that the accessibility-based transit need index value lowers from 90.0 to 88.3 in Option 1 and 87.4 for Option 2, meaning that more 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, it seems that the cost for building two new transit stops may be much less than the cost for increasing service span by two hours and increasing the service frequency of transit service. A detailed benefit/cost analysis would be needed to make the 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 transit disadvantaged population. The method for evaluating transport need presented in this paper is intended to aggregate the volume of transport disadvantaged workers who might be faced with limited mobility options in their community. In order 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. It was shown that the lack of transit service is highly correlated with large transit 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 dataset and provide useful insight into the relationship between transit need and service provision.

This paper examined the consistency of the model's result with the result of general approach used to identify transit disadvantaged areas. The comparison showed that the model was able to identify service gaps in transit service provision in a reliable

and defensible quantitative manner. Furthermore, the model is computationally straightforward and relatively easy to apply to the mapping of well-served and poorly served areas. The results should therefore be a solid basis for identifying shortcomings in service coverage and examining equity in transit service provision. This paper presented an example scenario with two options for increasing transit accessibility and predicted their effects on service need reduction using the model, demonstrating how this model can provide a basis for placing priorities on service improvements. Making equitable allocation of investments in transit service can increase access to community events for all people, particularly those who have limited transport 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 transit need index considering total transit disadvantaged populations (i.e., not only workers) would be useful in identifying the most needy population with mobility problems. An important consideration is that this model was developed based on very small sample datasets. Future research will validate and improve this model through application on larger metropolitan areas and statewide inter-city travel.

## **ACKNOWLEDGMENTS**

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## **CHAPTER 4: NEW HAVEN CITY CASE STUDY**

### **INTRODUCTION**

This chapter summarizes the framework for measuring service gap in transit service based on the research described in Chapter 2 and Chapter 3. The first application of the service gap measuring model was applied to the city of Meriden, CT. This area was selected due to its manageable size (only 17 census tracts) and its relatively isolated, small transit system with only 3 transit lines and 27 bus stops. This chapter aims to validate the methodology for a city having a large-scale transit system compared to that in Meriden. The transit accessibility and transit need-based approaches for measuring service gaps was applied to the city of New Haven bus service for representing the validation of the methodology and illustrating the potential for the methodology to be used as a planning tool.

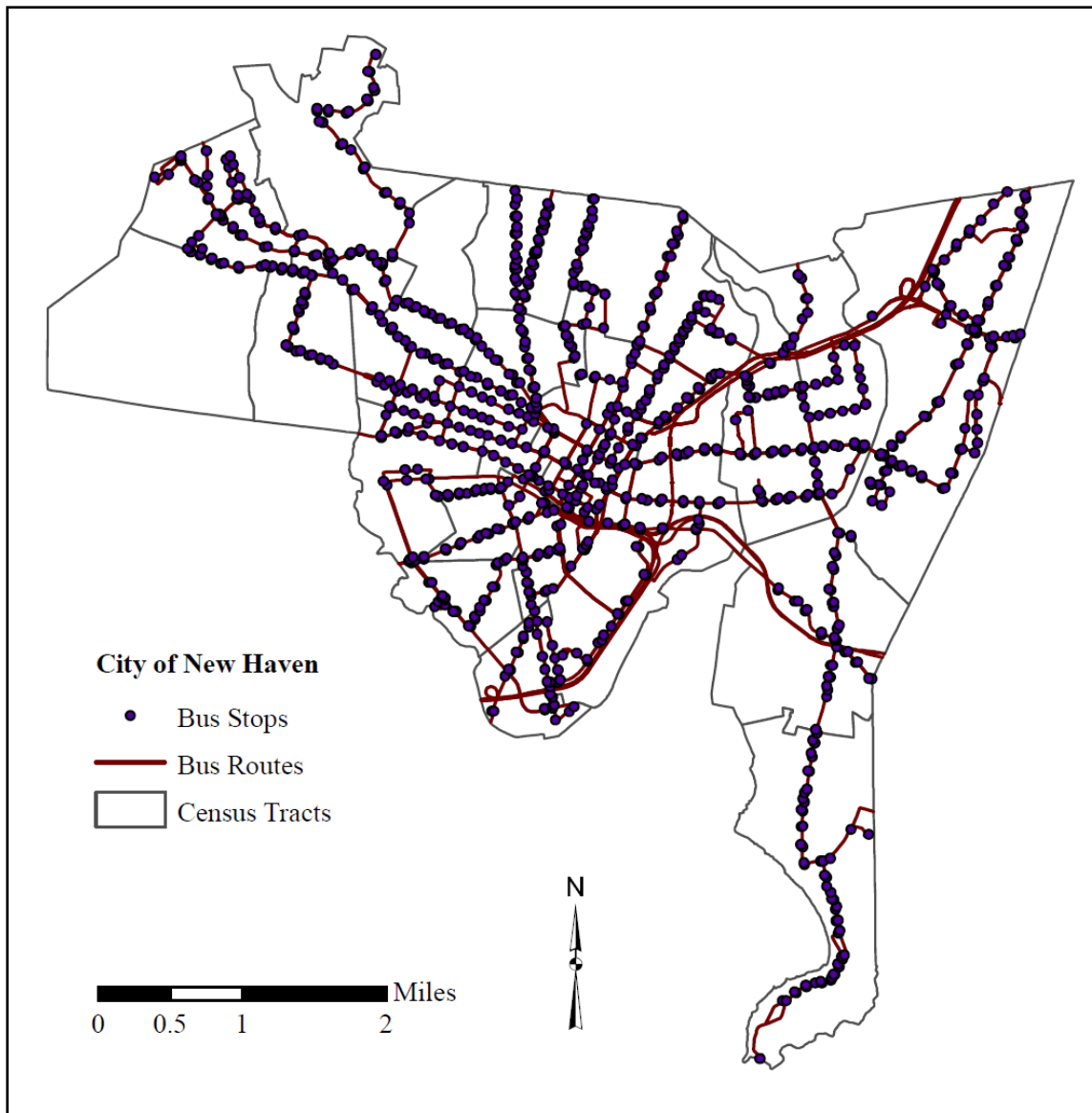
### **STUDY AREA**

The city of New Haven (Figure 1) had a 2000<sup>3</sup> population of 123,626 and a land area of 19.22 square miles. The 2000 Census counted 49,358 workers in the study area, giving an overall employment density of 4.01 workers per acre. Transit bus service in the New Haven metropolitan area is provided by Connecticut Transit (CTTransit). CTTransit operates a fleet of 35 passenger vehicles on 20 fixed routes serving 981 transit stops (Figure 2) for this study area. The regular routes provide service every 15 to 20 minutes throughout the usual service span of 5 am to 12 am, which represents frequent transit service compared to that in Meriden.

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<sup>3</sup> This research used US Census 2000 data for analysis. Census Tract level socioeconomic and demographic data for this study area was not yet available from US Census 2010.





**FIGURE 2 Bus Routes and Bus Stops Provided by CTTransit.**

### **FRAMEWORK FOR MEASURING SERVICE GAP**

The framework for determining the level of service gap for bus service in a study area, in this case, census tracts, consists of several steps. The steps are described as follows:

**Step 1:** Measure the level of accessibility to transit service using a composite transit accessibility index (*as described in Chapter 2*).

**Step 2:** Identify the total need for bus transit service, using transit disadvantaged worker characteristics.

**Step 3:** Determine the gap between current service provision and total need by comparing the two scores determined in **Step 1** and **Step 2**. This approach is identified as ***General Approach*** in this research.

**Step 4:** Determine service gap using a model-based approach, which requires service characteristics only. This step comprises sub-steps as follows:

**Step 4.1:** Identify transit disadvantaged workers who use auto as their mode of travel to work which is hereafter defined as the unmet need for bus transit service.

**Step 4.2:** Examine the relationship between unmet transit need (*Step 4.1*) and transit accessibility measure (*Step 1*) to explore the relationship between the need for service and service characteristics.

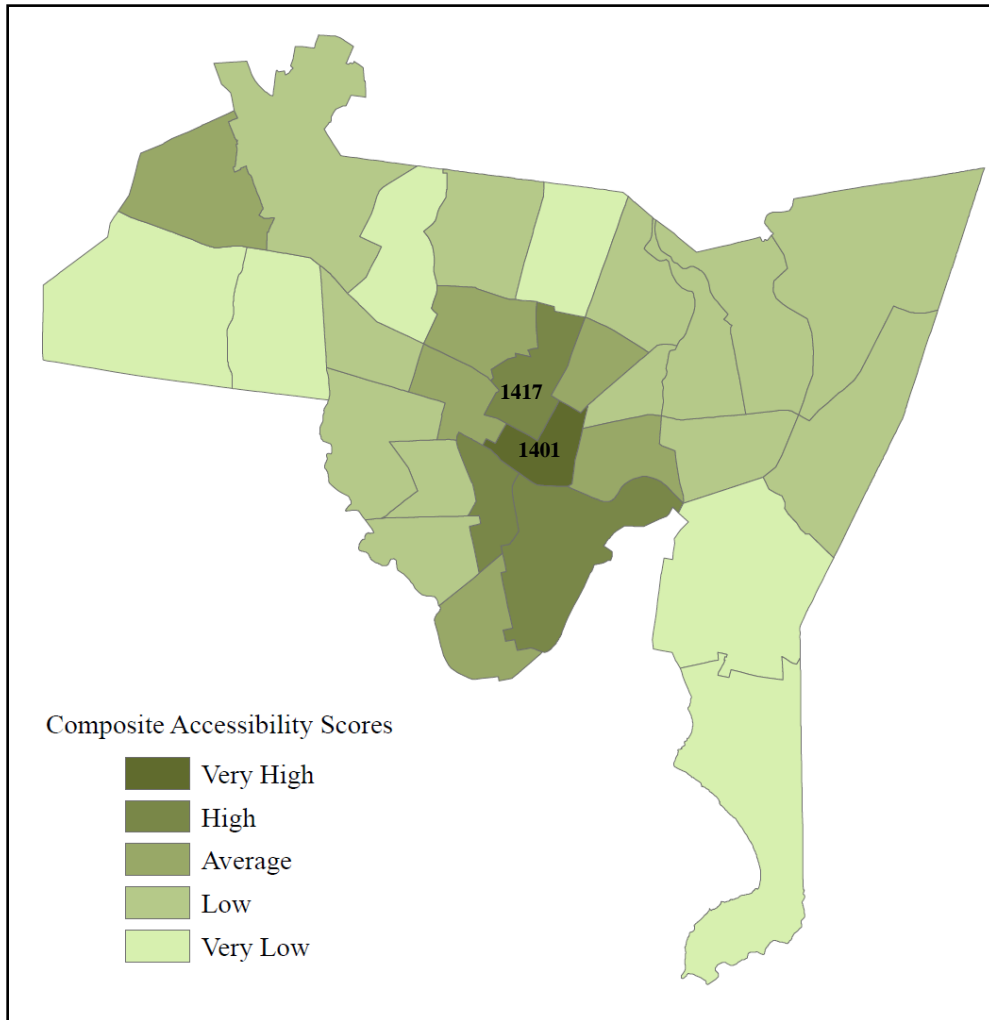
**Step 4.3:** Model the accessibility-based service gap measure using the unmet need for transit service as the dependent variable and service characteristics as the independent variables.

The model-based service gap results (*Step 4*) have been compared with the ***General Approach*** results (*Step 3*) for consistency and effectiveness. Results of the above mentioned steps for New Haven bus service system are described in the following sections.

### **Transit Accessibility**

Figure 3 depicts the calculated accessibility scores as measured by the composite accessibility measure for the city of New Haven. The accessibility scores (Table 1)

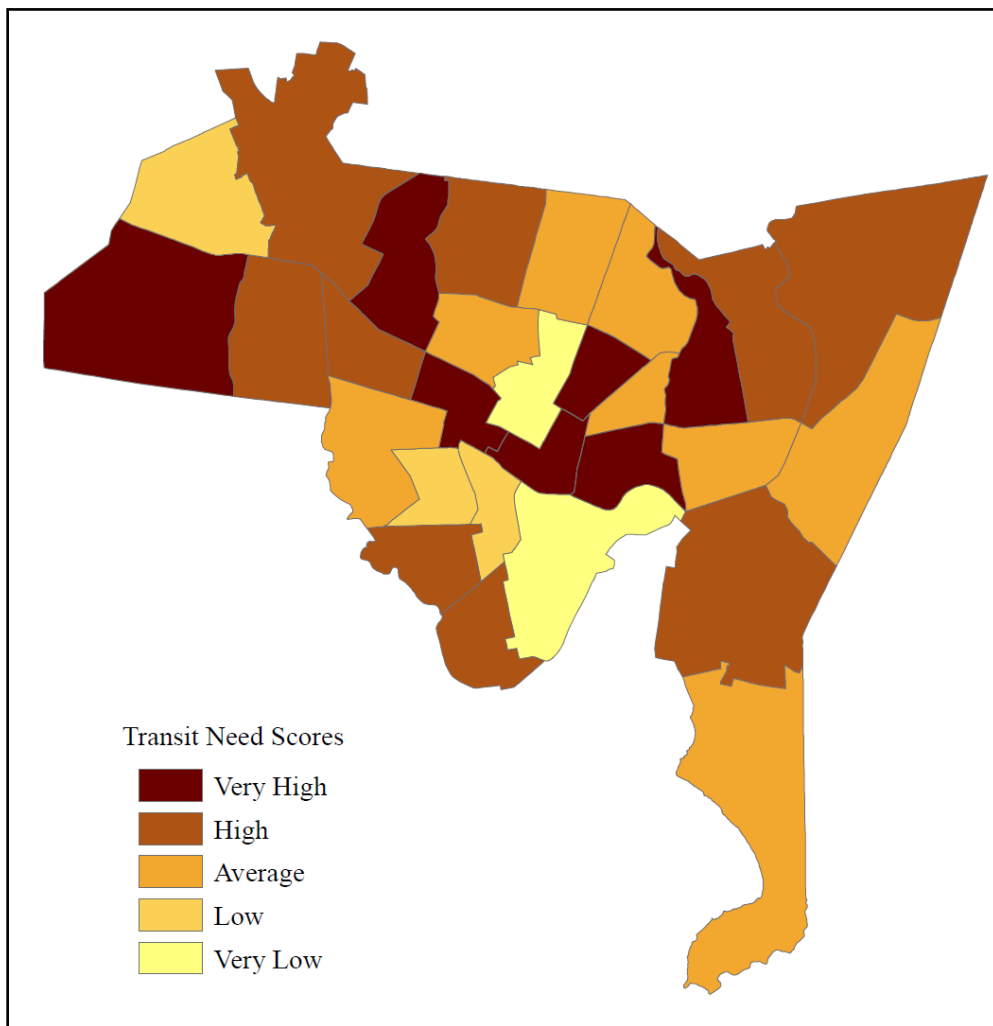
quantify three important aspects of public transit accessibility: spatial coverage, temporal coverage, and comfort. This tool is designed to provide a snapshot of the transit accessibility of a town, city, or region. This map provides an answer to the question “Which areas of a town/city/region have good, bad or average access to transit service?”



**FIGURE 3 Composite Transit Accessibility Scores of New Haven, Connecticut.**

In the map, scores are shown by standard deviation classification, generated with the GIS mapping functions. The areas with very high access to transit service (highest

accessibility scores) are shown in the darkest shading, the high scores are in the next darkest, and so on. As shown in Figure 3, accessibility scores were highest in the central portion of service area in tracts with high amounts of transit service. The central tracts (i.e., Tracts 1401, 1417, etc.) have high accessible scores due to having frequent (temporal coverage) bus service to and from the tracts (trip coverage). The bus stops in tracts 1401 and 1417 serve most of the New Haven bus routes and have high spatial coverage due to bus stop density.



**FIGURE 4 TDW as % of Tract Population of New Haven, Connecticut.**

## Transit Need Level

Need for transit service was calculated using the segments of the population who experience barriers to transit services such as the elderly, disabled, and low-income households. In much literature, these segments are often aggregately referred as “Transit Dependent”. This research utilizes a metric called “Transit Disadvantaged Workers (TDW)” to identify regions with substantial need for transit service and it is reported as a percentage of tract population (Table 1). Census Transportation Planning Products (CTPP) data from the 2000 Census was used to tabulate the percentage of a tract’s population that is TDW. TDW are defined as those meeting one or more of the following criteria (classifications are explained in detail in Chapter 3):

1. Low Income Earners: Workers in households with annual income < \$30,000
2. Workers over 65 years of age
3. Disabled workers
4. Workers in “Forced” Car Ownership (FCO) households.
5. Workers in Zero car households (ZCO)

Figure 4 depicts an overview of the need scores throughout New Haven. This distribution of TDW is provided to inform the other side of the accessibility question: “Which areas in a city or town have the greatest need for transit service?” It is worth noting that the distribution of TDW gives a different result that is expected. As one would usually expect that the areas with the highest percentage of TDWs would tend to have the highest degree of access as well (See Figure 3). However, there are exceptions for some tracts, and therefore it is required to evaluate the level of service gaps for the identification of priority areas for future investments in transportation infrastructure.

**TABLE 1 Service Gap Results From General Approach and Unmet Transit Need Scores**

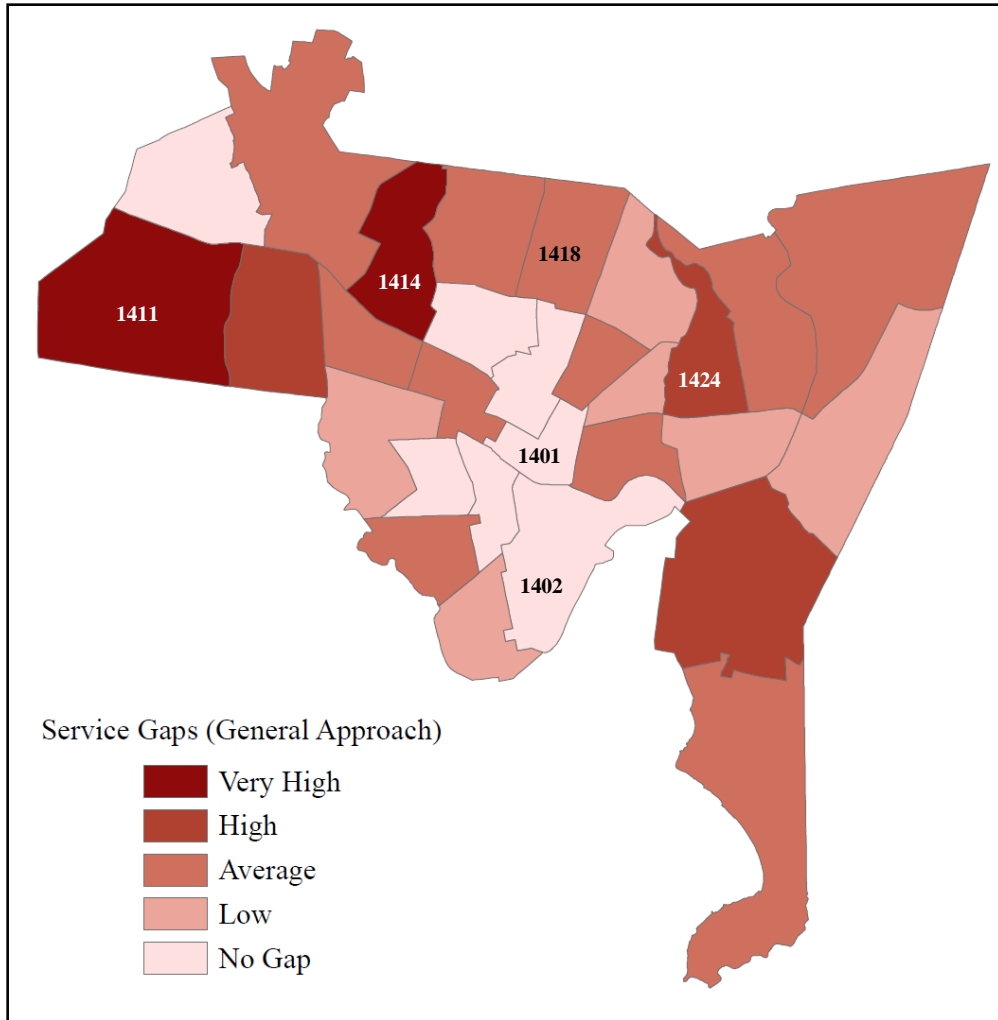
| <b>Census Tract</b> | <b>Accessibility Score</b> | <b>Level of Accessibility</b> | <b>Need Score<br/>(TDW as % of Tract Pop.)</b> | <b>Level of Need</b> | <b>Service Gap<br/>(General Approach)</b> | <b>Unmet Transit Need Score<br/>(% of Auto-using TDW in a Tract)</b> |
|---------------------|----------------------------|-------------------------------|--|----------------------|---|--|
| 1401                | 6.01                       | A (Very High)                 | 28.40  | A (Very High)        | No Gap                                    | 26.37  |
| 1402                | 0.92                       | B (High)                      | 14.16  | F (Very Low)         | No Gap                                    | 32.79  |
| 1403                | 0.71                       | B (High)                      | 16.39  | D (Low)              | No Gap                                    | 39.97  |
| 1404                | 0.83                       | C (Average)                   | 21.62  | B (High)             | Low                                       | 65.85  |
| 1405                | -0.68                      | D (Low)                       | 21.72  | B (High)             | Average                                   | 63.93  |
| 1406                | -0.22                      | D (Low)                       | 17.24  | F (Very Low)         | No Gap                                    | 46.51  |
| 1407                | 0.63                       | C (Average)                   | 28.03  | A (Very High)        | Average                                   | 32.16  |
| 1408                | -0.55                      | D (Low)                       | 19.50  | C (Average)          | Low                                       | 65.03  |
| 1409                | -0.24                      | D (Low)                       | 23.51  | B (High)             | Average                                   | 71.72  |
| 1410                | -1.30                      | F (Very Low)                  | 21.67  | B (High)             | High                                      | 70.56  |
| 1411                | -1.92                      | F (Very Low)                  | 25.48  | A (Very High)        | Very High                                 | 83.63  |
| 1412                | 0.06                       | B (High)                      | 16.68  | D (Low)              | No Gap                                    | 52.57  |
| 1413                | -0.71                      | D (Low)                       | 24.09  | B (High)             | Average                                   | 52.67  |
| 1414                | -0.93                      | F (Very Low)                  | 21.67  | A (Very High)        | Very High                                 | 65.97  |
| 1415                | -0.29                      | D (Low)                       | 22.15  | B (High)             | Average                                   | 68.59  |
| 1416                | 0.42                       | C (Average)                   | 20.65  | C (Average)          | No Gap                                    | 51.92  |
| 1417                | 3.99                       | B (High)                      | 11.51  | F (Very Low)         | No Gap                                    | 40.00  |
| 1418                | -0.92                      | F (Very Low)                  | 20.98  | C (Average)          | Average                                   | 35.36  |
| 1419                | -0.51                      | D (Low)                       | 18.25  | C (Average)          | Low                                       | 64.10  |
| 1420                | 0.09                       | C (Average)                   | 25.39  | A (Very High)        | Average                                   | 50.44  |
| 1421                | -0.28                      | D (Low)                       | 21.23  | C (Average)          | Low                                       | 57.71  |
| 1422                | 0.42                       | C (Average)                   | 24.78  | A (Very High)        | Average                                   | 57.39  |
| 1423                | -0.78                      | D (Low)                       | 17.65  | C (Average)          | Low                                       | 65.68  |
| 1424                | -0.30                      | D (Low)                       | 25.05  | A (Very High)        | High                                      | 65.91  |
| 1425                | -0.57                      | D (Low)                       | 22.01  | B (High)             | Average                                   | 42.52  |
| 142601              | -0.73                      | D (Low)                       | 21.78  | B (High)             | Average                                   | 69.58  |
| 142602              | -0.66                      | D (Low)                       | 17.85  | C (Average)          | Low                                       | 76.81  |
| 1427                | -1.22                      | F (Very Low)                  | 23.58  | B (High)             | High                                      | 72.59  |
| 1428                | -1.26                      | F (Very Low)                  | 17.64  | C (Average)          | Average                                   | 93.44  |



### **Service Gap: General Approach**

The General Approach for measuring service gaps in transit service requires measuring transit need and transit access separately, and then comparing the two scores to measure service gaps or identify transit disadvantaged areas (details in Chapter 3). Here, service gap is defined as the difference between need rating (Figure 4) and access rating (Figure 3).

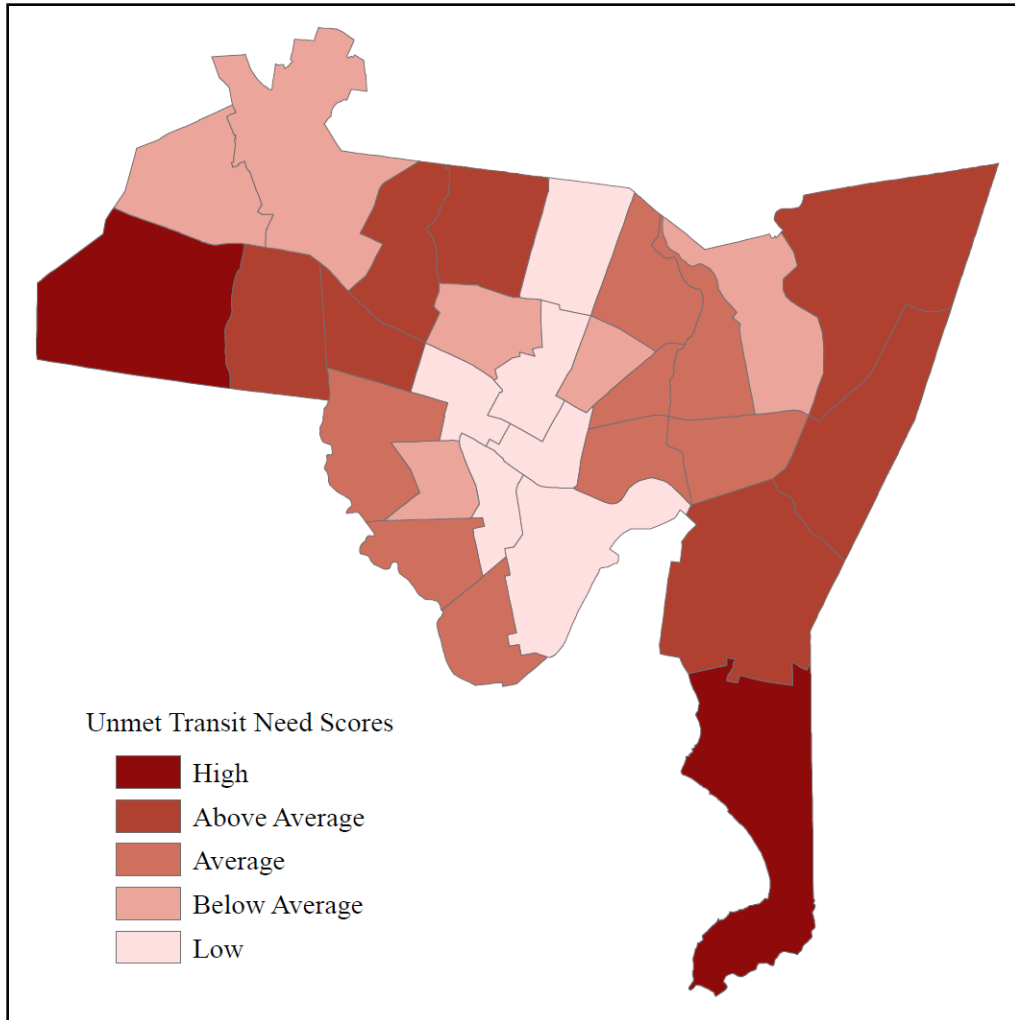
Figure 5 shows service gaps between accessibility and need in a particular tract, with the highest service gap in the darkest shading and no gap in the lightest shading. For example, tract 1411 and 1414 are identified as having a relatively very high transit need (as defined by TDW %). These tracts have very low access and result in a very high “Service Gap” (Figure 5). Tract 1424 has very high transit need and low access level, representing high service gaps whereas tract 1418 is an example of average-need, very low-access tract resulting in an average service gap. Tract 1401 has a very high need that is coupled with very high access, resulting in no gap. Tract 1402 is an example of a very low-need, high access and therefore no gap tract. In addition, this tract can be identified as a high development potential tract as it has high access but very low need for this service. The comparison of transit access and transit need scores, and the resulting service gaps are summarized in Table 1 for ease of interpretation.



**FIGURE 5 Transit Service Gaps (*General Approach*) of New Haven, Connecticut.**

#### **Unmet Transit Need: CTPP Data**

A primary objective of this research is to develop a model-based method that can predict the service gap with a single score by using different accessibility attributes. This research determines a measure called “unmet need for transit service” to identify service gaps between transit access and transit need. Unmet transit need was defined as the percentage of auto-using transit disadvantaged workers. Journey to work data for transit disadvantaged workers were collected from the CTPP 2000 database. Figure 6 shows the distribution of unmet transit need for each tract in New Haven.

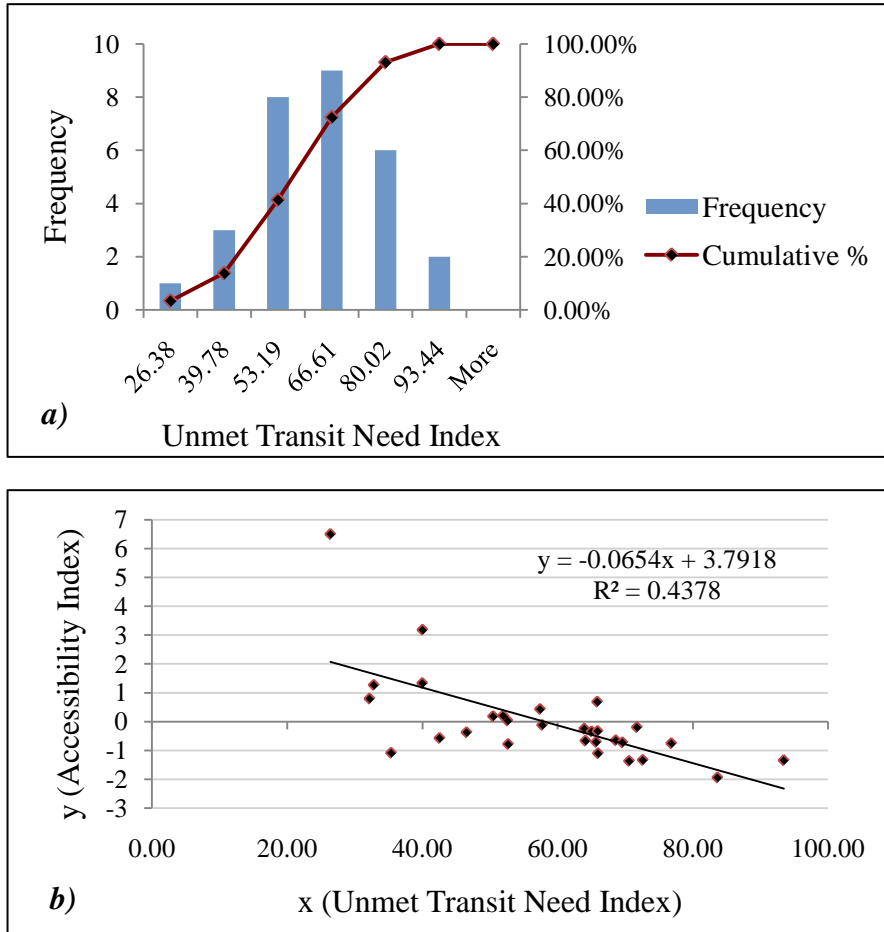


**FIGURE 6 % of TDW who Used Auto as Mode of Travel of New Haven, CT.**

### **Transit Accessibility as a Function of Unmet Transit Need**

The relationship between unmet transit needs (CTPP data) and accessibility scores forms the basis of modeling need as a function of service characteristics. It has been found that unmet transit need is strongly correlated to the lack of transit accessibility for city of Meriden (Chapter 3). This section provides the validation of this supposition for New Haven. The histogram shows (Figure 7(a)) that the unmet transit need scores are normally distributed and can be used for developing statistical models. A hypothesis test (*t-test* at

5% significance level) was conducted to determine whether there is significant relationship between unmet transit need and accessibility scores and it was found that the slope of the regression line (shown in Figure 7(b)) differs significantly from zero, which suggests that the unmet transit need is in fact correlated with the lack of service accessibility.



**FIGURE 7 Estimation of Linear Function Between Transit Accessibility and Unmet Needs (New Haven): (a) Histogram of Unmet Transit Need Index, and (b) Scatter Plot to Examine Relationship.**

### Service Gap: Model-Based Approach

A goal of this research is to establish a model estimating service gap based solely on service characteristics that do not require the extensive data processing but calculating the

indices requires. Modeling transit need measure as the function of service attributes followed the same methodology described in Chapter 3, and used similar service characteristics as independent variables for New Haven. This research recognizes that the model parameters (Model 1 in Chapter 3) used for Meriden cannot be used for New Haven as service characteristics are completely different (i.e., New Haven has 20 bus routes, 7 times higher than that of Meriden). Hence, a new model equation (Model 2) was formulated for New Haven. The regression analysis results for Model 2 is summarized in Table 2 and the functional form for this model is as follows:

**Model 2:** (for New Haven)

*Accessibility-Based Transit Need Index =*

$$98.62696 - 0.42229 * \%SERVICE\_AREA - 0.04542 * SEAT\_MILE/CAPITA$$

**TABLE 2 Accessibility-Based Service Gap Measure Regression Analysis Results**

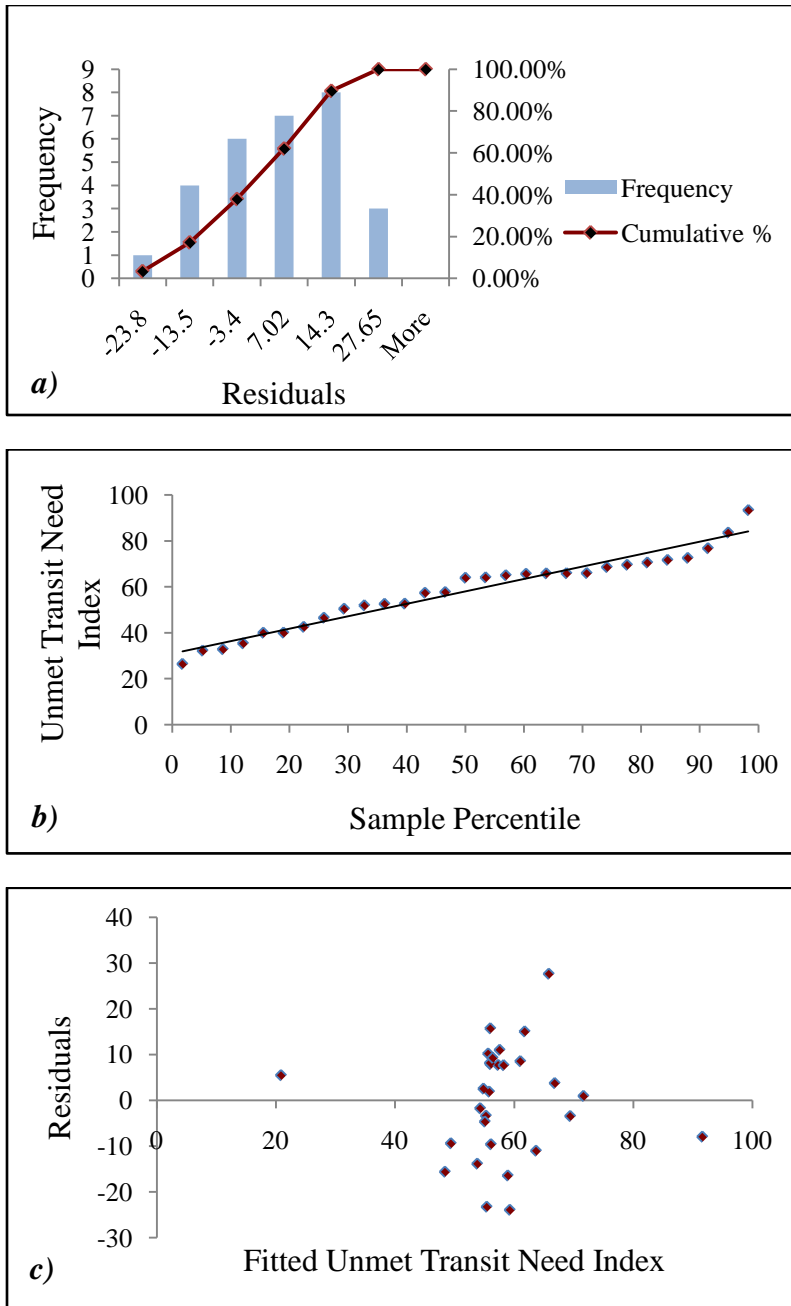
| <i>Regression Statistics</i> |          |  |  |  |
|------------------------------|----------|--|--|--|
| Multiple R                   | 0.66414  |  |  |  |
| R Square                     | 0.441082 |  |  |  |
| Adjusted R Square            | 0.398089 |  |  |  |
| Standard Error               | 12.63775 |  |  |  |
| Observations                 | 29       |  |  |  |

| ANOVA      |           |             |             |            |
|------------|-----------|-------------|-------------|------------|
|            | <i>df</i> | <i>SS</i>   | <i>MS</i>   | <i>F</i>   |
| Regression | 2         | 3277.060931 | 1638.530465 | 10.2592389 |
| Residual   | 26        | 4152.529483 | 159.7126724 |            |
| Total      | 28        | 7429.590414 |             |            |

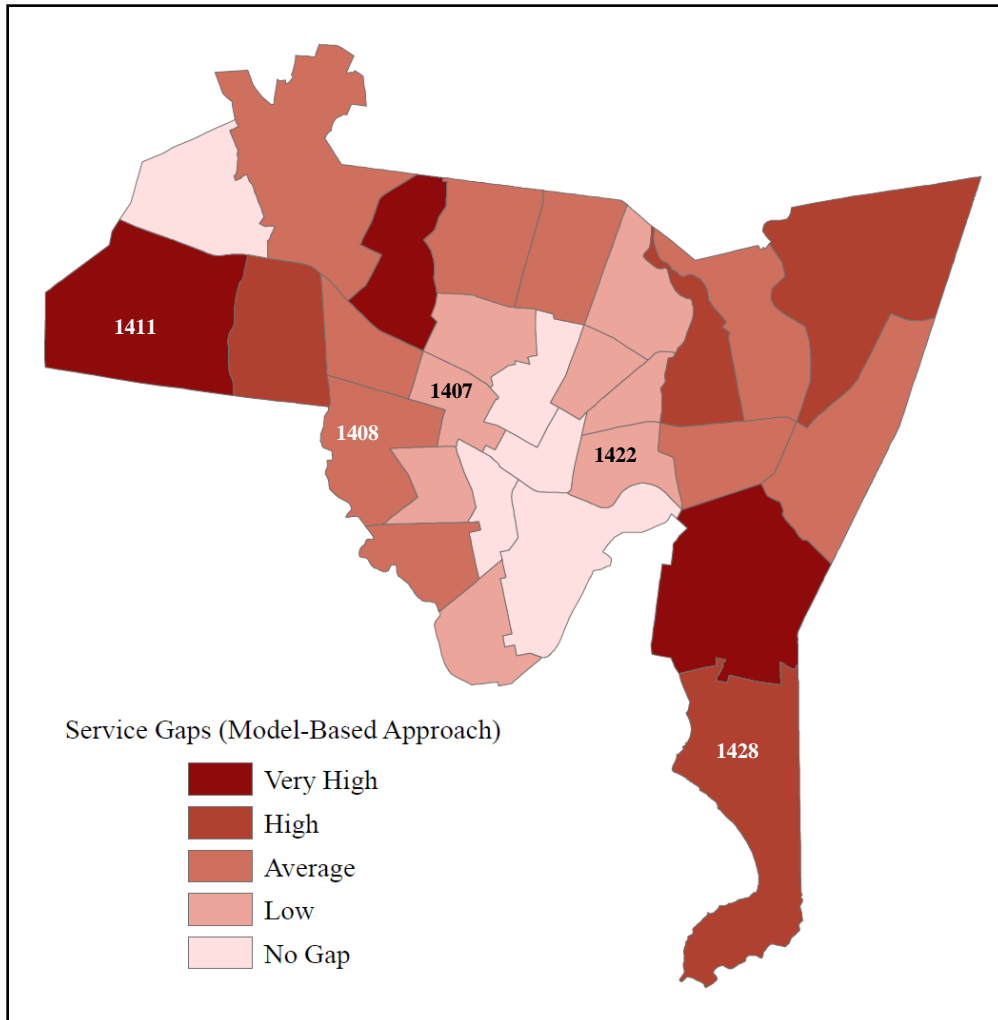
|                  | <i>Coefficients</i> | <i>Standard Error</i> | <i>t Stat</i> | <i>P-value</i> |
|------------------|---------------------|-----------------------|---------------|----------------|
| Intercept        | 98.62696            | 12.43313194           | 7.932591393   | 2.0723E-08     |
| %SERVICE_AREA    | -0.42229            | 0.137366985           | -3.074194723  | 0.00491166     |
| SEAT_MILE/CAPITA | -0.04542            | 0.016625619           | -2.732213808  | 0.01115679     |



**FIGURE 8 Verification of Regression Model Assumptions: (a) Histogram of Residuals, (b) Normal Probability Plot, and (c) Plot of Residuals vs. Fitted Unmet Transit Need Index Values.**

This model was checked for normality, linearity, homoscedasticity and for multicollinearity between independent variables. The details of checks for normality and linearity are shown in Figure 8. White's General test for constant variance

(heteroscedasticity) (1) was performed and no evidence of heteroscedasticity was identified. The variance inflation factors (VIF) were calculated to identify multicollinearity of independent variables and the model was found within an acceptable level of multicollinearity (i.e.,  $VIF = 1.3$ , which is lower than recommended threshold VIF of 5) (2, 3).



**FIGURE 9 Service Gaps (*Model-Based Approach*) of New Haven, Connecticut.**

Figure 9 depicts the spatial distribution of service gaps obtained from the accessibility-based modeling approach. Service gap results obtained from this model were compared to those from *General Approach* (Figure 5) for examining consistency.

For ease of interpretation the service gap results obtained from two approaches were assigned a service gap score of 5 for ‘very high service gap’ and a score 1, indicating “no service gap” for both measures (shown in Table 3).

**TABLE 3 Comparison of Service Gap Results Obtained from General Approach and Model-Based Approach**

| Census Tract | Service Gap      |                      | Service Gap Score |                      |            |
|--------------|------------------|----------------------|-------------------|----------------------|------------|
|              | General Approach | Model-Based Approach | General Approach  | Model-Based Approach | Difference |
| 1401         | No Gap           | No Gap               | 1                 | 1                    | 0          |
| 1402         | No Gap           | No Gap               | 1                 | 1                    | 0          |
| 1403         | No Gap           | No Gap               | 1                 | 1                    | 0          |
| 1404         | Low              | Low                  | 2                 | 2                    | 0          |
| 1405         | Average          | Average              | 3                 | 3                    | 0          |
| 1406         | No Gap           | Low                  | 1                 | 2                    | 1          |
| 1407         | Average          | Low                  | 3                 | 2                    | -1         |
| 1408         | Low              | Average              | 2                 | 3                    | 1          |
| 1409         | Average          | Average              | 3                 | 3                    | 0          |
| 1410         | High             | High                 | 4                 | 4                    | 0          |
| 1411         | Very High        | Very High            | 5                 | 5                    | 0          |
| 1412         | No Gap           | No Gap               | 1                 | 1                    | 0          |
| 1413         | Average          | Average              | 3                 | 3                    | 0          |
| 1414         | Very High        | Very High            | 5                 | 5                    | 0          |
| 1415         | Average          | Average              | 3                 | 3                    | 0          |
| 1416         | No Gap           | Low                  | 1                 | 2                    | 1          |
| 1417         | No Gap           | No Gap               | 1                 | 1                    | 0          |
| 1418         | Average          | Average              | 3                 | 3                    | 0          |
| 1419         | Low              | Low                  | 2                 | 2                    | 0          |
| 1420         | Average          | Low                  | 3                 | 2                    | -1         |
| 1421         | Low              | Low                  | 2                 | 2                    | 0          |
| 1422         | Average          | Low                  | 3                 | 2                    | -1         |
| 1423         | Low              | Average              | 2                 | 3                    | 1          |
| 1424         | High             | High                 | 4                 | 4                    | 0          |
| 1425         | Average          | Average              | 3                 | 3                    | 0          |
| 142601       | Average          | High                 | 3                 | 4                    | 1          |
| 142602       | Low              | Average              | 2                 | 3                    | 1          |
| 1427         | High             | Very high            | 4                 | 5                    | 1          |
| 1428         | Average          | High                 | 3                 | 4                    | 1          |



The difference between service gap results (shown in Table 3) shows that majority of census tracts (18 out of 29 tracts) have identical service gap results between two approaches. Only 3 tracts (e.g., 1407, 1420, and 1422) rated lower service gap results in the model-based method. All the three tracts rated as ‘Low’ service gap in modeling approach rather than ‘Average’ service gaps in general approach. For the other 8 census tracts (e.g., 1408, 1428, etc.), the model-based approach rated higher service gap results but did not alter service gap result by more than one level. For example, tract 1428 has an ‘Average’ service gap in the general approach, however it shows ‘High’ service gap in the model-based approach. Therefore, it can be said that the accessibility-based modeling approach tends to rate the tract service gap as higher than the general approach.

**TABLE 4 Chi-square Calculation**

| <b>Service Gap Category</b> | <b>Observed Frequencies, O<br/>(Model-Based Approach)</b> | <b>Expected Frequencies, E<br/>(General Approach)</b> | <b>(O-E)</b> | <b>(O-E)<sup>2</sup></b> | <b>(O-E)<sup>2</sup>/E</b>                |
|-----------------------------|---|---|--------------|--------------------------|---|
| Very High                   | 3   | 2   | 1            | 1                        | 0.5                                       |
| High                        | 4   | 3   | 1            | 1                        | 0.3333                                    |
| Average                     | 9   | 11  | -2           | 4                        | 0.3636                                    |
| Low                         | 8   | 6   | 2            | 4                        | 0.6666                                    |
| No Gap                      | 5   | 7   | -2           | 4                        | 0.5714                                    |
| <b>Total</b>                |   |   |              |                          | <b><math>\chi^2_{cal} = 2.4350</math></b> |

Furthermore, a chi-square test of goodness-of-fit was performed to determine whether there is significant difference between the model-based frequencies and the general approach frequencies in different service gap categories (shown in Table 4). The chi-square critical value ( $df = 4$ ,  $\alpha = 0.05$ ) is 9.488, which is greater than the calculated

chi-square value. Therefore, we failed to reject the null hypothesis and the evidence did not suggest that the distributions are significantly different.

### **Determining Service Improvement Options**

Very high service gap areas (i.e., very low level of public transit access coupled with very high need for transit) suggest that investment on public transit services and infrastructure should be prioritized for these areas as it has high potential to yield benefits. Moreover, the model for measuring service gaps provides a basis for assessing various service improvements or expansions policies and intends to serve as a decision-support tool in the service planning process. For example, tract 1411 has very high service gap (Figure 9). The model can be used to estimate the need impact of different hypothetical improvement options (i.e., building new bus stops, building new transit lines, increasing service span or service frequency, etc.).

The basic idea is that the model-based service gap score, measured with different service characteristics can be used to increase transit accessibility by placing priorities on service improvements. At this point it is difficult to demonstrate the correctness of using service characteristics to estimate unmet need/service gap in census tracts. The model is certainly not transferable to other cities, this is because each cities will have different service characteristics in different scales. However, it did accomplish the goal of estimating service gap using only service characteristics.

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## **CHAPTER 5: CONCLUSIONS**

### **CONCLUSIONS**

This research explores the importance of evaluating existing transit services to identify the areas where transit service is most intense and where it is lacking. A composite accessibility measure was developed accompanying three important accessibility coverage aspects (i.e., spatial coverage, temporal coverage and comfort) which provides a relative accessibility measure of the degree to which transit is reasonably available. The composite accessibility index considers three existing methods from different user perspective (i.e., developer, planner and operator) in order to represent a more robust and defensible measure of transit accessibility. The methodology used for integrating these three methods might help transit planners to select a set of accessibility measures and provides a method of combining them to produce a more defensible and reliable accessibility measure for their customers.

This research effort addresses the necessity of measuring needs for transit service along with levels of access to aid transit professionals in undertaking service expansion plans and policies. Transit need was measured by aggregating the volume of transit disadvantaged workers who might be faced with limited mobility options in their community. It was shown that the lack of transit service is highly correlated with transit disadvantaged workers, providing useful insight into the relationship between transit need and service provision. Based on the supposition that the unmet transit need is correlated with the lack of transit accessibility, a regression model was estimated for measuring accessibility-based transit need index. It was found that this accessibility-based need index can measure the service gaps in transit service provision. The service gap results

were compared with the results obtained from *General Approach* for consistency and completeness. The model-based approach for measuring service gaps is computationally straightforward and relatively easy to apply for identifying of shortcomings in service coverage. Mapping of transit disadvantaged areas provides a solid basis for placing priorities on service improvements. The resulting accessibility-based transit need distribution can help professionals and policy makers make more informed decisions regarding the design and equitable allocation of transit services. This model can also be used as a means to prioritize service improvement options by predicting their effects on service gap scores.

## **FUTURE RESEARCH**

Future research is needed to develop a more accurate measure for estimating service gaps by incorporating more accessibility indicators, such as travel time, pedestrian route connectivity to transit stops, and network connectivity. Addition of network connectivity as an accessibility indicator to this work would add another important coverage aspect (i.e., origin-destination (*O-D*) trip coverage) for transit service. An implication of conducting transit accessibility analysis for the rail service alongside the bus service might be a potential future research option for representing actual level of access to transit services. Further modifications in calculation of current accessibility indicators could be useful in measuring transit accessibility. For example, using a polygon area measure, other than the buffer area based on straight-line distance, could be appended with the improved service area calculation for a transit stop.

Transit disadvantaged population data, other than the transit disadvantaged worker, might provide a strong measure for estimating the neediest population with mobility problems. As an improvement upon this work, the current analysis technique could be enriched by using the updated available socioeconomic and demographic data. For example, Census 2010 data can be used instead of using Census 2000 data in the calculation of transit need scores in future.

Another possible direction for extending this research would be to analyze service gaps for different area types (i.e., urban, suburban, rural, etc.) and to draw a relationship between those measures for estimating a unique model that can be applicable to any resolution of service area.

## APPENDIX

### Survey Questionnaire

#### 1. What type of agency are you?

- ☐ Public transit system
- ☐ Government human services agency
- ☐ Regional Planning organization/ Association
- ☐ Private nonprofit human services agency
- ☐ Private nonprofit transportation provider
- ☐ Private for-profit transportation provider
- ☐ Other (Please specify):

#### 2. What types of service does your agency provide?

- ☐ Fixed-Route City Bus (FR)
- ☐ Demand-Response Small Vehicle (DR)
- ☐ Both Fixed-Route City Bus (FR) and Demand-Response Small Vehicle (DR)
- ☐ Deviated Fixed-Route
- ☐ Express Service- Commuter-oriented Express Bus Service
- ☐ ADA Paratransit
- ☐ Accessible Taxi
- ☐ Shuttle Service
- ☐ Rail
- ☐ Other (Please specify):

If you are a Transit Provider please complete **Part 1** and **Part 3**

If you are a Transit Planner please complete **Part 2** and **Part 3**

#### Part 1: Transit Provider (Q. 3 – Q. 9)

#### 3. Please provide your agency's regular service times for the periods listed. (Or please attach schedule brochures or provide website address regarding service schedule)

Monday to Friday:  to

Saturday:  to

Sunday:  to

Website:

4. Please provide a list of total number of vehicles and their capacity that your agency operates for transportation service.

| Vehicle Type |                      | Seating Capacity | Number of Vehicles |
|--------------|----------------------|------------------|--------------------|
| Bus          | Passenger Van        |                  |                    |
|              | Mini Bus             |                  |                    |
|              | Midsize Bus          |                  |                    |
|              | Standard City Bus    |                  |                    |
|              | Suburban Service Bus |                  |                    |
|              | Double-Decker Bus    |                  |                    |
|              | Articulated Bus      |                  |                    |
|              | Tractor-Trailer Bus  |                  |                    |
|              | Trolley Bus          |                  |                    |
|              | Other                |                  |                    |

| Vehicle Type |                        | Number of Vehicles |
|--------------|------------------------|--------------------|
| Rail         | Heavy Rail/Metro       |                    |
|              | Commuter/Regional Rail |                    |
|              | Light Rail/Tram        |                    |
|              | Streetcar/Trolley      |                    |
|              | Other                  |                    |

5. At what spatial level is transit service data collected? *(Please check all that apply)*

- ☐ Parcel  
☐ Census Block  
☐ Traffic Analysis Zone (TAZ)  
☐ Census Tract  
☐ Regional  
☐ Other (Please specify):  
☐ Not Applicable

6. What type of area are you serving?

- ☐ Urban  
☐ Suburban  
☐ Rural  
☐ Other (Please specify):



**7. What is the method(s) used at your agency to collect transit data?** *(Please check all that apply)*

- ☐ O/D studies
- ☐ Ride checking by transit staff
- ☐ Electronic Registering Fareboxes (ERFs)
- ☐ Smart cards
- ☐ Mobile Data Terminals (MDTs)
- ☐ Automatic Passenger Counters (APCs)
- ☐ Automated Vehicle Location (AVL)
- ☐ Other (Please specify):
- ☐ Not Applicable

**8. Please specify the service area size of your transportation service.** *(Please provide as much detail as possible)*

No. of Counties:

No. of Towns:

Square Mileage:

Other (Please specify):

**9. Listed below are a number of possible coordination activities with mobility planners/co-operative agencies you undertake or wish to undertake to improve access to public transit. Please indicate your agency's current status in these coordination activities by checking the appropriate box and listing the coordinating agency(s).**

**Coordination Activity 1:** *Providing transportation services, or more transportation services, under contract to another agency.*

- ☐ Activity currently exists
- ☐ Interested to undertake
- ☐ Not interested
- ☐ Unavailable

Name of the Agency(s):

Barriers:

**Coordination Activity 2:** *Joining together with another agency or municipality to consolidate the operation of transportation services.*

- ☐ Activity currently exists
- ☐ Interested to undertake
- ☐ Not interested
- ☐ Unavailable

Name of the Agency(s):

Barriers:

**Coordination Activity 3:** *Purchasing transportation services from another organization, assuming that the price and quality of service met your needs.*

- ☐ Activity currently exists
- ☐ Interested to undertake
- ☐ Not interested
- ☐ Unavailable

Name of the Agency(s):

Barriers:

**Coordination Activity 4:** *Coordinating schedules and vehicle operation with nearby paratransit providers so that riders can transfer from one service to another.*

- ☐ Activity currently exists
- ☐ Interested to undertake
- ☐ Not interested
- ☐ Unavailable

Name of the Agency(s):

Barriers:

**Coordination Activity 5:** *Highlighting connections to other fixed-route or demand-responsive services on your schedules or other information materials.*

- ☐ Activity currently exists
- ☐ Interested to undertake
- ☐ Not interested
- ☐ Unavailable

Name of the Agency(s):

Barriers:

**Coordination Activity 6:** *Adjusting service hours or frequency of service.*

- ☐ Activity currently exists
- ☐ Interested to undertake
- ☐ Not interested
- ☐ Unavailable

Name of the Agency(s):

Barriers:

**Other Coordination Activity:** *(Please Specify)*

- ☐ Activity currently exists
- ☐ Interested to undertake
- ☐ Not interested
- ☐ Unavailable

Name of the Agency(s):

## Part 2: Transit Planner (Q. 10 – Q. 11)

**10. Do you use any Origin-Destination (O-D) data in your planning model?**

- ☐ Yes  
☐ No

If “Yes”, Please answer the following questions.

***What is the geographic extent of your Planning model?***

Counties:

Towns:

Mileage:

***When the O-D data was last updated?***

***What is the source of this O-D data?***

***How does O-D data contribute to your planning activities?***

***What are the sources of travel demand/census data that you used in your planning model?***

**11. What type of travel demand modeling information do you use in your planning activities?**  
(Please check all that apply)

- ☐ No. of Cars Available  
☐ Household income  
☐ Population density  
☐ Employment density  
☐ Total land area  
☐ No. of Drivers in Household  
☐ No. of Adults in Household  
☐ Land Use  
☐ Race

- ☐ Age  
☐ Education  
☐ Other (Please specify):

If you use *Cars available* data, please explain how car ownership/cars available data does assist your planning activities.

If *Household income* is considered, please specify the threshold value for low income:

- ☐ Annual Income Less than \$15,000  
☐ Less than \$20,000  
☐ Less than \$30,000  
☐ Less than \$40,000  
☐ Other (Please specify):

### Part 3: Transit Provider & Planner (Q. 12 – Q. 17)

12. Please rank each of the following measures on a scale of 1 to 10 indicating the measure's importance in maintaining and improving access to public transportation services in your service area, where 1 is the most important and 10 is the least important. *(Please use each number only once)*

| Accessibility Measures  | Rank |
|---|------|
| More Bus Routes and Stops and More Areas Served   |      |
| More Frequent Service and Better Service Span   |      |
| Stop Area Development Density   |      |
| Trip Coverage   |      |
| Better On-time Performance  |      |
| More Parking Availability   |      |
| Safer Environment at Stops and Shelters   |      |
| Better Pedestrian Access to/from Stops  |      |
| Encouraging Interaction Across Modes (i.e. Bike Racks)                                  |      |
| Better Serving Disadvantaged Population (i.e. Limited Income, Poor English Proficiency) |      |

- 13. From your perspective, what are the most critical gaps/unmet needs (in service or other areas) in your provided public transportation/transit service?**

- 14. What are the top challenges/barriers facing passenger transportation/transit in your service area?**

- 15. What are the opportunities in your community/county/service area for expanding, improving, and enhancing passenger transportation/transit?**

- 16. What strategies do you employ to increase the efficiency/level of service of your transportation operations?**

- 17. Do you have any additional comments or insights you'd like to share?**

**TABLE A.1 Ranking of Accessibility Measures**

| <b>Accessibility measures</b>   | <b>Average Ranking</b> | <b>Ranking</b> |
|---|------------------------|----------------|
| More Bus Routes and Stops and More Areas Served   | 2.5                    | <b>2</b>       |
| More Frequent Service and Better Service Span   | 1.9                    | <b>1</b>       |
| Stop Area Development Density   | 7.7                    | <b>9</b>       |
| Trip Coverage   | 6.9                    | <b>8</b>       |
| Better On-time Performance  | 5                      | <b>4</b>       |
| More Parking Availability   | 8.4                    | <b>10</b>      |
| Safer Environment at Stops and Shelters   | 5.7                    | <b>5</b>       |
| Better Pedestrian Access to/from Stops  | 4.8                    | <b>3</b>       |
| Encouraging Interaction Across Modes (i.e. Bike Racks)                                  | 6                      | <b>7</b>       |
| Better Serving Disadvantaged Population (i.e. Limited Income, Poor English Proficiency) | 5.8                    | <b>6</b>       |

**TABLE A.2 Unmet Transportation Needs**

|  |
|--|
| <b>Increased services, improved reliability, expanded service hours, increased capacity on existing routes</b>   |
| <b>Poor bus route connection to the job centers, enhanced inter-district connections</b>                         |
| <b>Adjusted frequency of local service to enable service to interface with rail and other bus service</b>        |
| <b>Increased/enhanced elderly &amp; disabled service</b>   |
| <b>Ability to transfer passengers from one agency to other agencies from for both local and statewide level.</b> |
| <b>Increased headways, dedicated transit stops and corresponding schedules</b>                                   |
| <b>Integrated statewide fare policy/ fare collection technology</b>  |
| <b>Real time travel information- delays, location, next arrival (for commuter rail)</b>                          |