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# Measuring and Improving Seniors' Access to Medical Facilities

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**Measuring and Improving Seniors' Access to Medical Facilities**

Angelika Zygo

B.S., Civil Engineering, University of Connecticut, 2014

A Thesis

Submitted in Partial Fulfillment of the

Requirements of the Degree of

Master of Science

At The

University of Connecticut

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APPROVAL PAGE

Master of Science Thesis

Measuring and Improving Seniors' Access to Medical Facilities

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## Table of Contents:

### **Chapter 1:** Measuring Seniors' Access to Medical Facilities Using the

Transit Opportunity Index.....	1
1.1 Abstract.....	2
1.2 Introduction.....	3
1.3 Literature Review.....	7
1.4 Methodology.....	14
1.5 Case Study.....	18
1.7 Conclusions.....	29

### **Chapter 2:** Providing Equitable Access to Medical Facilities for Seniors by

Optimizing Transit Network for Equity.....	31
2.1 Abstract.....	32
2.2 Introduction.....	33
2.3 Literature Review.....	34
2.4 Problem Formulation.....	38
2.5 Model Validation.....	41
2.6 Case Study.....	43
2.7 Results.....	53
2.8 Conclusions.....	57
<b>References.....</b>	<b>60</b>
<b>Appendix.....</b>	<b>64</b>

**Chapter 1:     Measuring seniors’ access to medical facilities using the  
                  Transit Opportunity Index**

1.	Abstract.....	2
2.	Introduction.....	3
3.	Literature Review.....	7
4.	Methodology.....	14
5.	Case Study Application.....	18
6.	Conclusions.....	29

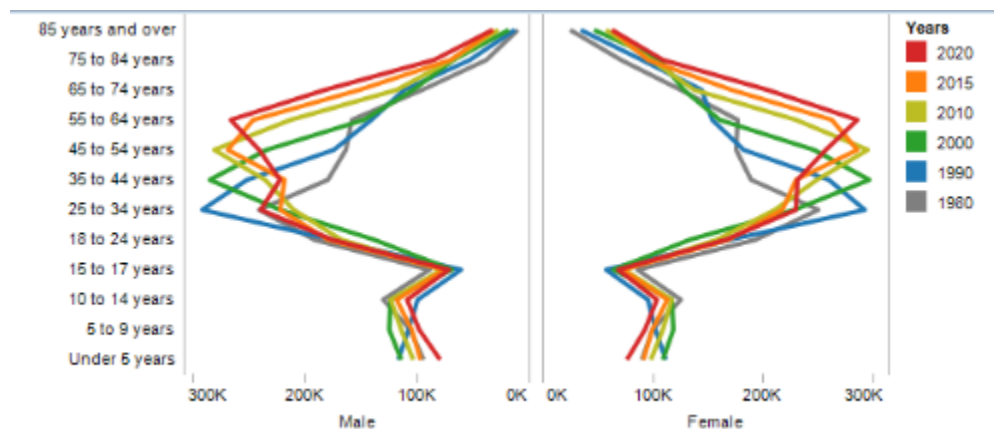
## **ABSTRACT**

The travel behaviors of older adults often shift as they retire, begin second careers and make residence location choices geared towards aging in place. Those who rely on transit as their primary mode of transportation can face many accessibility and connectivity challenges when travelling to basic amenities due to their unique travel behaviors and declining mobility with advanced age. This paper focuses on a subset of these travel behaviors through a literature review then evaluates the ability of public transportation to meet the specific mobility needs of older adults (defined in two ways: as those adults >65 years of age and >85). The ability of transit to provide older adults with access to medical facilities is measured using a pair-wise Transit Opportunity Index (TOI), a comprehensive measure of transit accessibility between origin-destination pairs. This analysis focuses on CT Transit New Haven, a fixed-route bus system operating in New Haven, Connecticut. In particular, this study focuses on assessing whether seniors in various age groups have better or worse access to medical facilities than the general population. The results suggest that seniors within the transit service area do not have better access to medical facilities than the general population in the same area. Future research could incorporate the time of day travel characteristic, which is unique for seniors, to study whether access for seniors to medical facilities is better or worse in the off peak hours.



## **INTRODUCTION**

The world's population is aging. For the first time in history, people aged 65 years and older are projected to outnumber children who are 5 years old (Kinsella and Wan 2009). Furthermore, researchers estimate that the world's population aged 80 or older will increase 233% between 2008 and 2040, compared with 133% for population aged 64 or older and 33% for all other ages (Kinsella and Wan 2009). Figure 1 shows the shift in peaks throughout time for different age groups based on gender in Connecticut. A clear pattern is apparent: Connecticut's population is shifting and will continue to shift toward a larger proportion of older adults in coming years. It is projected that 55 to 64 age group will be the most dominant age group for both genders by 2020. This projection is supported by the finding of the Connecticut Commission on Aging (2015) which shows that nearly every one of the 169 Towns in Connecticut will see the proportion of adults over 65 years of age top 20% in the next decade. As stated by the "Commission on Women, Children and Seniors"- Connecticut has the 3rd highest life expectancy in the nation, at 80.8 years. It is the 7th oldest state in the nation, based on median age. Between 2010 and 2040, Connecticut's population of people age 65 and older is projected to grow by 57%. Its population of people age 20 to 64 is projected to grow by less than 2% during the same period.



### **Figure 1 Population change throughout time for Connecticut, by gender.**

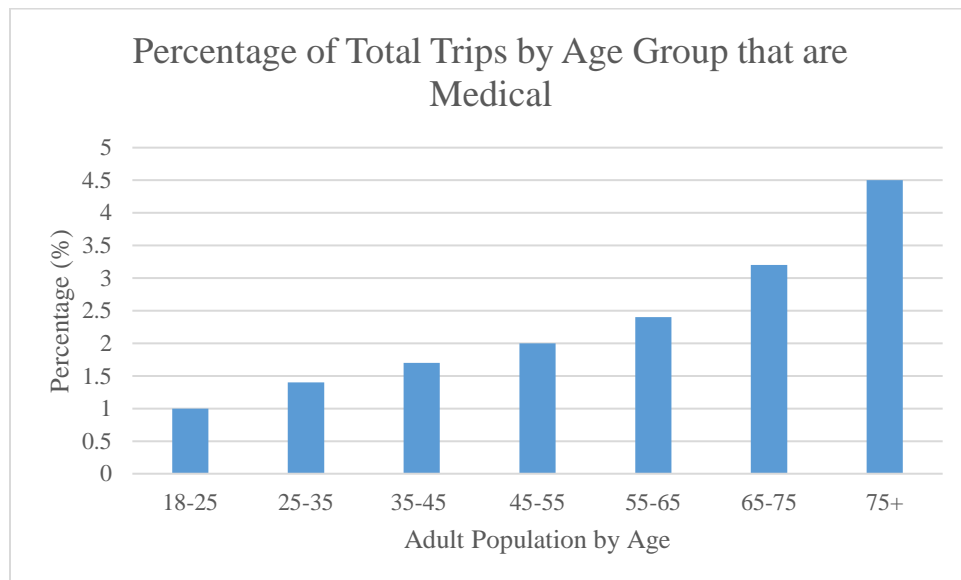
Such a significant change poses many new challenges on city planners and policy makers.

Increased education and income levels, along with longer life expectancy contribute to different life expectations of seniors. Current research suggests that seniors are more mobile, active, and independent than in past generations

Transportation systems are designed to help residents participate in their communities and reach necessary goods and services. “Accessibility determines how well transportation systems serve its residents and indicates the collective performance of land use and transportation systems (El-Geneidy and Levinson 2006)”. Providing easy access to everyday destinations for seniors may become an increasingly important challenge to address, especially given the recent trends favoring aging in place and relocating to urban environments amongst older adults. Rosenbloom (2004) found that elderly are the least likely to move of all citizens. This tendency has dropped consistently over the last 20 years where older people are about  $\frac{1}{4}$  as likely to move in any given year as adults age 30-44 and  $\frac{1}{2}$  as likely as adults age 45-64. Furthermore, the study states that roughly 60% of all moves by seniors 65 or older are within the same county as their previous home. As seniors become increasingly reliant on transit to complete their daily activities once driving becomes unsafe or once they chose not to drive especially those with a medical condition who are less able, improving transit accessibility is of increasing importance. There are numerous factors that can affect driving skills and the ability to safely operate a vehicle due to which license renewal may become an issue for seniors. Although varies between different states, Connecticut requires those of age 65 or older to undergo a vision test, allows renewing license for only 2 year period and may impose license restrictions due to age-related cognitive skills like memory, coordination and flexibility (Department of Motor

Vehicle Connecticut 2017). Medical trips increase in frequency for seniors as presented by Rosenbloom (2004) and the Connecticut Statewide Travel Survey Data (2016) as presented in figure 2. Figure 2 shows that as the age increases the percentage of medical trips also increases. Rosenbloom's study shows that the trip purpose being medical trips is 5% of all trips for seniors who are 65 or older compared to 1% for adults aged 16-64 where for Connecticut medical trip purpose accounts for 7% of all trips compared to the top trip purpose which is exercise being 9% of all trips compared to 3% for all 18-64 age group (Connecticut Statewide Travel Survey Data 2016). Rosenbloom's (2004) study also states that older people are more likely to walk to their destinations than those under age of 65 with an exception of medical trips and that older people are more likely to use taxi for their medical trips. These findings imply that seniors may also consider traveling by transit to reach a medical facility but due to implications such as infrequent service or simply lack of access to a transit service causes seniors to use taxis as a mode of transportation to medical facilities. Rosenbloom (2004) also states that the current 3% transit use by older adults shows that the potential of public transportation is not being fully realized. She also points out the need for public and private transportation operators to make their systems more older-adult friendly, which would consider the physical and functional impairments that limit or inhibit system use by older adults such as (walking to stops, infrequent service, recognizing entry and departure points, waiting outside in the weather, climbing aboard, standing in vehicle in motion) which need to be considered in the design and operation of the transportation system. Therefore quantifying transit access to medical facilities is of particular importance for those studying ways to accommodate the changing travel needs of an aging population. Health literature defines accessibility by criteria that include: affordability,

availability, accommodation, acceptability however this paper focuses solely on physical accessibility.



**Figure 2 Percentage of medical trips for Connecticut residents by age based on the Connecticut Statewide Travel Survey data (2016).**

The objective of this paper is to provide an analysis of how well the current bus transit system for the City of New Haven, Connecticut provides its senior residents with access by bus to healthcare facilities as compared to the rest of the population.

Connecticut transit, referred to as CTtransit, is a bus system serving much of the Connecticut state and is overseen by the Connecticut Department of Transportation (CT DOT), which also provides an operating budget. CTtransit provides bus service through contract providers for seven different metropolitan areas in the state, mostly concentrated in Hartford and New Haven counties. CT transit is arranged into multiple divisions such as Hartford division, New Haven division, Stamford Division, Waterbury division, New Britain and Bristol divisions, Meriden division, Wallingford Division and CTfastrack.

This paper is organized as follows: Section 2 provides extensive literature review on the travel habits of senior population. Section 3 presents a methodology for gathering input data to calculate the TOI measure of public transportation access. Section 4 describes the case study application, while Section 5 summarizes the findings and discusses future research.

The below literature review focuses on the travel behavior of seniors which is unique for this age group. It consists of mode choice, trip purpose and walking distance. These characteristics are unique for seniors in the following way: in terms of a mode choice- seniors are becoming reliant on other modes of transportation other than driving due to physical and functional impairments as opposed to the general population who primarily uses a private auto as a means of transportation. Seniors have a different travel purpose than the rest of the population such as shopping, run errands, entertainment and medical trips compared to the general population who primarily travels to work. Walking distance is an important characteristic for seniors as their walking ability decreases with age due to health implications.

Those unique travel characteristics of seniors are captured by the transit opportunity index (TOI) which is a comprehensive transit accessibility measure. The TOI is composed of three components: spatial, temporal and trip coverage and will be discussed in more detail below in the methodology section. However, to give a basic understanding to the reader of what the TOI score is it assigns a score based on the travelers' ability to reach a bus stop from their home, the frequency of buses at these local stops and the number of stops they can reach within a reasonable amount of time (Bertolaccini 2013).

## **LITERATURE REVIEW**

### **Mode Choice**

The impact of the automobile and the auto-centered transport system on the American environment, which originated in the 1910s and 1920s, is still significant and clearly directs the mode choice of residents when it comes to travel. Mattson and Wade (2012) quantified travel behavior and mobility based on age, defined as general population 19-64, senior population who are 65 to 85 years of age and those seniors who are 85 or older between 2001 and 2009 using National Household Travel Survey data. In terms of personal automobile usage as a mode of transportation, this study found that driving rates of senior population aged 65 or older slightly increased between 2001 and 2009 and will continue to rise. Mattson and Wade (2012) also found that driving a private automobile as a means to complete daily activities accounts for 90% in the mode choice category for age group of 19 to 64 years old. Seniors who are 65 to 85 years of age use private automobile to complete 80% of their daily activities and seniors who are 85 or older use private car only 53%, which is similar with findings presented by Boschmann and Brady (2013). High driving rates amongst seniors, which lead to a private automobile being top mode choice for travel, is supported and consistent with Choi et al. (2013) study that found the percentage of “never or former” drivers appeared to decrease between 1993 and 2008 for seniors aged 70-85. These findings regarding driving rates for seniors align with the percentage of driver’s license holders amongst the elderly as well, where the gap is the biggest between males and females for older adults (Hjorthol et al. 2010; Kim 2011; Turcotte 2012). Mattson and Wade (2012) also identified a gap in driving rates between the genders as increasing with increasing age based on rural and urban environment. In this context, the urban and rural classifications are based on the definitions used in the National Household Travel Survey Data (NHTS). Urban is defined to include an urban cluster, an urbanized area or an area surrounded by urbanized areas. Urbanized areas have 50 000 or more people while urban clusters have at least 2 500 people. All

other areas are defined as rural. For seniors aged 85 or older the difference is significant: 68% of males are drivers versus 38% of females in urban environment and 64% versus 41%, respectively for rural environment (Mattson and Wade 2012).

Such increasing gap in driving rates for seniors with increasing age is explained by the physical and function impairments which can affect driving skills and the ability to safely operate a motor vehicle. There are many driving restrictions and mandatory testing requirements with respect to renewing driver's license or obtaining one by a senior citizen that are specific in each of the states. In Connecticut, seniors are allowed to renew license for a 2 year period rather than the usual 6 year period and in addition to undergoing a vision test may be asked to take a written knowledge as well (Department of Motor Vehicle Connecticut 2017). Other restrictions may be placed due to the driver's medical condition. Providing a transportation alternative for seniors who can no longer drive or are simply less able due to functional limitations or medical condition but choose to remain independent is important.

Boschmann and Brady (2013) furthermore explored the travel behavior of seniors compared to the rest of the population by a study conducted in Denver, Colorado metropolitan area, which could be used to draw conclusion on the possible alternative modes of travel seniors use once they can no longer drive to remain independent. Their findings on travel mode suggest that that women aged 85 or older are most likely the group to rely on other types of transportation such as being a passenger instead of walking or use of transit in their trip making process while males were found to replace driving with use of public transit, walking or being a passenger. Walking/biking accounts for 8% and public transit use accounts for 3%, which is consistent with arguments regarding mode choice provided by Mattson and Wade (2012). Their study shows that seniors aged 65 or older took 2.5% of trips by transit and 9% of trips by

walking. Both studies observed an increase in transit use for seniors 85 or older: from 3% to 6% in Boschmann and Brady (2013) study and from 2% to 3% in Mattson and Wade (2012) study. Mattson and Wade (2012) also identified transit mode share increase for different senior age groups from 2001 to 2009 in the United States. They found that transit mode share increased by 62% for those aged 65-74 (from 1.3% to 2.0%) and by 31% for those aged 75-84 (from 1.7% to 2.2%). Transit mode share increase is the highest for seniors compared to the rest of the population. It has been also found that older adults took more than 1 billion trips on public transportation in 2009, which was a 55% increase over trips recorded in 2001 (Mattson and Wade 2012). Another interesting finding coming from NHTS analysis is that use of public transportation is much higher in urban areas than in rural areas (Mattson and Wade 2012). People with medical conditions or low-income households (which could imply retired seniors) are more likely to use public transportation in both urban and rural environment (Mattson and Wade 2012).

Low percentage of transit use amongst seniors is consistent with arguments that public transit is typically designed to meet the travel needs of the working age group rather than seniors. Rosenbloom (2004) also agrees with the above statement by stating that “the current 3% use by older adults shows that the potential of public transit is not fully realized”. Rosenbloom (2004) also observes the fact that public and private operators need to make their systems more older-adult friendly. The design and operation of transportation systems need to consider the physical and functional impairments that limit system use by older adults such as walking to stops or infrequent service.

### **Trip purpose**



Studies found that shopping and running errands are common trip purpose for seniors (Boschmann and Brady 2013; Horner et al. 2015; Winters et al. 2015) accounting for roughly 30% of all trips taken (20% of all trips made by 60-64 age cohort (9), 28% of all trips for 75-84 age group (Boschmann and Brady 2013)). However, there is a significant implication of a medical trip purpose which is one of the top trip purposes for seniors aged 65 and over. Mattson and Wade (2012) found that the trip purpose is different between different age cohorts. In particular, medical trips increase from 2% of trips for those under age 65 to 7% of trips for those 75 or older. This finding is consistent with the finding from the Connecticut Statewide Travel Survey (2016) study which shows that seniors defined as those 65 or older make 7% of trips that are medical compared to 3% for those aged under 65 (Connecticut Statewide Travel Survey Data 2016). Connecticut Statewide Travel Survey (2016) data also shows that the top trip purpose accounts for 9% of all trips therefore an inclusion on the importance of a medical trips for Connecticut residents who are 65 or older can be made with that number of 7% being close to 9%. Medical trips are amongst top common trip purposes for seniors (Boschmann and Brady 2013; Horner et al. 2015; Winters et al. 2015) and are of a particular importance to this study given the fact that seniors choose taxi as a form of transportation to a medical facility (Rosenbloom 2004) rather than walking aside from using a private automobile. This finding implies that seniors possibly consider using transit for their medical trips but given the infrequent or lack of service they opt out to using taxi. Use of a taxi as a form of transportation also implies the seniors' need to remain independent. Good transit system would provide an alternative for increasing mobility and independence amongst seniors, as presented by Rosenbloom (2004), especially those who travel to medical facilities. The average medical trip distance decreases from 10-11 miles for those aged 34 to 64 to 8.5 miles for those 65 to 74, which is a direct

indication of the physical and function impairments that older adults are experiencing which impose direct limitation when it comes to their physical capabilities of accessing medical facilities (Mattson and Wade 2012; Rosenbloom 2004). This decreases even further to 7 miles for those 75 or older, which could imply that seniors choose to reside nearer medical facilities as their medical needs increase. Rosenbloom (2004) found that elderly are the least likely to move of all citizens. This tendency has dropped consistently over the last 20 years where older people are about  $\frac{1}{4}$  as likely to move in any given year as adults age 30-44 and  $\frac{1}{2}$  as likely as adults age 45-64. Furthermore, the study states that roughly 60% of all moves by seniors 65 or older are within the same county as their previous home. Therefore these findings imply a need for a good transportation system in the areas where seniors reside in order to accommodate this type of population due to their unique travel characteristics given the fact that seniors' mobility and the desire of independence increased: which implies transportation alternatives when seniors can no longer drive.

Since a transit system could potentially be an important alternative mode of transportation to medical facilities for seniors, the applicability of a medical facility as a possible destination for this study was assigned based on data available in Table 1 from National Center for Health Statistics (Center on Disease Control and Prevention 2015). It shows the percentage distribution of outpatient health care visits for different age groups of seniors versus the rest of the population. Outpatient facilities are the focus of this table because they require patients to find transportation.

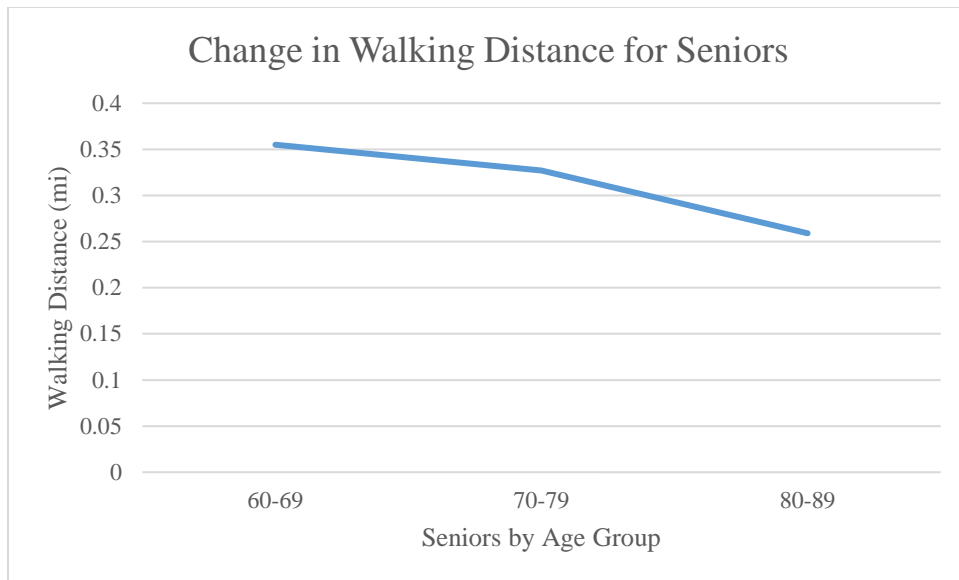
**Table 1: Visits to hospital outpatient departments by age: United States, selected years (from Health, 2015).**

Visits to hospital outpatient departments <sup>(from Center on Disease Control and Prevention, 2015)</sup>		
Characteristic	Number of visits per 100 persons	
	2010	2011
65+	51	56
65-74	50	56
75+	52	56
Total (all ages)	33	40

As shown in this table, seniors make visits to hospital outpatient departments at a 40% higher rate than the general population. The data and research provides strong evidence that seniors make more medically related trips than the general population and therefore access to medical facilities is of particular importance.

### **Walking Distance**

Walking distance literature review was used to determine the appropriate walking distance buffer around transit bus stop, which is implicit assumption of the TOI. Findings from European studies discussed in this section follow closely findings based on studies for US cities as mentioned below. Medical research suggests interesting findings in terms of seniors, which are useful when analyzing accessibility. Figure 3 shows the decrease in comfortable walking distance of 3 senior age groups from 1/3 of a mile to 1/4 of a mile (Troosters et al. 1999, Steffen et al. 2002).



**Figure 3 Change in 6 MWD for seniors by age based on Steffen and Mollinger study (Steffen et al. 2002).**

These specific studies align with the findings from US data for the comfortable walking distance which also varies between  $\frac{1}{4}$  mile to  $\frac{1}{2}$  mile (Neilson 1972; Kuby et al. 2004; Guerra et al. 2012; Daniels and Mulley 2013). Walking distance being an important component of a transit trip plays an important role when choosing the appropriate transit quality of service measure with respect to senior population. The walking distance of  $\frac{1}{4}$  mile coincide with the assumption implicit to the Transit Opportunity Index, which was chosen as the accessibility measure for this analysis.

## **METHODOLOGY**

### **The Transit Opportunity Index (TOI)**

The Transit Opportunity Index (TOI) (Mamun et al 2013) is a comprehensive measure of transit accessibility which considers both transit accessibility and connectivity. Transit accessibility is composed of spatial and temporal coverage while transit connectivity considers trip coverage. Specific components of the TOI are briefly discussed below including the alteration made with respect to senior population.

### ***Spatial Coverage***

Spatial coverage ( $R_{il}$ ) is the proportion of the area of highly senior populated census block group origin  $i$  served by the transit line  $l$ . It is computed using the ratio of the spatial coverage area of a transit line ( $B_{il \text{ buffer}}$ ) to the total area ( $B_{il \text{ total}}$ ) from the following equation:

$$R_{il} = \frac{B_{il \text{ buffer}}}{B_{il \text{ total}}}$$

A spatial coverage area is usually measured as the area covered by a particular route, by the area within a walking distance threshold of ¼ mile of a transit stop.

### ***Temporal Coverage (per capita service frequency)***

Per capita service frequency ( $S_{ijl}$ ) is measured by the *daily available seats per capita* from an origin  $i$  to a destination  $j$ . The daily available seats per capita is calculated as the ratio of the product of daily bus runs from  $i$  to  $j$  and bus capacity ( $U$ ) to the total population ( $P_i$ ) of origin  $i$  based on the following equation:

$$S_{ijl} = \frac{v_{ijl} U}{P_i}$$

Spatial coverage and per capita service frequency are combined to obtain transit accessibility ( $A_{ijl}$ ) for each  $i$ - $j$  pair in the network connected by transit line  $l$ .

$$A_{ijl} = R_{il} S_{ijl}$$

### ***Connectivity parameter***

A binary connectivity parameter ( $\delta_{ijl}$ ) is included with spatial coverage and per capita service frequency to measure access to possible trip destinations, which are medical facilities such as outpatient clinics and hospitals from a particular trip origin. This connectivity parameter represents the presence or absence of a direct transit route (trip coverage between O-D pairs).

$$\delta_{ijl} = \begin{cases} 1 & \text{If a transit line } l \text{ directly connects origin } i \text{ to destination } j \\ 0 & \text{otherwise} \end{cases}$$

### ***Decay function***

The binary connectivity parameter assigns the same level of connectivity to all destination regardless of the trip distance. The decay function used implies that the level of transit connectivity decreases gradually up to a certain travel time. Estimated  $\alpha$  and  $\beta$  parameters are based on a 60 min commute time. This implicit assumption is a good estimation of how far seniors are willing to travel to reach a medical facility destination.

$$f_{ijl} = \frac{L}{1 + \alpha e^{-\beta T}}$$

### ***Transit Opportunity Index***

$$TOI_{ij} = \frac{\sum_l A_{ijl} \delta_{ij} f_{ijl}}{\sum_i \sum_j \sum_l A_{ijl} \delta_{ij} f_{ijl}}$$

For more information on calculating TOI, please refer to Mamun et al (2013). Bertolaccini and Lownes (2015) created a Python-based tool which automates the calculation of the Transit Opportunity Index (TOI) for a transit service area using only general transit feed specification (GTFS) data and basic census data. The script was written in Python 2.7.2 for use with ArcGIS 10.1 and is used to conduct the following case study analysis.

### **Service Area**

Service area is defined as all block groups within walking distance of a CT Transit New Haven bus stop. Walking distance for seniors was defined by the Euclidean distance around a bus stop at ¼ mile based on comfortable walking distance for seniors specified by 6MWD results identified in the literature. Although the comfortable walking distance varies for seniors from 1/3 of a mile to ¼ of a mile as shown in figure 3, an assumption of a ¼ mi walking distance for all age groups of seniors is a good approximation based on the provided literature review. All block groups within ¼ mile of transit bus stops are considered part of the service area. Table 2 shows that percentages of seniors living in the service area relative to the total population.

**Table 2 Population count and percentage for the service area by age.**

System Total	Total Population		65+	75+	85+
	Count	548,222	80,475	39,408	15,023
	Percentage	100	14.68	7.19	2.74

### **Procedure to designate specific census block groups as origins**

Using the American Community Survey 5-year estimates for population and senior breakdown for the City of New Haven at the block group level, the count and percentage of New Haven's total and senior population was estimated. If the percentage of seniors in the block group exceeded the percentage of seniors in the service area, the block group was designated as having a high senior population. A limiting assumption implies that if a portion of a block group is within the buffered area, the whole block group has access to the service. These block groups are the origins of interest for TOI calculation.

### **Medical facilities as destinations**

The literature review identified medical trips as particularly important to seniors. In order to identify and map possible medical destinations, relevant data was obtained from the State of Connecticut's eLicense Website (eLicense online 2016), which provided addresses of medical facilities in New Haven County. A list of possible medical facilities that could be possible senior destinations was identified from the available data set, which included Healthcare Practitioners, Hemodialysis Centers, Hospitals, Clinics, Long-Term Care, Assisted Living Facilities, Home Health Care/Hospice. Furthermore, the applicability of each destination was assessed based on the health statistics report from the Center on Disease Control and Prevention (2015) website. As a result outpatient clinics and hospitals were used as destination for this analysis. It is evident from health statistics report that emergency department visits and outpatient departments are the

most frequent visits made by seniors within past few years as presented in table 3. When looking at the visits to specific facilities, number and percentage distribution of trips follow the same idea that seniors make significant portion of these medical trips when compared to the total from all age groups combined (Table 3). For example, seniors make above 50 trips to outpatient departments compared to all other ages which make 33 of those trips per 100 people. Based on this data, point locations which included at least one or more of the following medical facilities where chosen as destinations.

**Table 3 The number of hospital outpatient visits and percent distribution of emergency department visits by age: United States, selected years (from Center on Disease Control and Prevention, 2015).**

Emergency department visits <sup>(21)</sup>	
Characteristic	2010
Percent distribution	
65+	23.7
65-74	20.7
75+	27.4
Total (all ages)	21.4
Visits to hospital outpatient departments <sup>(21)</sup>	
Number of visits per 100 persons	
65+	51
65-74	50
75+	52
Total (all ages)	33

## **CASE STUDY APPLICATION**

The Transit Opportunity Index (TOI) was applied to the transit network of the City of New Haven, Connecticut. The data preparation was conducted entirely in ArcGIS, which identified origin and destination pairs connecting areas with large share number of seniors to areas with



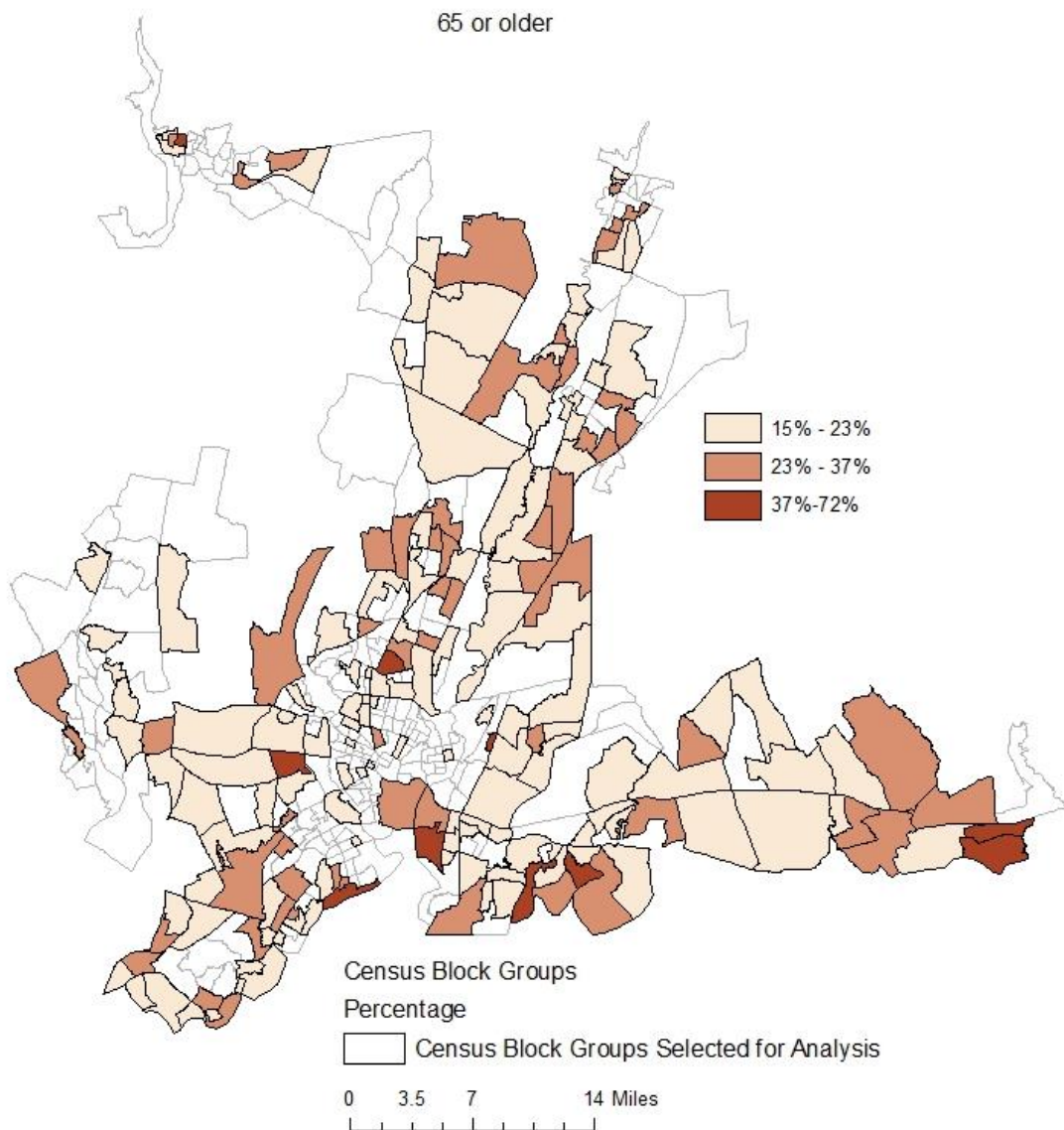
medical facilities, mainly outpatient departments and hospitals. The TOI score was then calculated for specific set of origin and destination pairs, which led to 3 different outputs. Origin shapefiles used as inputs for the TOI script included age-based census block groups for seniors aged 65 or older, 85 or older and the total population of the service area, which are shown in figure 2. The three subfigures show census block groups delineated with a block line which were used for each separate run of the TOI script as an origin input.

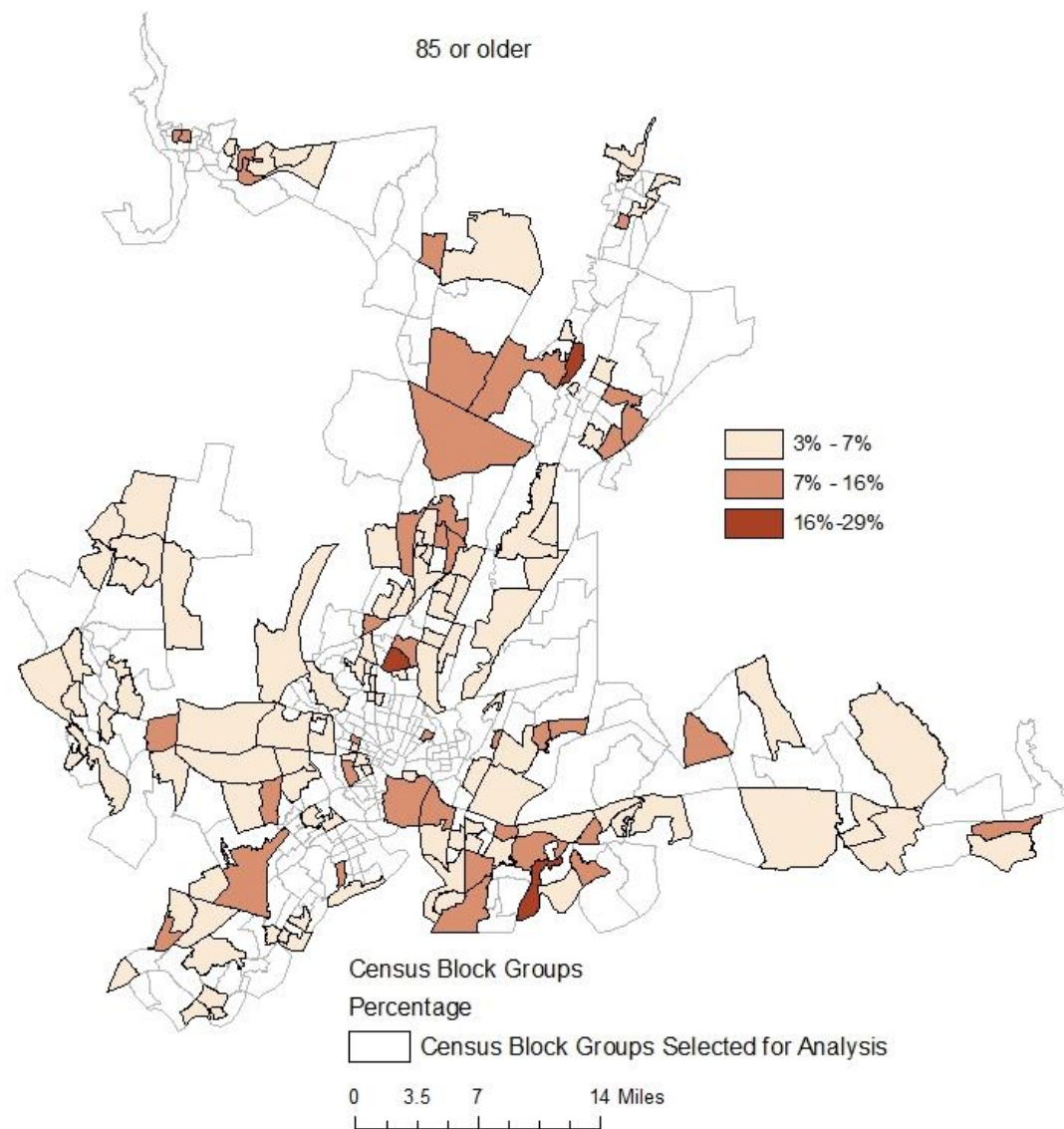
The TOI accessibility measure described in “Methodology” section is a useful measure of the level of accessibility that a given census block group has when compared with other block groups within the system. Therefore, the TOI score between 2 senior population subgroups was compared to the TOI score of the entire population of the service area. The TOI score is a single value calculated by the script for each input census block group. Based on that score/value as outputted by the script the level of access of those particular input census block groups can be assessed by grouping those scores into high or low. The goal is to obtain the access score/value from the script for each of the senior population census block group for their 2 age groups and then compare those values with the TOI values outputted for the entire system. For example: if we would like to draw a conclusion regarding access of a highly senior 65 or older populated census block group to a nearby medical facility as compared to the access that all other people have in the system, we would input origin file (census block groups that have high senior 65 or older population as shown by brown color hue in first subfigure of figure 2) and the destination file (medical facilities: outpatient clinics and hospitals as shown in figure 3) into the TOI Python script. After running it, we would receive a score for that origin input file which would range from 0 to 100 000, implying a low access level to a high access level. The same thing would be done over again with the exception of the origin file input: which would be all census block

groups within the transit system. After the script would be run, the TOI score for each origin census block group would be outputted also ranging from 0 to 100 000. Next, we could draw a conclusion based on the comparison of highly senior 65 or older populated census block groups to how their TOI score falls within the entire system by using a Chi Squared test. This would allow us to see how many census block groups based on the overall system fall within let's say a score of 5000. This would be our observed number of census block groups which should have a score of 5000, which let's say could be 50. We would furthermore observe how many senior 65 or older census block groups fall within a score of 5000, which let's say could be 20. This would be our expected value. Now the comparison could be made between expected and observed number of census block groups with an access level of 5000. We could conclude that we would observe 50 highly senior 65 or older census block groups to have a score of 5000 but there are only have 20 if the level of access was the same as the one of the entire population of the system. This implies that seniors do not have a better access to the medical facilities then the rest of the population of the service area.

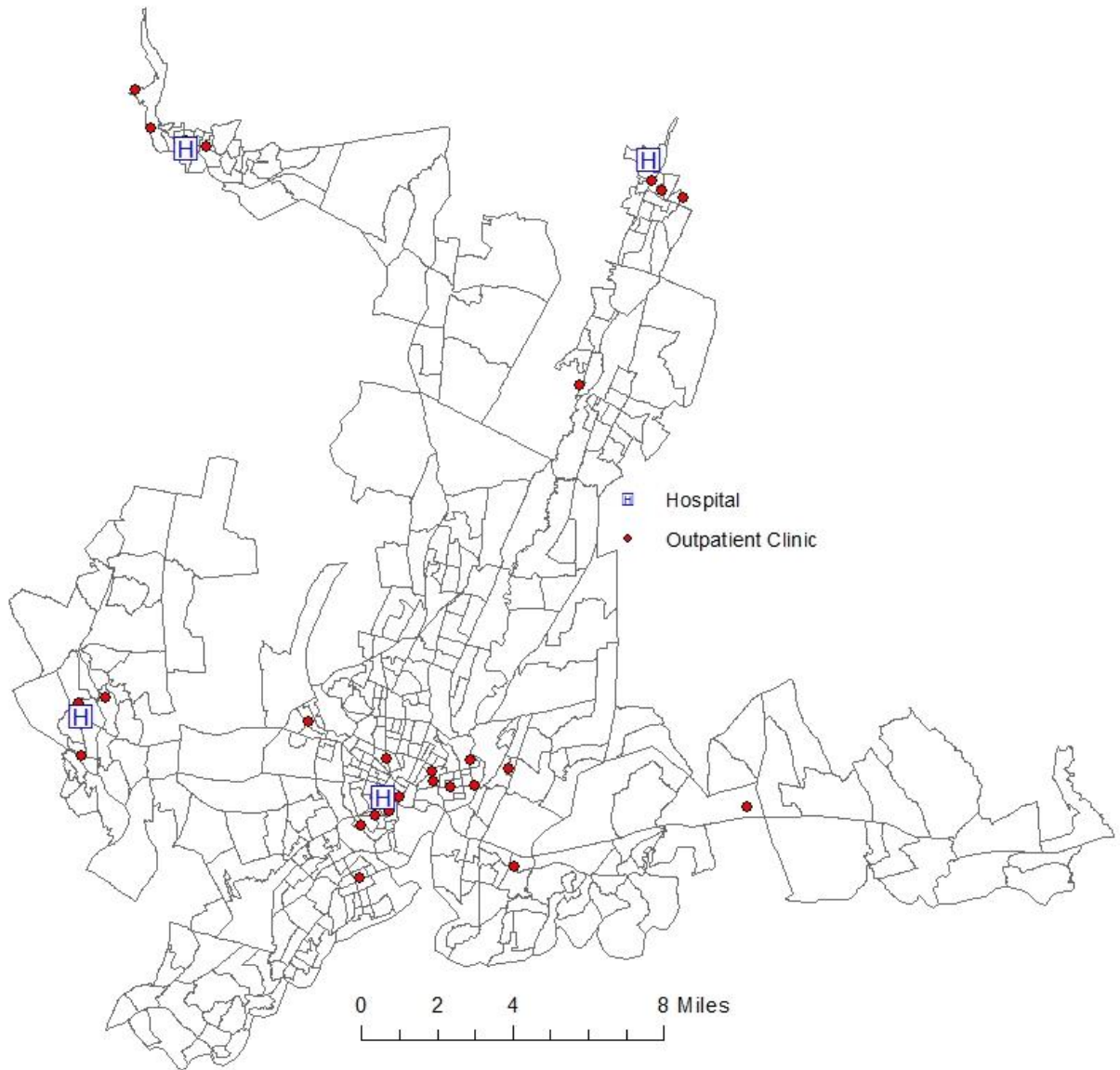
The TOI run for the entire population was based on all census block groups as origins (no age distinction). The TOI run for population aged 65 or older was based on the census block groups delineated with a black line as shown in the "65 or older" subfigure of the figure 2 as origin. The TOI run for population aged 85 or older followed the same idea as the TOI run for seniors "65 or older". The percentage breakdown and cut off values for each population type used in this analysis are also shown in the Figure 2 and follows information specified in table 2. For senior population origin inputs, a census block group was identified as an origin if the percentage of seniors 65 or older was greater than 14.68%, and if greater than 2.74% for seniors 85 or older. Different colored census block groups (light yellow, brown and dark brown) shown for senior 65

and 85 or older subfigures specify the different concentration of seniors in the chosen census block groups to show the variation in concentration throughout the region. Figure 3 shows the location of medical facilities for the transit system of the study area. The destination shapefile was created based on each point feature representing each medical facility (outpatient clinics and hospitals) and was used as the destination shapefile input for the TOI script run.





**Figure 2 Census Block Groups selected as origins for the TOI analysis by senior population.**



**Figure 3 Location of medical facilities for the service area.**

The TOI Python script was run for 3 different origin inputs and 1 destination input for the New Haven transit system. Figure 4 presents the overall view of the output of the analysis and the distribution of the TOI scores throughout the system, with zoomed in areas that have higher TOI score shown in figure 5. Orange, yellow and green areas indicate higher levels of accessibility. The meaning of block group TOI scores can be difficult to interpret on their own and are useful to look at in comparison to other block groups within the system service area. Therefore, this

analysis compares senior (defined by 2 age groups) block group TOI score to the general population block group TOI score as shown in the 3 subfigures of figure 4 and figure 5. The cut off values were estimated using natural breaks (jenks) with 5 classes.

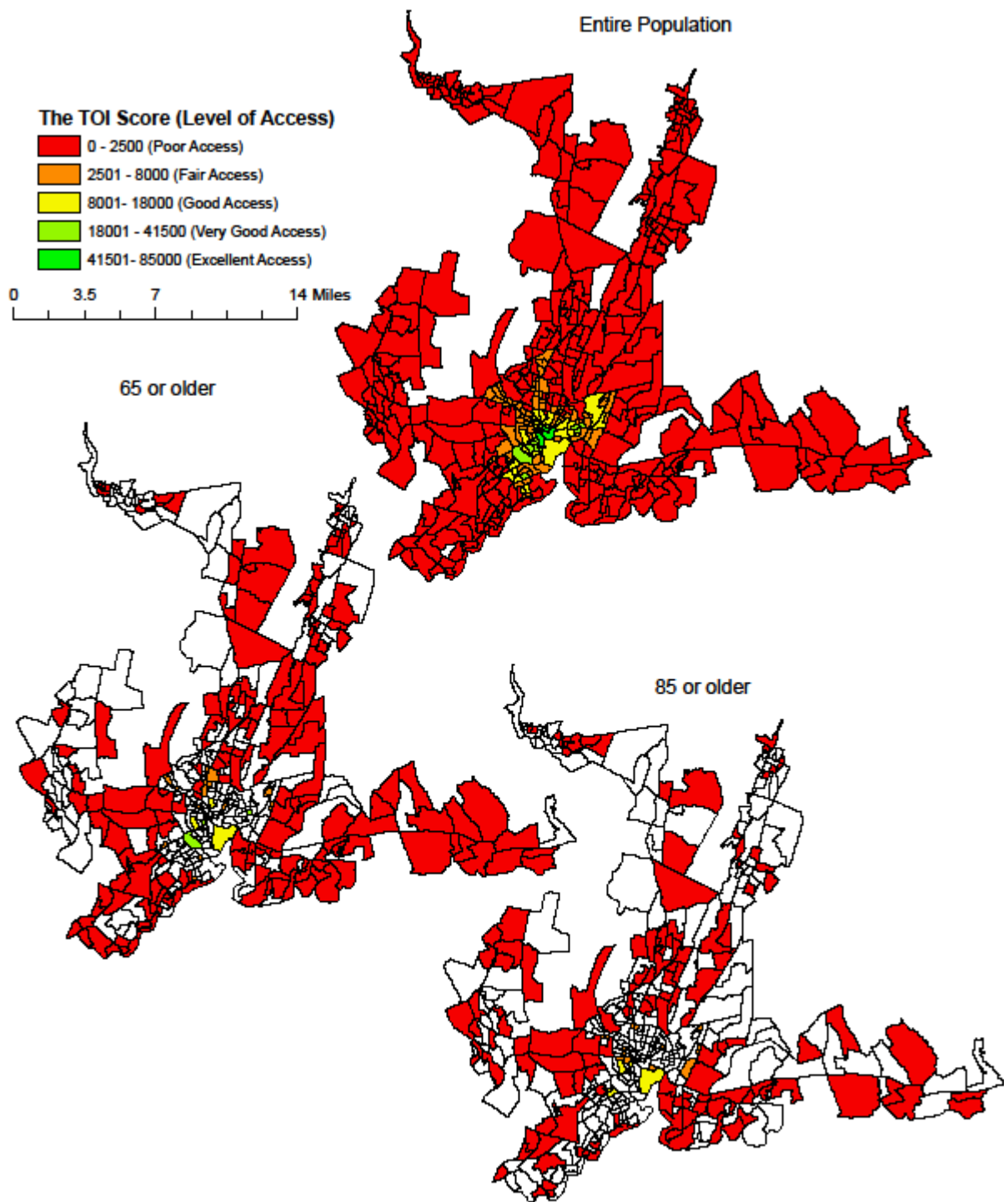
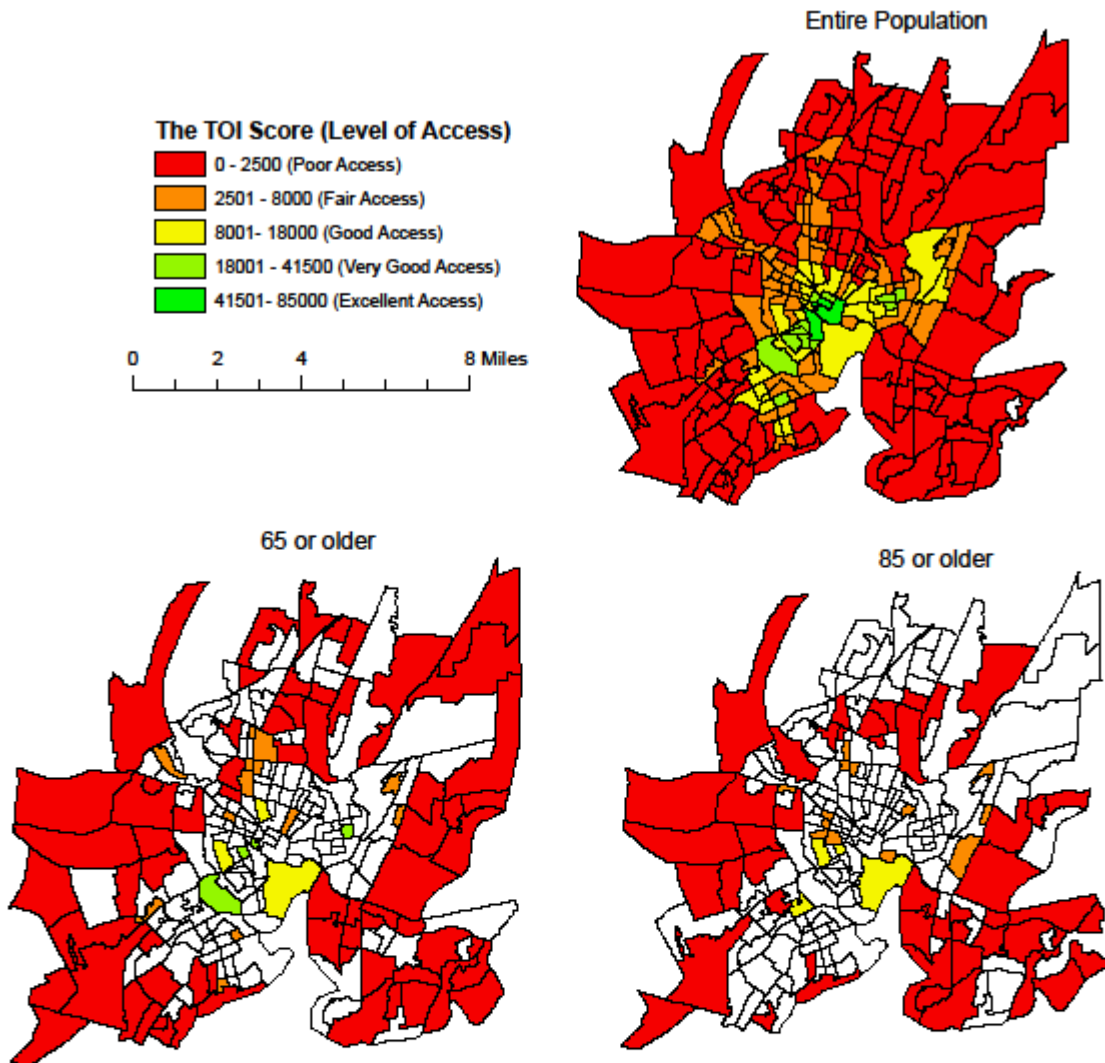


Figure 4 The TOI score for the entire population, seniors 65+ and 85+ of the service area.

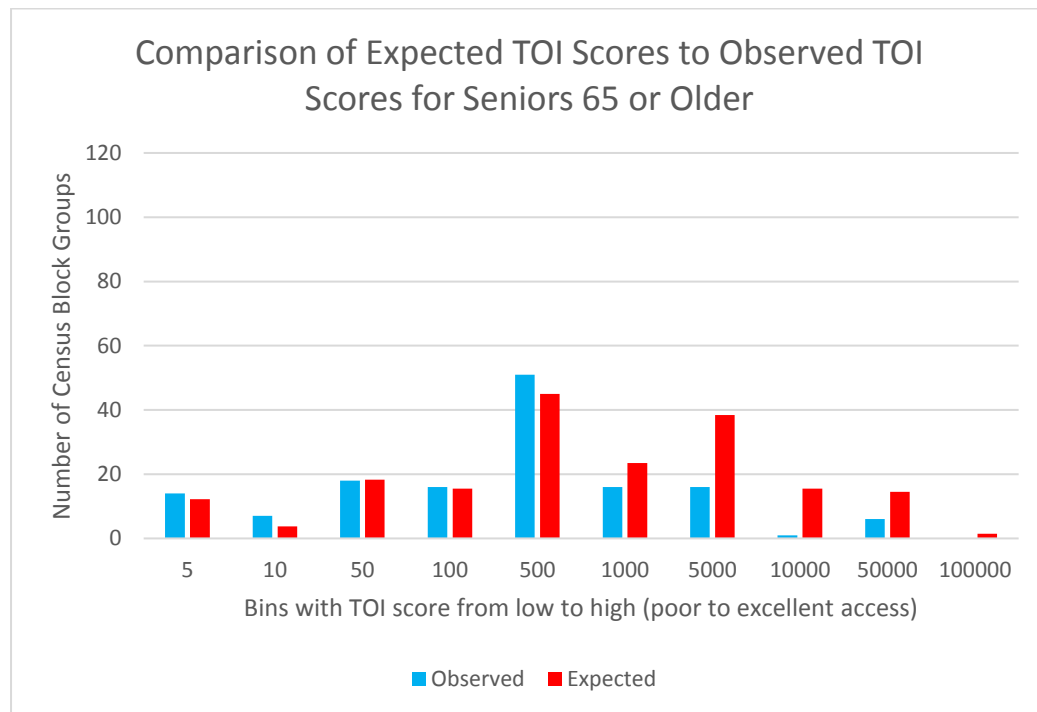


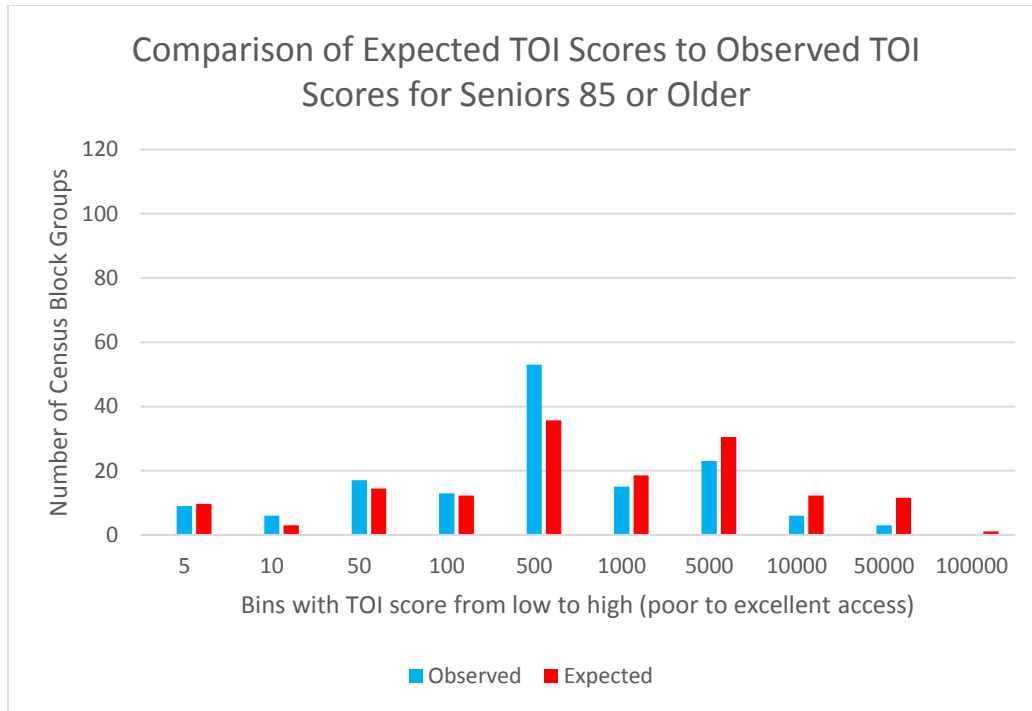
**Figure 5 The TOI score for the entire population, seniors 65+ and 85+ of the service area zoomed to sections with fair to excellent access.**

Figures 4 and 5 shows that there are highly populated senior block groups which have a good, very good and excellent access to medical facilities. The TOI outputs a high score for areas with good access and lower score for areas with poor access. Scores range from 0 to 100 000 adjusted seats/day. This analysis was conducted on a typical weekday in (2013). Because the resulting TOI scores were very large and the heavy skew of the distribution, logarithmic scale was used in order to group the scores into 10 bins (5- 100000 in logarithmic scale) for the purpose of



histogram representation. The histogram in Figure 6 shows how the TOI score compares between the entire population of the service area, 65 or older and 85 or older. For example, when looking at the first subfigure of figure 6 we would observe to have 16 highly senior populated census block groups to have a TOI score of 5000 but there is actually 38 of senior census block groups that have a score of 5000. This implies that seniors do have a better access to medical facilities if the level of access distributions were the same for senior subgroups as the one for the total population.





**Figure 6 TOI score distribution for the general population and selected age groups of seniors.**

Chi Squared test was conducted to compare the distributions of TOI scores between different age groups and validate the obtained results. Two population sub-samples of seniors 65+ and 85+ were studied to determine if there is a significant difference in access between those two age groups and the rest of the population. The null hypothesis tested in this Chi Square test states that there is no significant difference in transit access between the general population and specific senior age groups. Alternative hypothesis states that transit access for seniors is statistically different from for the general population.

The computed Chi Squared statistics of 40 and 25, which compares the general population's access to medical facilities versus seniors' 65+ and the general population's access to medical facilities versus seniors' 85+ respectively, are much greater than the critical value of 16.2 at 5%

confidence level ( $\alpha = 0.05$ ) for 9 degrees of freedom. Null hypothesis is rejected with the computed statistics being greater than the critical value, leading to accepting alternate hypothesis. This provides statistically significant evidence at  $\alpha = 0.05$  level that there is a difference in the distribution of transit access to medical facilities between the general population and seniors. The computation of Chi Squared statistic of 32 between the differently aged seniors 85+ to 65+ also does provide statistically significant evidence to show that there is a difference in transit access between these two senior age groups.

## **CONCLUSIONS**

The Chi Squared Test suggest that transit access to medical facilities is statistically different in highly senior populated block groups compared to the population at large implying that seniors do have a better transit access to medical facilities than the rest of the population. This could be a result of seniors choosing to live in neighborhoods which are either close to medical facilities or have transit access to them. Another possible interpretation is that that transit planners are focusing on providing better access in these locations after seniors choose to locate there. There is no difference in access between different age group of seniors.

Shortcomings of this paper include the service area being defined by the transit system, which excludes seniors who live in neighborhoods that do not have access to transit, which could explain the low percentage of transit (Mattson and Wade, 2012; Rosenbloom, 2004, Boschmann and Brady, 2013). In addition, paratransit is not considered.

There is an assumption implicit to the TOI, which may not be accurate for elderly people. The TOI is based on the  $\frac{1}{4}$  mile Euclidean buffer used along the public transit lines to estimate spatial coverage. Based on the literature review the walking distance for seniors is age dependent and

changes between  $\frac{1}{4}$  mile and  $\frac{1}{3}$  of a mile. This study generalized all senior ages to one walking distance of  $\frac{1}{4}$  mile.

One specific inclusion pertaining this study is the following: even though the TOI results indicate that seniors have better access to medical facilities via public transit it does not necessarily mean that public transit for this service area adequately addresses their mobility because of the actual percentage of seniors who live within transit system area is low (table 2).

### **ACKNOWLEDGEMENT**

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### **DISCLAIMER**

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security.

## **Chapter 2: Providing Equitable Access to Medical Facilities for Seniors' By Optimizing Transit Network for Equity**

1.	Abstract.....	32
2.	Introduction.....	33
3.	Literature Review.....	34
4.	Problem Formulation.....	38
5.	Model Validation.....	41
6.	Case Study Application.....	43
7.	Results.....	53
8.	Conclusion.....	57

## **ABSTRACT**

Equitable access became a concern with passing of non-discrimination requirements specified in Title IV of Civil Rights Act of 1964 (U.S. Congress, 1964) and Executive Order 12898 on environmental justice (Clinton, 1994). Increasing need for new methodologies to incorporate equity into network design quickly gained interest of transportation researchers. Although very few methodologies have been developed on the subject, this study builds on available tools on transit network optimization. It develops a frequency setting model for equitable access to medical facilities with respect to elderly population. This research is motivated by findings related to travel characteristics of this particular group, mainly, the time of day of travel and trip purpose. Seniors tend to travel during off peak hours at a rate higher than the rest of the population (Connecticut Department of Transportation et al. 2016, Kim et al. 2004). Seniors also tend to have a different travel purpose than the rest of the population. Research shows that they make frequent medical trips (Connecticut Department of Transportation et al. 2016, Health 2012), along with shopping and running errands all done during off peak hours. Based on the recognition of the need for more frequent service during off peak hours to accommodate the needs of increasing population of seniors in Connecticut, a frequency setting model is applied to the transit network for the City of New Haven, Connecticut. The model is tested on two demand scenarios: a base case in which all demand is treated equally, and a scenario in which a population weight factor is included in the objective function to prioritize the demand of protected populations. Results show improved access by increasing bus frequency to routes serving areas with higher population of seniors.

## **INTRODUCTION**

The growth of automobile industry in the mid twentieth century caused an economic revolution around the United States, which furthermore contributed to the urban sprawl. Lower land rates, improved infrastructure, lower tax rates and lack of urban planning encouraged people to move further away from cities leading to a segregated land use. As a consequence, equal access to basic economic and social opportunities became a problem especially for minority and low-income populations who do not always have an option to rely on the use of private auto as a means of transportation. Children, older adults, low income families and people with certain disabilities very often rely on public transportation services to which their physical access is often limited.

In the light of changing demographics, in which the proportion of seniors is projected to grow by 57% between 2010 and 2040 in Connecticut (Commission on Women, Children and Seniors, 2016), addressing equitable access issue is a major concern for transit planners and service providers. Two studies that examined good transportation systems confirm that a transportation system can improve access to jobs if it provides frequent and reliable service at times when people need it to travel (Rotger et al. 2015, Yi 2006). These studies findings suggest that providing transportation service which people can rely on at any time of day is important in improving access.

Frequency of service is of a particular importance when it comes to vulnerable or transit-dependent populations. Older adults or people with disabilities choose to travel at a particular time of day which may be different from the rest of the population. As research suggests, seniors travel mostly during off peak hours (Kim et al. 2004, Connecticut Department of Transportation

et al. 2016) and make many more medical trips compared to younger age cohorts (Connecticut Department of Transportation et al. 2016, Mattson and Wade 2012, Health 2012, Horner et al. 2015). Thus accommodating their travel needs by providing more frequent service during times they are most likely to travel to their unique destinations is an effective way to improve access of this particular minority group.

Setting route frequency is one of the four primary components of a complex transit network design problem (Desaulniers and Hickman 2007, Farahani 2013). Although available research offers very few tools which incorporate equity into transit network design, this paper aims at addressing equity concerns in the formulation of the transit frequency setting model. The goal is to provide an equitable access to healthcare for seniors by increasing bus frequency on routes serving relevant origin destination pairs. The analysis uses publicly available General Transit Feed Specification (GTFS) and census data for the City of New Haven, Connecticut.

## **LITERATURE REVIEW**

Recognition of the importance of public transportation access and equitable transportation services arose when the executive order 12898 entitled Federal Actions to Address Environmental Justice (EJ) in minority populations and low-income populations was passed. The executive order 12898 alerted public transportation field about the need for methodologies which could help in determining whether a transportation project would cause a disproportionate impacts on minority or low-income populations.

Several methods focus on assessing equity of existing public transportation systems. Equity has been studied in terms of the level of access or mobility experienced by minority, disadvantaged or low-income populations. Lucas et al. (2009) studied transport and social exclusion by



identifying changes in travel behavior in the United Kingdom case study, which were caused by the growing policy awareness of the transport problems for “deprived areas”, explored the impacts and contributions of those policies on the quality of life and economic opportunities (1). Currie et al. (2009) also used series of case studies to look at social exclusion and well-being in terms of being a transport disadvantaged population (2). This study aimed at quantifying associations between lack of transport and social exclusion for Australian residents who do not have access to a private car for their travel needs. Lucas and Currie, illustrated the need for methodologies to include transport equity explicitly into design.

Little research has been done on incorporating equity into a network design problems. Connors et al. (2005) showed how equity can be incorporated into the objective function or as a constraint into the network design problem in order to consider the distribution of resulting benefits and costs across the population of travelers instead of only focusing on how a set of tolls maximize social welfare (3). Duthie and Waller (2008) incorporated equity of congestion and travel time as objective functions into their network design problem. Developed model was formulated to solve the problem of achieving environmental justice through a selection of network improvement strategies with environmental justice defined to mean that no protected population is disproportionately affected (4).

Furthermore equity has been incorporated into the transit network design problems. Bertolaccini et al. (2015) studied equity in terms of vehicle routing problem and proposed a genetic algorithm for solving it. Bertolaccini and Lownes (2013) also measured the inequality of a system by extending already developed Gini Coefficient measure to measure impacts of selecting different

scales, boundaries and demand measures has on assessing the calculated Gini Coefficients. Chen and Yang (2004) formulated two stochastic network design models which include spatial equity and demand uncertainty with spatial equity being defined as the “benefit distribution among network users” (5). Ferguson et al. (2012) took a step further into transit network design and proposed a methodology which focuses on incorporating equity and access into a frequency setting design problem part of transit network design (6). This study compared access via personal vehicle and transit between different origin-destination sets with objective function structured to minimize that difference. Transit access is modeled to be improved using access by personal vehicle as a reference to meet basic needs in auto-oriented society. The result transit service provides an equitable difference between access by car and access by transit given operating constraints. This methodology can be applied to find the frequencies for each bus route of a sub-study area which maximize equity given fixed capital and operating costs. Next, the difference in accessibility by car and transit was calculated for each origin-destination pair. Furthermore the difference between these accessibility measures and between the mean of all accessibility measures across all pairs is calculated.

Although equity was considered in few transit network design studies, majority of transit network design problems focus on minimizing operating and user costs without considering equity or access for disadvantage populations. Lampking and Saalmans (1967) develop a model which efficiently optimizes the route structure, frequencies, compile time tables and designs bus schedules so that the whole system operates on the least number of needed buses bases on a small case study, while reducing the annual operating cost without decreasing the overall level of service offered (7). Work done by Pattnaik et al. (1998) also focused on minimizing overall cost

modeled as a function of travel time constrained by fleet size and total operating cost (8). Yu et al. (2009) developed a bus frequency design model which optimizes bus frequencies and minimizes the total travel time constrained by the fleet size accounting for the route choice of passengers. Optimal frequencies are determined based on iterative process between the passenger assignment and frequency optimization in order to reduce passengers who do not fit into a bus caused by overcrowding (9). Koutsopoulos et al. (1985) proposed a model where the objective function minimizes costs due to passenger waiting times, operating cost and the cost of crowding constrained by fleet size and total operating cost and vehicle capacity (10). Desaulniers and Hickman (2007) offer a comprehensive overview of various stages of public transit planning process along with models and approaches for solving public transit problems (11). Public transit planning consists of strategic, tactical and operation planning. Strategic planning involves network design to meet the passenger demand. Tactical planning involves improving service to the passenger by selection of frequencies on a bus route and timetabling. Operational planning involves vehicle scheduling, duty scheduling, crew rostering, parking and dispatching and maintenance scheduling. The frequency setting problem, which current research has not thoroughly explored in terms of equity yet, is an important part in the relationship between the tactical and operational problems in a way that it defines the main input for the operational planning phase.

The subsequent sections adapt concepts established in the above literature review on transit network design problem and equity. General Transit Feed Specification (GTFS) data is evaluated to assess the change in bus frequency on different routes at different times of day when examining different weighting schemes favoring senior populations and their access to medical facilities. The contribution of this paper is the development of a model and methodology for the

reallocation of transit resources (bus frequencies on routes) to accommodate shifts in demand during off-peak periods to better serve a vulnerable population and their needs: senior travels accessing medical facilities.

### **PROBLEM FORMULATION**

The proposed frequency setting model is mathematically formulated as a Mixed Integer Program (MIP). The objective function minimizes the travel time between origin  $i$  and destination  $j$  on a route  $r$  as a function of both in-vehicle travel time and wait time. The model is described as follows:

#### **Sets and Indices**

$i, j \in N$	bus stops
$r \in R$	bus routes

Set  $N$  contains all transit bus stops for the system, while set  $R$  includes all bus transit routes for the transit system.

#### **Data and Parameters**

$t_{ijr}$	in-vehicle travel time (IVTT)
$d_{ij}$	demand for travel $i, j$
$t_r^R$	round trip time on route $r$
$U$	capacity of a bus
$B$	total fleet size
$\delta_{ij}^r = \begin{cases} 1 \\ 0 \end{cases}$	if $i, j$ is served by $r$ otherwise
$P_i$	population weight factor at origin $i$
$A_j$	destination weight factor at destination $j$

The parameter  $t_{ijr}$  describes a time that a passenger spends traveling from origin  $i$  to destination  $j$  using route  $r$ . It is based on arrival and departure times available for each route in stop times file from GTFS. The parameter  $d_{ij}$  is the demand traveling from origin  $i$  to destination  $j$ . The parameter  $t_r^R$  is a round trip travel time for each route  $r$ . Round trip travel time is calculated as a

time it takes a bus to travel from an origin to a destination and back. Scalar  $U$  is a capacity of a bus and scalar  $B$  is a total fleet size operating in a system. Parameter  $\delta_{ij}^r$  is a binary variable which takes a value of 1 if origin destination pair  $i-j$  is served by a route  $r$  or 0 if it is not. Parameter  $P_i$  is a population weight factor at origin  $i$ . Parameter  $A_j$  is a weight factor at destination  $j$ .

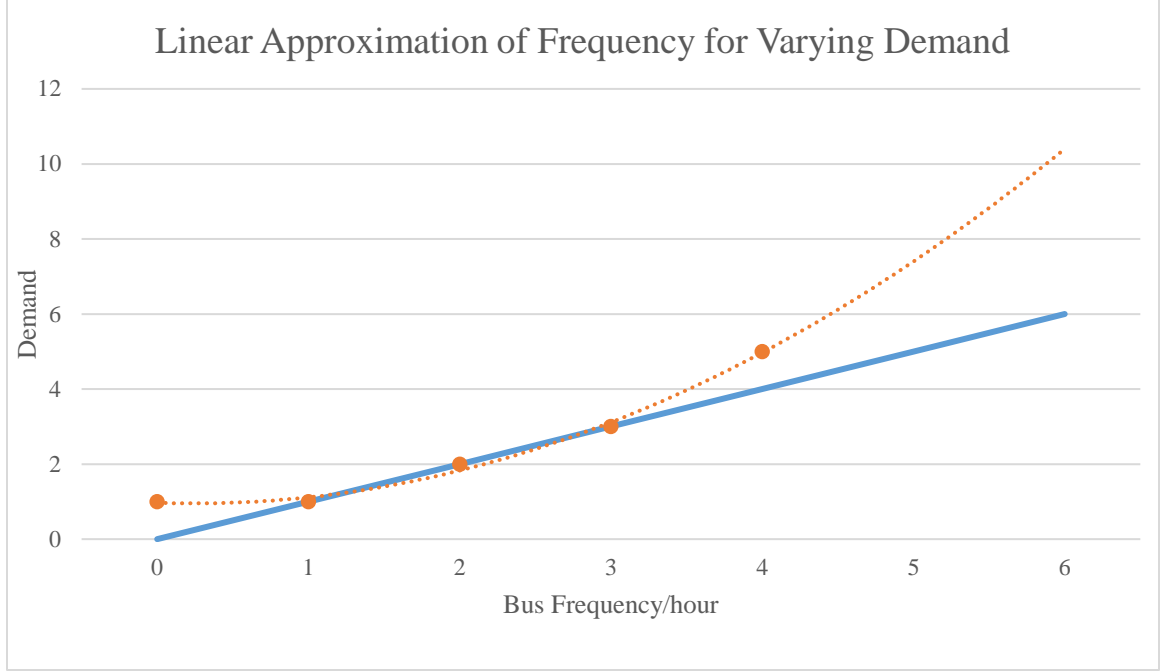
### Decision Variable

$f_r$  bus frequency on route  $r$

### Objective Function

$$\min z = \sum_{i \in N} \sum_{j \in N} \sum_{r \in R} P_i A_j d_{ij} \left( t_{ijr} + (33 - 3f_r \delta_{ij}^r) \right) + \sum_{r \in R} \frac{t_r^R}{3600 f_r} \quad (1)$$

The linear function to be minimized described above consists of two components. The first component is the in-vehicle and wait time experienced by each passenger from  $i$  to  $j$  on route  $r$ . It involves a linearization of wait time and is shown in figure 1. Second part of the objective function minimizes the total round trip travel time on a given route.



**Figure 1 Linear approximation of frequency for varying demand.**

### Constraint Set

$$\sum_{r \in R} \frac{t_r^R}{3600} f_r \leq B \quad (2)$$

$$(6f_r - 5) U \geq \sum_{i \in N} \sum_{j \in N} d_{ij} \delta_{ij}^r \quad \forall r \in R \quad (3)$$

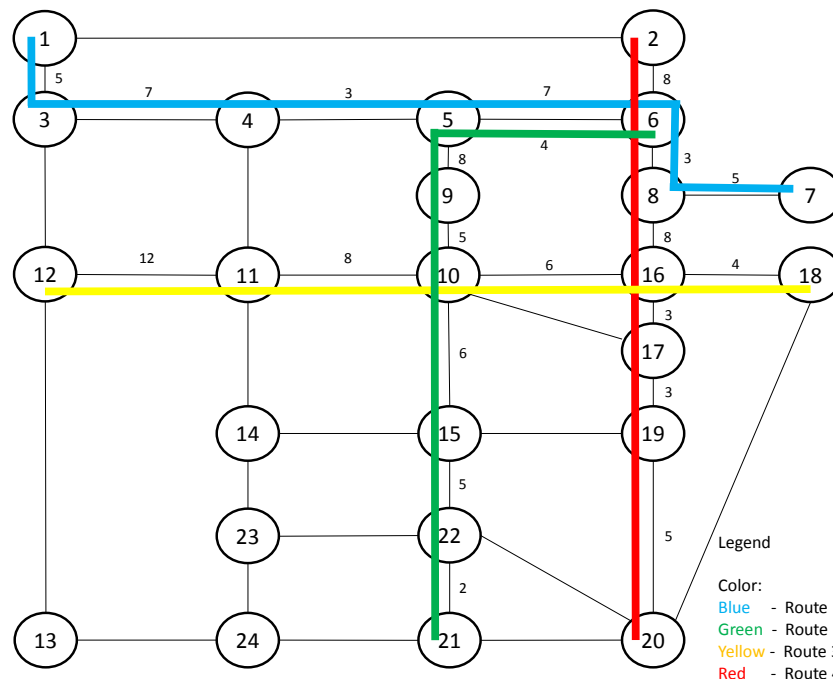
$$f_r \in \mathbb{Z}^+ \quad \forall r \in R \quad (4)$$

Constraint 2 ensures that the round trip travel time for route  $r$  being a subset of all routes  $R$  times the frequency on that route does not exceed the available fleet size for the system. Constraint 3 ensures that the capacity of a bus is greater than the demand traveling between origin destination pairs. Constraint 4 imposes frequency to be an integer value.

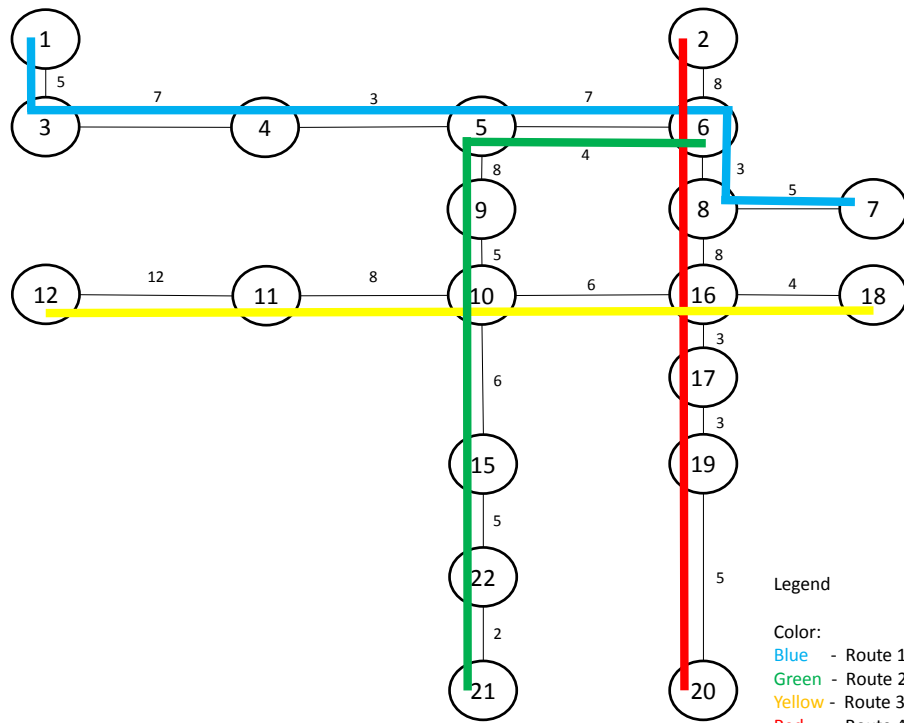
The analysis was performed using the General Algebraic Modeling System (GAMS) which is a mathematical programming and optimization software for complex modeling applications.

## MODEL VALIDATION

The proposed model is tested for validation using a Sioux Falls network with sample general transit news feed (GTFS) data developed for this purpose. The Sioux Falls is a commonly used test network with 24 nodes and 76 links (Transportation Network Test Problems, 2013). For the validation purpose it is assigned with 4 bus routes with assigned cost of traveling on each link. The sample general transit news feed developed for this scenario allowed creating necessary files needed for optimization software. Such files included round trip travel time for each of the 4 routes, in-vehicle travel time on each link and binary variable file specifying whether a node is served by a route or not. The demand file used for this analysis consisted of random numbers assigned to each node combination of the sample network. Figure 2 presents full network for reference, while Figure 3 shows nodes and links used for validation testing only.



**Figure 2 Full Sioux Falls network.**



**Figure 3 Nodes and links used for analysis.**

The sample scenario is constrained by a capacity of a bus being 40 seats and total fleet size of a system being 20 buses. The results of the distribution of available buses for each route based on the node-to-node demand is presented in Table 1 and shows a fairly even distribution of buses for each route. When the demand of some node pairs is weighted more heavily, the solution suggests the shift in frequency of buses serving those node pairs. In this case the node pairs which were assigned with higher demand are served by the blue route and include nodes 1-8 and 8-1.

**Table 1 Bus frequency for each route in the study region based on normal and higher demand.**

Route	Frequency
Blue	5
Green	6
Yellow	4



		Route	Frequency
		Blue	8
		Green	5
		Yellow	3
Red	5	Red	4

The purpose of this sample testing analysis is to provide a framework for the case study described in next section. This proof of concept on the Sioux Falls Network was helpful in suggesting the correctness of the model because a change in service frequency was observed on two routes which served a highly weighted origin destination pair for the weighted higher demand model.

### **CASE STUDY**

A case study is presented to look at an application of the model in more detail using the datasets as outlined in Table 3. Purpose of this study is to develop a model which would improve the existing transit service to provide a better service for senior residents by aligning it better with their unique travel characteristics. Therefore, the focus is put on obtaining an equitable bus frequency to route assignment for varying node demand based on two demand scenarios.

Varying node demand is designed to change and increase service frequency for origin and destination pairs which are given higher weights complementing their importance in the system versus other unweighted origins and destinations. Such prioritization designates areas with high senior population and areas which are their unique travel destinations: healthcare facilities. The developed frequency setting model is tested for its sensitivity to the origin destination prioritization by observing the change in frequency to route assignment. Ideally working model would assign more frequent service to routes which are providing access for heavier weighted origin destination pairs. Therefore the model is tested whether such change in frequency could be observed based on two scenarios. The first scenario is a node demand based on entire population of the service area, with no special consideration given to any particular subpopulation. The

second scenario weights nodes within high senior populated regions (origin) and nodes where medical facilities are located (destination) more heavily. Weighting is achieved by doubling the demand on those origin destination node pairs, which suggests that there is double the demand traveling from particular origin to particular destination making those pairs a priority in the system. Two scenarios are compared to observe changes in bus frequency structure on routes.

CT Transit New Haven is used in this case study application. The entire system is composed of 3135 bus stops and 26 bus routes. Assumed parameter values are presented in Table 2 and are based on the Connecticut Department of Transportation- CT Transit New Haven Division 2014 Annual Agency Profile.

**Table 2 Assumed Values for Case Study.**

Parameter	Value
Capacity of a bus	40 seats per bus
Total fleet size	74 buses

## Data sources

The relevant data used in the above MIP model is outlined in Table 3 along with visual representation shown in Figure 4. Transit system information was obtained from GTFS feed available online (Google Developers, 2016). A GTFS feed is a collection of comma delimited files contained within a ZIP file. Together, the related CSV tables provide a description of transit system's scheduled operations as visible to the riders. This data is designed for various analytical applications of public transportation systems. GTFS files allow users to determine stop locations, in-vehicle travel time, headways and routes available for particular transit system. The GTFS specification defines the following files as being required: agency, stops, routes, trips, stop\_times and calendar. Optional files are: calendar\_dates, fare\_attributes, fare\_rules, shapes, frequencies, transfers and feed\_info. Class diagram presenting the relationships among various GTFS files

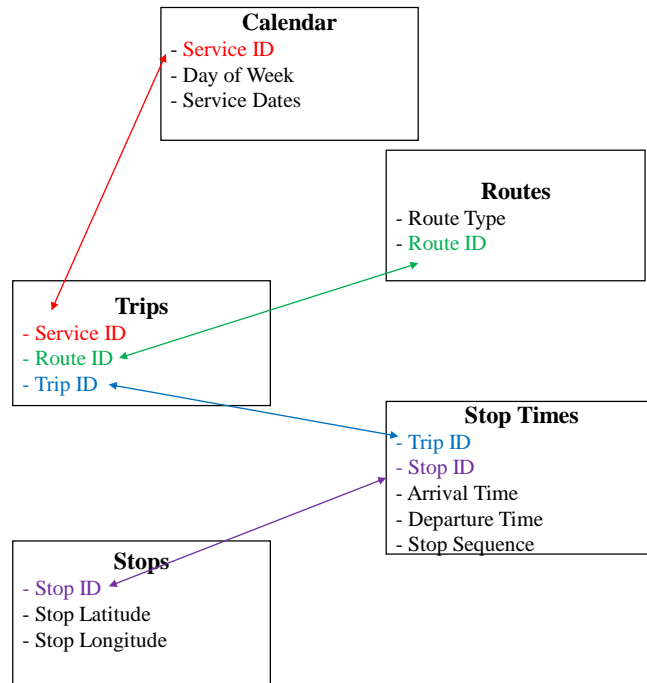
used in this analysis can be found in Figure 4 (CT Transit, 2016, Bertolaccini, 2015). A study presented in this paper used “routes” file to obtain the number of bus routes in the system needed to identify Sets and Indices as presented in the Problem Formulation section. A representative inbound and outbound trip for each route from “trips” file was used to obtain the following:

- “stop id” also needed to define bus stop sets,
- “stop sequence” of a particular representative trip which allowed obtaining in-vehicle travel time on each link needed for calculation of round trip travel time on each route,
- in-vehicle travel time on each link for the given stop sequence of a representative trip for each route
- in-vehicle travel time and round trip travel time on each route was obtained based on arrival and departure times available in “stop times” file

In addition to the transit system data, the analysis required basic population data. Connecticut population data at the block group scale used to develop this analysis uses data from the US Census Bureau.

**Table 3 Datasets used for the model formulation.**

Sets/Indices	Source	Date
Transit Bus Stops	CT Transit New Haven General Transit News Feed (GTFS)	2013
Transit Bus Routes	CT Transit New Haven General Transit News Feed (GTFS)	2013
Data/Parameters	Source	Date
In-Vehicle Travel Time	CT Transit New Haven General Transit News Feed (GTFS)	2013
Round Trip Time on Route	CT Transit New Haven General Transit News Feed (GTFS)	2013
Demand for Travel	US Census Bureau Data from Mamun et al. (2013) study	2010



**Figure 4 GTFS file diagram (Bertolaccini, 2015).**

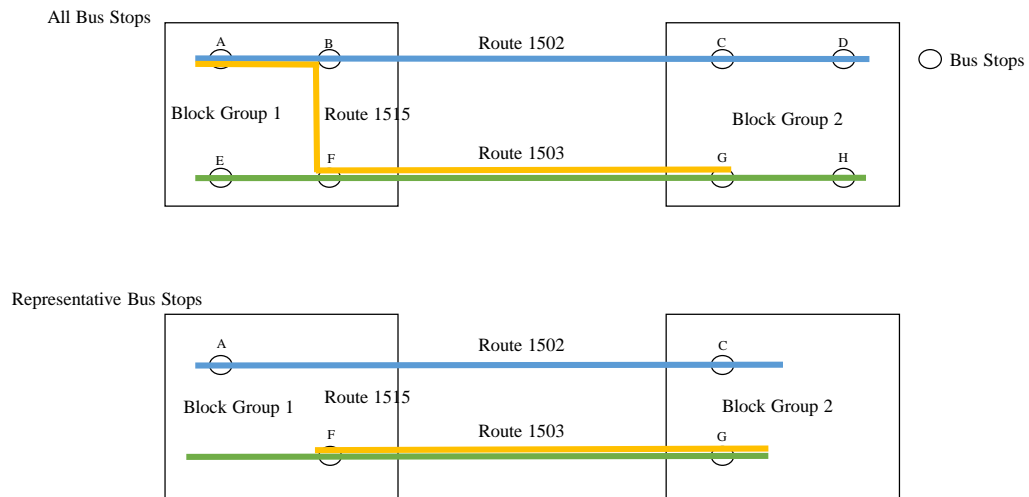
## Data preparation

In-vehicle travel time on each link, round trip travel time for each route, demand and binary variable files used with GAMS were generated using Python programming language from New Haven GTFS files (see Table 3, Figure 4 and Figure 5 for dataset reference). Bus stops are treated as “nodes” in this case study. This analysis uses 22 out of all 26 routes. It focuses on local bus routes as those routes primarily serve city streets and may also operate into malls, hospitals and shopping centers. Express and connector routes are excluded.

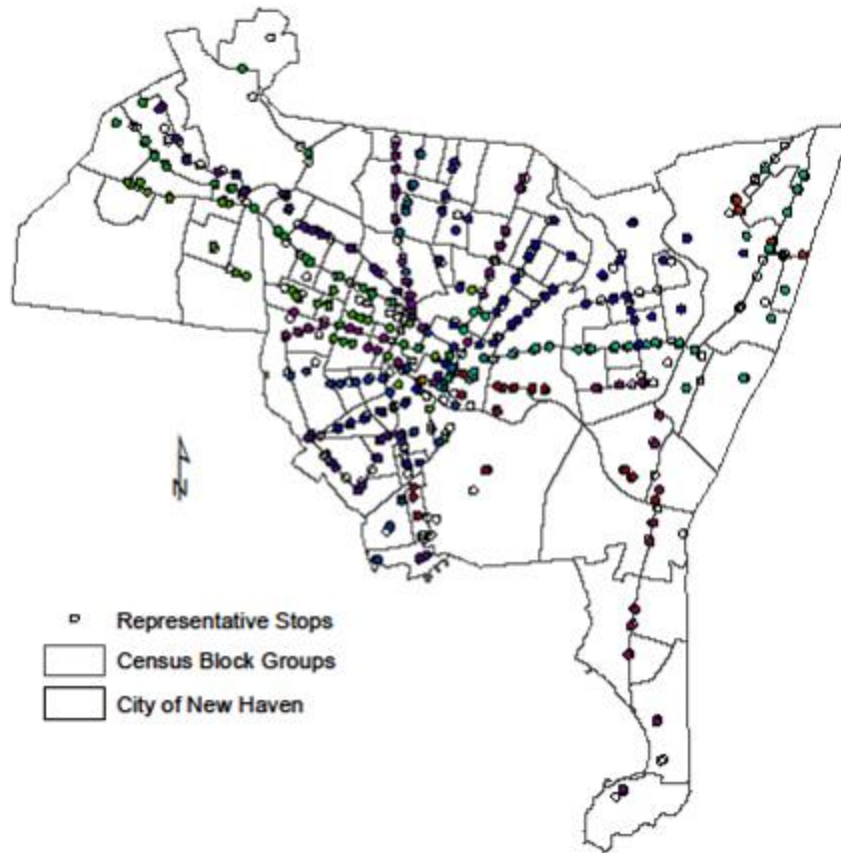
## Representative Stops

Representative stops were determined for each route for each census block group in the service area. In dense areas such as the downtown of New Haven City where multiple routes are servicing that area, there were representative stops which were shared by different routes. In such cases one representative stop was assumed to be serving all of those routes which shared the

same representative stop. If only one route runs through a representative stop then that stop was taken as a representative stop for that route. Some census block groups resulted in having multiple representative stops while had only one unique stop. Based on this assumption, stop pairs on each route were determined. Figure 5 shows an example of how representative stops were assigned while figure 6 presents all representative stops of the service area. First sub graphic titled “All Bus Stops” of figure 5 shows bus stops available in block group 1 and 2 for routes 1502, 1503 and 1515. Both routes 1502 and 1503 run through 2 bus stops (A and B, E and F, respectively) in block group 1 and 2 bus stops (C and D, G and F, respectively) in block group 2. Route 1515 runs through 3 bus stops (A, B and F) in block group 1 and 1 bus stop (G) in block group 2. Next, the sub graphic titled “Representative Bus Stops” shows a representative bus stop for each route. One representative stop was assigned for each route for each block group. As a result, route 1502 uses bus stop A in block group 1 and bus stop C in block group 2. Route 1503 uses bus stop F in block group 1 and bus stop G in block group 2. Route 1515 uses bus stop F in block group 1 and bus stop G in block group 2. Route 1503 and route 1515 are using the same representative stop F. Also both block groups resulted in having 2 representative stops. Figure 5 also depicts the generalization of the representative stop assignment.



**Figure 5 Logic used to designate a representative stop for each route for each block group.**



**Figure 6 Representative stops for each census block group for the service area.**

#### In-vehicle travel time

In-vehicle travel time  $t_{ijr}$  is the travel time by transit from origin  $i$  to a destination  $j$ . This transit travel time is computed based on the node to node travel time (bus stop to bus stop travel time).

Node to node travel time is computed as the difference in arrival and departure times available for each node (bus stop) from GTFS “Stop Times” file. Each particular route has a representative node (bus stop) sequence.

#### Round trip travel time for each route

Round trip time  $t_r^R$  is defined as the time it takes a bus to travel from origin  $i$  to destination  $j$  and back. It is computed for each of the 22 routes of the system based on node to node travel time. It uses a representative bus stop sequence for a representative trip on each particular route.

## Demand

### *Demand scenario 1: Unweighted Model*

Demand  $d_{ij}$  for New Haven City includes census block group to census block group demand arriving from trip based travel demand model study and is defined as the total system demand making trips from origin  $i$  to a destination  $j$ . An assumption is made to distribute the demand according to the representative stops in each census block group. If multiple routes run through the same representative stop in a census block group and serves the same destination then the demand is divided into the respective number of routes. When looking at figure 5, if there was a total demand of 90 people traveling from block group 1 to block group 2, then route 1502 would be assigned with 30 people, route 1503 with 30 and route 1515 with 30 people. Therefore, a representative stop pair AC (route 1502) would need to accommodate 30 people, stop pair FG (route 1503) 30 people and stop pair FG (route 1515) 30 people.

### *Demand scenario 2: Weighted Model*

Demand  $d_{ij}$  scenario 2 prioritizes the demand of protected populations in the service area by using a weight factor. It is defined as the total demand of protected population (seniors) residing at origin  $i$ . Demand analysis does not account for variations in income or demographics of vulnerable populations.

### *Weight Factor for Origin*

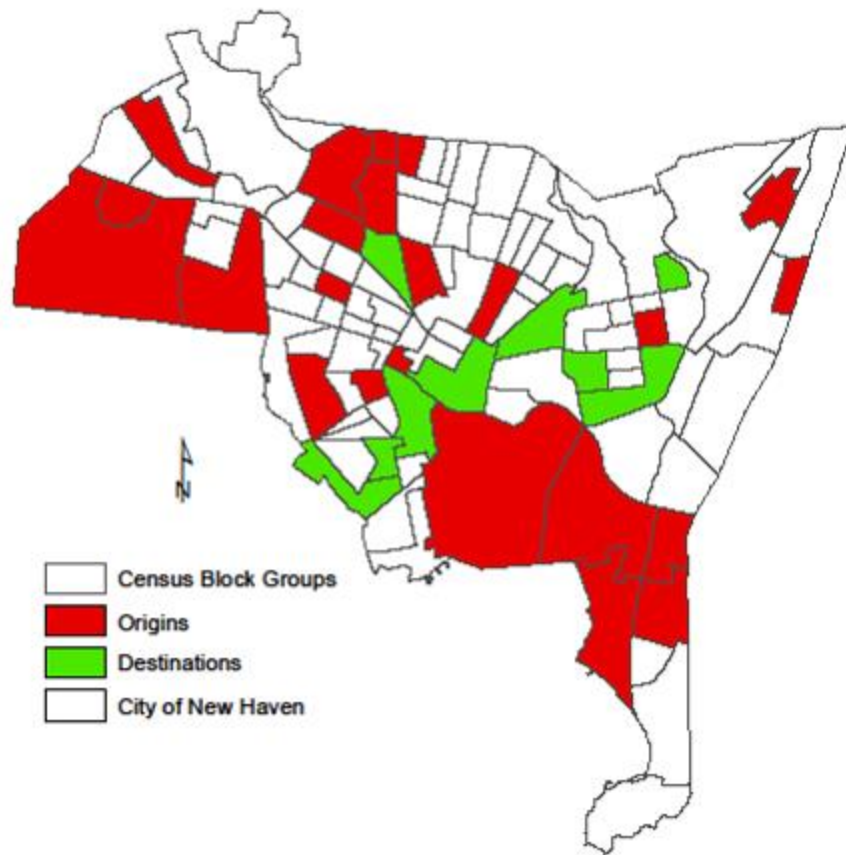


A weight factor  $P_i$  for origin  $i$  file is also created for a representative stop serving each census block group. It is defined by all census block groups within the service area assigned with respective weights. If a census block group was observed to have higher percentage of senior population of 65 or older than 10%, then those census block groups were given a weight of '2', or double that of a non-senior block group. The remaining census block groups (which did not have high senior population percentage) are assigned with '1'. The critical value of 15% is computed as the ratio of seniors 65 or older residing in the service area to the entire population of the service area.

#### *Weight factor for Destination*

The destination  $A_j$  for destination  $j$  file follows similar logic to that of determining origin files and used also a representative stop for each census block group as a base. A destination block group's weight is defined based on whether it contains one or more medical facility (either hospital and/or outpatient clinic). In this file each census block group which contained a medical facility is assigned with a weight factor of '2' and all other block groups received a weight factor of '1'.

Figure 7 below shows all origin and destination census block groups for the service area and highlights the ones which are heavily weighted in order to be prioritized in this analysis.

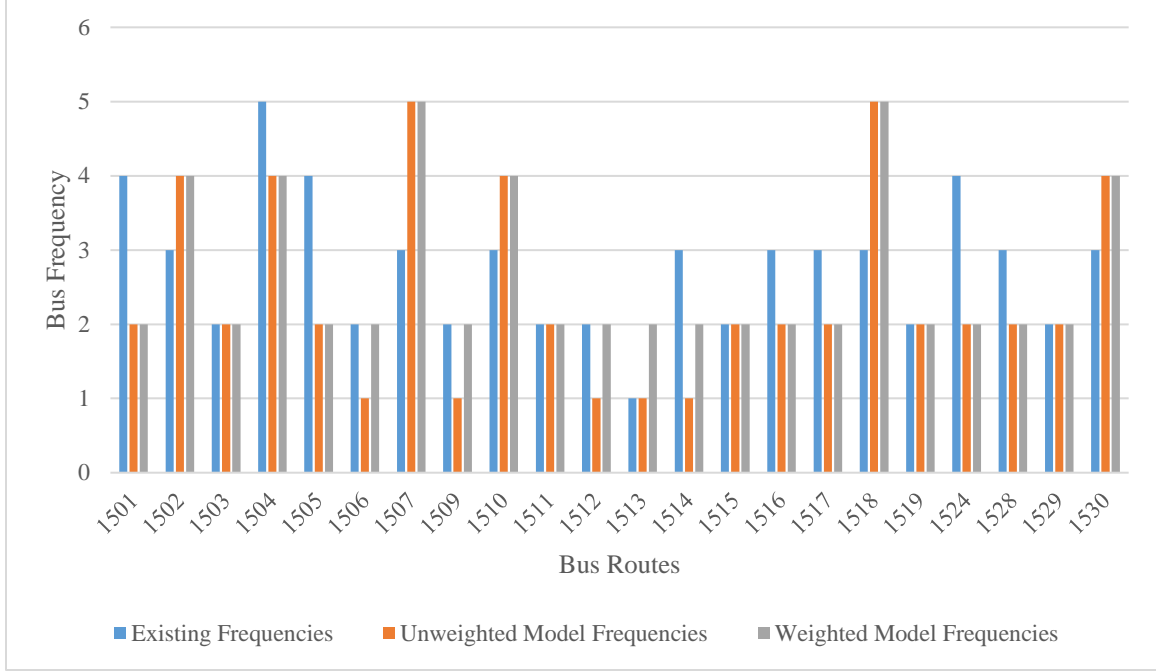


**Figure 7 Service area census block groups with highlighted critical census block groups origins and destinations.**

Such a weighting scheme of origin and destination block groups allowed prioritizing areas with higher senior population and their common travel destinations, which as presented in literature review section include medical facilities. This data prepared as described above led to 2 runs of the MIP program. The first run was carried out to set a baseline for the system to validate frequency of buses on each route when all origins and all destinations are treated equally. The second run allowed observing the changes in bus frequencies on each route when particular origin block groups and destination block groups are given priority in the system. Results are presented in the next section.

## **RESULTS**

Results from comparing existing bus service to the bus service produced by the proposed model are discussed below. Discussion of the influence the weight factor parameter has on the bus frequencies is also provided. The comparison between existing and model outputted frequencies is shown in Figure 8. Figure 8 shows existing frequencies, unweighted and weighted model frequencies for each of the 22 routes servicing New Haven area used in this analysis. Blue bars represent existing frequencies as in CT Transit New Haven Schedule. Orange bars represent bus frequencies as outputted from this analysis by the unweighted model, while grey bars show bus frequencies outputted by the analysis of the weighted model. Taking route 1513 as an illustration of the comparison of route frequencies in figure 8, weighted model frequency is slightly higher than existing frequency and that outputted by the unweighted model. This means that weighted model analysis responded to the weighting factor specified for more desirable origin destination pairs. Furthermore, this indicates that service on route 1513 is improved compared to the existing service providing an improved access for highly populated senior origin and their most common destination. This suggests a service improvement to better align service with the unique travel characteristics of seniors on that particular route. Based on that the frequency setting model formulated in this analysis is capable of addressing and improving specific access needs of seniors due to their unique travel characteristics. By simply introducing higher weights the model adjust route frequencies to increase frequencies providing access to desirable origin destination pairs.



**Figure 8 Comparison of existing frequencies as on CT Transit New Haven schedule to model outputted frequencies for each route.**

Furthermore, when proposed frequency setting model is evaluated under demand scenario 1 (unweighted model), which does not prioritize any population and treats the entire population of the service area equally, bus frequencies outputted by our model are similar to the existing frequencies as in CT Transit New Haven schedule. Bus frequencies shown in figure 8 were used to calculate the total number of buses used to service the area for existing condition, unweighted and weighted model. Number of buses on each route for each of the 3 conditions were calculated using the constraint equation 2 which can be found in the Problem Formulation section. Round trip travel time (in seconds) for each route is multiplied by the bus frequency on each route to calculate the number of buses on each route. Sample calculation for route 1513 is presented using the constraint equation 2 below:

$$\frac{t_r^R}{3600}(f_r)$$

$$\text{Existing: } \frac{3720}{3600} (1) = 1 \quad \text{Unweighted Model: } \frac{3720}{3600} (1) = 1 \quad \text{Weighted Model: } \frac{3720}{3600} (2) = 2$$

The existing schedule uses 40 buses out of 74 available in the system. The objective function of the proposed model reaches an optimal solution assigning 35 out of 74 available buses suggesting efficient service. Small frequency per route variations between the existing and model output are present (variation in frequency of 1 or 2 buses per hour). However, performing a Chi-Squared Test to assess the goodness of fit between existing and unweighted model outputted frequencies suggests that there is no significant difference between the expected and observed results on confidence level of  $\alpha = 0.1$ . The null hypothesis states that there is no significant difference in the distribution of frequencies between the existing and unweighted model.

Alternative hypothesis states that the distributions of bus frequencies for unweighted model are statistically different from the distribution of bus frequencies of the existing model. Computed test statistic of 10.7 is less than the test statistic of 29.615 with 21 degrees of freedom at  $\alpha = 0.1$ . Based on that null hypothesis fails to be rejected concluding that the distributions between the bus frequencies of existing service and unweighted model result frequencies are statistically equal or in other words that there is no significant difference in frequencies between the existing and unweighted/weighted model.

Evaluation of proposed frequency setting model under demand scenario 2 suggests increase in bus frequencies on routes 1506, 1509, 1512, 1513 and 1514. Therefore, proposed weighted model behaves as expected and suggests more variation in service frequency compared to unweighted model. Increasing the value of the objective function by assigning a heavier weighting to highly senior populated census block groups and desirable destination block groups, increased the bus frequencies on 5 routes indicating that a higher degree of equity is achievable

as some origins and destinations are weighted more heavily. Objective function reaches an optimal solution by assigning 39 buses out of 74 available, which is very close to the total of 40 buses that the existing service is using. Performing a Chi-Squared Test to assess the goodness of fit between existing and weighted model outputted frequencies suggests that there is no significant difference between the expected and observed results on confidence level of  $\alpha = 0.1$ . The null hypothesis tested in this case states that there is no significant difference in frequencies between the existing and weighted model. Alternative hypothesis states that bus frequencies for weighted model are statistically different from the bus frequencies of the existing model. Computed test statistic of 9.2 is less than the test statistic of 29.615 at 21 degrees of freedom at  $\alpha = 0.1$ . The null hypothesis fails to be rejected concluding that there is no significant difference between the bus frequencies of existing service and weighted model result.

Both scenarios suggest much lower usage of buses than the available fleet size of 74. This seems like a reasonable amount because an operator would not use the entire available fleet size at one time as some vehicles may serve in case of an emergency such as a bus break down or an accident. Also, the exclusion of express and connector routes explains the lower number of buses available for service as outputted by our model than the actual existing available fleet size.

Naturally, if those routes were also considered in this analysis the total number of buses would be higher (by 4 buses) and closer to the total existing available fleet size. The total number of buses used in the excluded express and commuter service routes include 4 buses.

This analysis shows that weighted model uses 39 buses compared to 35 buses used by the unweighted model. Weighted model uses almost as many buses as the existing service, which uses 40 buses. This is another way of interpreting the sensitivity of the weighted model.

Increased number of buses, which almost matched the existing service, suggests that frequency

setting model formulated and analyzed in this paper is capable of improving the existing service to provide a better access between desirable origin destination pairs. The number of buses increased for the weighted model compared to the unweighted model meaning that route frequencies also increased, which suggests that some routes operate at a higher bus per hour frequency than other routes. In this case, routes which were assigned with higher bus frequency were the routes serving senior population origin and healthcare destination.

## **CONCLUSION**

Problem formulation and analysis using proposed model presented in this chapter provides a reliable tool for city planners and service providers who wish to optimize their transit service under fleet size constraint and bus capacity constraint. This frequency setting model shows to improve service frequency for routes serving desirable origin destination pairs. It means that access to most common travel destination of seniors, medical facilities, from highly senior populated origin by public transit is improved by increase in route frequencies. Based on this it shows that it is possible to better align public transit service to provide a better access for senior population based on their unique travel characteristics. The problem formulation is simple and easy to implement because it requires readily available, easily accessible public data. It could be a valuable contribution to transit planners' who wish to improve their transit systems by realigning it with changing travel patterns of seniors. The results obtained from model formulated in this chapter show that it is capable of accommodating access needs of different types of transit dependent populations as specified by the user. This model can be also applied to address access to needs other destinations than medical facilities such as shopping or employment opportunities.

There are a few assumptions made by the author which could be improved in further research. This study is relying on a major assumption of using a condensed list of bus stops to represent a route. Using full list of bus stops serving each route would improve the accuracy of this model in terms of demand assignment. Currently demand from a census block group is assigned to a representative stop disregarding the position of that stop in a block group. In other words representative stop for a given route, for a given census block group could be positioned in a corner of a census block group and all demand from that census block group is assigned to this representative stop. Above assumption leads to another major approximation, mainly, the level of analysis in terms of common destinations used in this study. Destination weight factor files (which signify a presence of medical facility) are also created on a census block group level. This assumption states that if a census block group contains a medical facility then the entire census block group is a desirable location. Using actual point location of medical facilities would greatly improve the accuracy of this study. Another assumption implicit to the problem formulation section includes linear estimation of the nonlinear frequency-demand function and wait time function. Future work could improve this assumption by applying a non-linear solver to a non-linear model for more optimal results.

Future research could also focus on incorporation of paratransit into this analysis along with improvements of above assumptions. Another important benefit from using the frequency setting model in means of access improvement for elderly population, which could be addressed in future work is its ability to conduct a transit frequency setting analysis for specific time of day. This aspect is important when studying senior population because the time of day is a part of their unique travel characteristics. Therefore, future work could incorporate time of day into frequency setting analysis to compare variations in bus frequencies based on different times of



day. In that case, this analysis would outline existing conditions (for all times of day) for frequency setting problem with respect to elderly population.

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## APPENDIX

```
**** TRANSIT FREQUENCY-SETTING PROBLEM FOR CITY OF NEW HAVEN ****

** SETS AND INDICES
$include bus stops and routes sets.inc

** DATA AND PARAMETERS
$include delta.inc
$include round trip time on route.inc
$include demand for travel.inc
$include IVTT.inc
$include origin weight factor.inc
$include destination weight factor.inc

Scalar
    U capacity of a bus /40/
    B total fleet size /74/

parameter routedemand(r);
routedemand(r) = sum((i,j), d(i,j) * delta(i,j,r));
display routedemand;

** DECISION VARIABLE
Variables
    f(r) frequency of buses on route r
    z value of objective function;

integer variable f(r);

f.lo(r) = 1;
f.up(r) = 6;

Equations
    objective objective function
    fleetSize fleet size
    frequency(r) frequency times capacity has to be greater than demand;

** OBJECTIVE FUNCTION
objective.. z =e= sum((i,j,r), P(i)* A(j)* d(i,j) * (t(i,j,r) + (33 - 3*f(r)
    * delta(i,j,r))))+ sum(r, time(r)/3600*f(r));

** CONSTRAINT SETS
fleetSize.. sum(r, time(r)/3600 * f(r)) =l= B;
frequency(r).. (6*f(r)-5)* U =g= sum((i,j), d(i,j)* delta(i,j,r));

model freqSetting /all/;
solve freqSetting using MIP minimizing z;
display f.l, f.m ;

parameter buses(r);
buses(r) = (time(r) * f.l(r))/3600;
```

