

ENHANCING LIVABILITY WITH FEEDER TRANSIT SERVICES:  
FORMULATION AND SOLUTIONS TO FIRST/LAST MILE CONNECTIVITY  
PROBLEM

A Dissertation

by

SHAILESH CHANDRA

Submitted to the Office of Graduate Studies of  
Texas A&M University  
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2012

Major Subject: Civil Engineering

ENHANCING LIVABILITY WITH FEEDER TRANSIT SERVICES:  
FORMULATION AND SOLUTIONS TO FIRST/LAST MILE CONNECTIVITY  
PROBLEM

A Dissertation

by

SHAILESH CHANDRA

Submitted to the Office of Graduate Studies of  
Texas A&M University  
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Approved by:

Chair of Committee,	Luca Quadrifoglio
Committee Members,	William Eisele
	Francisco Olivera
	Bruce Wang
Head of Department,	John Niedzwecki

August 2012

Major Subject: Civil Engineering

## ABSTRACT

Enhancing Livability with Feeder Transit Services: Formulation and Solutions to  
First/Last Mile Connectivity Problem. (August 2012 )

Shailesh Chandra, B.Tech., Indian Institute of Technology, Delhi; M.S., Texas  
A&M University

Chair of Advisory Committee: Dr. Luca Quadrioglio

This dissertation begins with proposing a novel street Connectivity Indicator (C.I.) to predict transit performance by identifying the role that street network connectivity plays in influencing the service quality of demand responsive feeder transit services. This new C.I. definition is dependent upon the expected shortest path between any two nodes in the network, includes spatial features with transit demand distribution information and is easy to calculate for any given service area. Subsequently, a methodology to identify and locate critical links within a grid street system for operating feeder transit services is also developed. A ‘critical’ street link causes the largest change in transit performance due to the link’s removal or addition to an existing network. The most important contribution of this section on link criticality is to present a simple closed-form analytical formula in locating the critical link(s) for a grid street network system of ‘any’ size. Easily computable formulas have been provided and validated by simulation analyses. Another related model is proposed to compute the optimal grid street spacing that would enhance performance of a demand responsive feeder transit system. The model is tested using simulation. Lastly, an analytical model is also developed for estimating optimal service cycle length or headway of a demand responsive feeder transit service designed to serve passengers, especially during peak periods of demand.

Simulation analyses over a range of networks have been conducted to validate the new C.I. definition. Results show a desirable monotonic relationship between transit performance and the proposed C.I., whose values are directly proportional and therefore good predictors of the transit performance, outperforming other available indicators, typically used by planners. Further, useful insights indicate a monotonic decrease in link criticality as we depart from the centrally located links to those located at boundaries. Using a real case example from Denver of the Call-n-Ride system operating similar to a demand responsive feeder transit, optimal cycle lengths differed very modestly from those computed using the model. Extensive simulations performed for different sets of feeder service areas and demand densities, further validated the optimal cycle length model.

DEDICATION

To  
*Lord Narasimha*  
&  
His devotees

## ACKNOWLEDGMENTS

First and foremost, I would like to thank my committee chair – Dr. Quadrifoglio who has been a great source of inspiration for me to pursue a career in academia – and my committee members – Dr. Eisele , Dr. Olivera, and Dr. Wang – for providing valuable comments and inputs during the course of this research and dissertation writing.

A special thanks also goes to Maxine Williams, Civil Engineering Program Assistant – for having immense patience in answering any academic questions and going through helping me to meet submission deadlines on time.

I also want to extend my gratitude to the Southwest Region University Transportation Center (SWUTC) for supporting this research and dissertation.

I would like to extend my love for my elder sister, younger brother, and parents, and not to forget the two naughtiest kids on earth – my lovable nephew, Savya, and niece, Ishi.

A special thanks also to all my friends and roommates since my first day here in College Station. I am quite fortunate to have four of the most reliable and super-smart friends of my life – Ehsan, Prem, Negi and Rakesh, who were the source of motivation during my entire journey of my PhD study.

Several other friends of mine have been a catalyst in making me successfully cruise through my research at A&M . When I was not doing research, I would find myself chatting with my friends and those uncountable trips to Austin and Houston would not have been fun without Varma, Niranjana, Saurabh, Hari and Rahul Putha. Thanks to my friends and past roommates Alok, Surjyendu and Shardul for playing those occasional loud music and giving me a break from my arduous research to shout at them. Another group of friends that I would like to thank are Harsha , Vamsi , Shreyas, Naveen and Aravind for often sharing their honest thoughts about the present academic system. Another motivating friend of mine, Bhargav , deserves

a special thanks for the best Indian food one could cook in College Station. A part of my interest in cooking has come from him. I am also grateful to Rahul, Bhatia, and Viral for being awesome roommates.

The most important thanks to all the TAMU Student Recreation Center staff members for providing a means to spend my time during Summers when life in College Station comes to standstill.

## TABLE OF CONTENTS

	Page
ABSTRACT . . . . .	iii
DEDICATION . . . . .	v
ACKNOWLEDGMENTS . . . . .	vi
TABLE OF CONTENTS . . . . .	viii
LIST OF TABLES . . . . .	xi
LIST OF FIGURES . . . . .	xiii
1. INTRODUCTION . . . . .	1
2. LITERATURE REVIEW . . . . .	8
2.1 Street Connectivity Indicators . . . . .	8
2.2 Link Criticality . . . . .	15
2.3 Transit Performance . . . . .	17
2.4 Transit Scheduling . . . . .	17
3. A NEW STREET CONNECTIVITY INDICATOR . . . . .	22
3.1 Methodology . . . . .	22
3.1.1 Expected Street-based Shortest Path . . . . .	25
3.1.2 Ideal Network I . . . . .	26
3.1.3 Ideal Network II . . . . .	34
3.1.4 Connectivity Indicator . . . . .	35
3.2 Other Connectivity Indicators . . . . .	36
3.2.1 Gamma Index . . . . .	36
3.2.2 Transportation Planning Indicator . . . . .	37
3.3 Simulation Results and Discussions . . . . .	37
3.3.1 Effect of Demand Distribution . . . . .	42
3.4 Summary and Research Contribution . . . . .	44
4. CRITICAL LINKS IN STREET NETWORKS . . . . .	46
4.1 Modelling – Street Network Set-up . . . . .	46
4.1.1 Link Removal – Decrease in Average Travel Distance . . . . .	49
4.1.2 Link Removal – Increase in Average Travel Distance . . . . .	52



	Page
4.1.3 Determination of Critical Link . . . . .	53
4.2 Simulation Experiments . . . . .	56
4.3 Summary and Research Contribution . . . . .	59
5. OPTIMAL GRID STREET NETWORKS . . . . .	60
5.1 Background . . . . .	60
5.2 DRT Operational Challenges . . . . .	61
5.3 Design Framework . . . . .	62
5.4 Modeling . . . . .	65
5.4.1 Street Design for DRT Shuttle . . . . .	65
5.4.2 Street Design for Pedestrians . . . . .	67
5.5 Block Design – Objective Function . . . . .	68
5.5.1 Rigorous Solution . . . . .	70
5.5.2 Approximation to Rigorous Solution . . . . .	74
5.6 Simulation Results and Discussions . . . . .	76
5.7 Summary and Research Contribution . . . . .	81
6. OPTIMAL TRANSIT SCHEDULING STRATEGY . . . . .	82
6.1 Methodology . . . . .	82
6.1.1 DRT Service Design . . . . .	82
6.1.2 Model Comparison . . . . .	87
6.1.3 Modeling DRT Operations and Optimal Cycle Length . . . . .	89
6.1.4 Service Disutility . . . . .	97
6.2 Simulation Experiments . . . . .	102
6.3 Results and Discussions . . . . .	106
6.4 Summary and Research Contribution . . . . .	117
7. POLICY OBJECTIVES AND ISSUES FROM SOME BEST PRACTICES	119
7.1 Mason County Transportation Authority (MCTA) . . . . .	119
7.1.1 Policy Objectives . . . . .	119
7.1.2 Operational Issues and Recommendations . . . . .	121
7.2 St. Joseph Transit . . . . .	121
7.2.1 Policy Objectives . . . . .	121
7.2.2 Operational Issues and Recommendations . . . . .	123
7.3 Potomac and Rappahannock Transportation Commission (PRTC) . . . . .	123
7.3.1 Policy Objectives . . . . .	123
7.3.2 Operational Issues and Recommendations . . . . .	125
7.4 Charleston Area Regional Transportation Authority (CARTA) . . . . .	125
7.4.1 Policy Objectives . . . . .	125
7.4.2 Operational Issues and Recommendations . . . . .	127
7.5 Omnitrans . . . . .	127

	Page
7.5.1 Policy Objectives . . . . .	127
7.5.2 Operational Issues and Recommendations . . . . .	129
8. CONCLUSIONS . . . . .	130
REFERENCES . . . . .	144
VITA . . . . .	145

## LIST OF TABLES

TABLE	Page
2.1 List of transit performance measures . . . . .	18
3.1 Sample values of expected shortest street-based distance between two random points . . . . .	33
3.2 Connectivity indicators evaluated for ten selected real street networks . .	41
5.1 Average street length from different cities of the world . . . . .	64
6.1 Cycle lengths for different demands with $L=2.0$ mile, $W = 0.5$ mile . . .	90
6.2 Cycle lengths for different demands with $L=1.5$ mile, $W = 0.5$ mile . . .	91
6.3 Cycle lengths for different demands with $L=1.0$ mile, $W = 0.5$ mile . . .	92
6.4 Cycle lengths for different demands with $L=1.0$ mile, $W = 1.0$ mile . . .	93
6.5 Expressions for $h$ , $f$ and $g$ . . . . .	100
6.6 Expression for right hand side coefficients of equation (6.17) . . . . .	102
6.7 Input settings for the simulation model . . . . .	107
6.8 Case 1: Simulation results . . . . .	111
6.9 Case 1: Analytical results with Design Method I . . . . .	112
6.10 Case 1: Analytical results with Design Method II . . . . .	112
6.11 Case 1: Analytical results with Design Method III . . . . .	112
6.12 Case 1: Analytical results with Design Method IV . . . . .	113
6.13 Case 2: Simulation results . . . . .	113
6.14 Case 2: Analytical results with Design Method I . . . . .	113

TABLE	Page
6.15 Case 2: Analytical results with Design Method II . . . . .	114
6.16 Case 2: Analytical results with Design Method III . . . . .	114
6.17 Case 2: Analytical results with Design Method IV . . . . .	114
6.18 Performance and service information data for RTD Call-n-Ride . . . . .	116

## LIST OF FIGURES

FIGURE	Page
2.1 Block size illustration (Source: Dill (2004)) . . . . .	10
2.2 Link-node ratio connectivity (Source: Dill (2004)) . . . . .	11
3.1 Sketch of on-demand bus stop nodes on street links . . . . .	23
3.2 A grid section of the street network system of the town of Hempstead, TX (Source: TNRIS (2011)) . . . . .	27
3.3 Model for a perfect street network system . . . . .	29
3.4 Location of the closest demand on a node from a known node ( $Z$ ) along the grid . . . . .	31
3.5 Examples of ten different real street networks in the United States . . . . .	39
3.6 Cumulative density functions for the US work-trips (NHTS (2009)) . . . . .	40
3.7 Variation of DRT performances versus different connectivity indicators values . . . . .	41
3.8 Different demand distributions within selected street network (6) . . . . .	43
3.9 Disutility versus Connectivity Index variation for different demand dis- tributions . . . . .	44
4.1 Removal of a link to create a ‘new’ network from an ‘old’ network . . . . .	47
4.2 Grid street system of Manhattan, NY (Source: StreetMap (2011) ) . . . . .	48
4.3 Sketch depicting the ‘target’ node in the street network system . . . . .	50
4.4 Split regions to create target node for any intermediate node . . . . .	51
4.5 Identification of nodes for computing $R_{(X,Y)}$ . . . . .	52
4.6 Variation of $\Delta_d$ along the cross-section of the street network . . . . .	56

FIGURE	Page
4.7 Sequential link closures/removals 1-2-3-4-5 to create five different sets of street networks . . . . .	57
4.8 Performance effects on DRT for the sequential link closures/removals . .	58
5.1 A hybrid network structure (adapted from Nourbakhsh and Ouyang (2012), and Daganzo (2010)) . . . . .	61
5.2 Grid street system with on-demand stops. . . . .	65
5.3 Computation of $A_W$ within a block . . . . .	67
5.4 Comparison of the rigorous term, $A$ , and the approximate term, $B$ , in $\min(Z_1)$ . . . . .	76
5.5 Grid street system set-up for simulation . . . . .	77
5.6 Simulation output for transit performance with varying block length . . .	79
5.7 Passenger disutility/discomfort variation with block length (penalty-function)	80
5.8 Pedestrian disutility/discomfort variation with block length . . . . .	80
6.1 Illustration of expected closest distance between terminal and a passenger	84
6.2 Shuttle pick-up/drop-off strategy . . . . .	86
6.3 Shuttle service operated using random pick-up/drop-off strategy . . . . .	87
6.4 Illustration of passenger requests and service times using slots of duration $C$ . . . . .	96
6.5 Trip data for the entire United States. (Source: NHTS (2009)) . . . . .	104
6.6 CDF representing trip travel time for commuting . . . . .	105
6.7 Case 1 disutility versus cycle length variation for passenger demand = 100	110
6.8 Case 2 disutility versus cycle length variation for passenger demand = 100	111

FIGURE	Page
6.9 Denver RTD Call-n-Ride System Map . . . . .	115
7.1 Route 5, Mason County Transportation Authority (Source: MCTA (2012))	120
7.2 Route 11, St. Joseph Transit (Source: SJT (2012)) . . . . .	122
7.3 Woodbridge/Lake Ridge Omnilink transit system (Source: PRTC (2012))	124
7.4 Flex Bus Route 402 for Isle of Palms and Sullivan’s Island Zone shown as dotted line (Source: CARTA (2012)) . . . . .	126
7.5 Flexible public transportation service in the Chino Hills (Source: Omni- trans (2012)) . . . . .	128
7.6 Flexible public transportation service in the Yucaipa area (Source: Om- nitrans (2012)) . . . . .	129

## 1. INTRODUCTION

Public transportation is in constant competition with private vehicle for providing mobility to the general public and has seen a decline in bus ridership, which is the most widely used transit mode, within the United States during the last decades (APTA (2012)). The U.S. Department of Transportation recently identified the general lack of transport connectivity as one of the main reasons for it. Policies which encourage the desired reduction of Vehicle Miles Traveled (VMT), reduction of greenhouse gases and even an increase of “livability” depend on solutions to the issue of first/last mile access to transit and multi-modal solutions. This calls for an effective planning, designing, and implementation of efficient transit services, connecting residential areas to major fixed-route transit lines. Thus, public transportation must continue to explore and evaluate innovative ways of providing safe, convenient, and efficient public transportation options to properly address the issue and improve the performance of their services. However, this cannot be fully achieved without analyzing the role of street networks on transit performance.

The primary purpose of a street network system is to connect spatially separated places and provide movements from one place to another. The nature of these connections varies depending on the structure and design of the street network system from being one to many, direct to indirect or even divided among the kinds of connections to support different modes of travel. Qualitatively, these connections are expressed as the “connectivity” of the street network and influence the accessibility of potential destinations in a community. Connectivity has important implications as its quality influences the efficiency of public transportation, travel choices, emergency access and adds to the ‘livability’ of a community.

---

This dissertation follows the style of *Transportation Science*.



Early 19th century street network systems in residential areas were characterized by a grid pattern which is considered to be suitable for pedestrian as well as vehicle movements. With a gradual increase in the automobile use, these street patterns gave way to curvilinear street network systems. By the 1980s, most of the planning aimed at separating the residential subdivisions from the vehicular road network through the introduction of cul-de-sac kind of street patterns (Southworth and Owens (1993)). Cul-de-sacs or dead ends not only serve as a barrier to the pedestrian movements across the streets, but also delays and obstructs vehicle navigation. As the need for better connectivity has lately grown among planners and engineers, particularly within residential areas, there is an increasing advocacy by city transport officials to revert to promoting the grid network kind of street structure back in place across the U.S. The State of Virginia, for example, has already outlawed cul-de-sacs type of street system design (VDOT (2010)).

Street networks are planned and designed to improve accessibility in order to benefit future land development programs. In particular, planners prepare street designs that can enhance market opportunities for a new community. Subsequently, traffic engineers perform the task of fine tuning the streets by making them work efficiently for different transportation modes. It is expected that street network meets certain given level of service requirement as an indicator of its performance. Usually, minimized vehicular delay is considered to be the most important performance indicator for a network besides safety and other costs involved. If large volumes of traffic are expected the intersections are signalized to optimize vehicular flows through the networks. Readers can refer to Manual on Uniform Traffic Control Devices (MUTCD (2009)) for warrants that recommend having a signal at an intersection. If the traffic volume is low, safety considerations make it mandatory to have stop signs at intersections. The bigger picture, however, is in achieving best practices to keep vehicular traffic moving smoothly and safely over these transportation networks. Whatever the practice is when transportation networks are designed keeping vehicular traffic

in mind, a sense of the loss in livability conditions of a community with no consideration to non-motorized walking atmosphere develops.

Street networks also serve as a means to providing connectivity between their user's origin and destination points. An efficient mobility between points is facilitated only when individual street links function properly and do not fail due to capacity overflow or due to incidents that block these flows. In real world, some links become extremely vital for users and are always favored for traveling. This results in an uneven distribution of traffic over the network and subsequently, burdens certain links beyond their capacities. Sometimes, absence of an alternative route also forces traffic to pile up on these links, thereby, making them more important to be analyzed on a frequent basis. Studying these links becomes even more important when they lie on a major transit line such as a major bus route, as its failure would affect a large number of users. Advance knowledge of location of these links within a network can be vital for helping transit buses reroute their regular path to cause a minimal delay to the passengers in case of link failures. The transit system that has a flexible route option has more freedom in this regard than the one that operates over a fixed route. A good example of a flexible transit system that can benefit from a priori information regarding link failures is a Demand Responsive Transit.

Typically, a Demand Responsive Transport or Demand Responsive Transit (DRT) is characterized by a flexible routing and scheduling of a bus/shuttle operating in shared-ride mode between pick-up and drop-off locations according to passengers' needs. The requests for using this type of transit service are made in advance by its passengers either by phone call or on internet. In many areas DRT is instead known as Dial-a-Ride Transit (Wilson and Roos (1971)) or Call-n-Ride (CnR) systems. These transit systems have been proven effective in responding to the need of low density or low demand areas and are welcomed by passengers as they provide an increase flexibility and higher service level compared to 'regular' fixed-route services. These services are, however, much more costly to deploy for the operators. Typical

examples, other than feeder services, include ADA Paratransit services, rural services or other hybrid systems. Usually, DRT schemes are fully or partially funded by the local transit authority in the form of socially necessary transport. At other times, DRT service is provided by private operators. In any case, the main aim of the operators is to ensure best service standards for the transit users.

Though the extreme of living in a community with no vehicles is not possible, street designs must take into consideration other non-motorized transportation systems as well. Vehicular overflows on street networks can be checked by motivating people to take to more of transit thereby also making streets safer to walk and bike. A social understanding seems to be working among daily commuters in a community who are often willing to adopt strategies to mitigate congestion and delays. Carpooling and ridesharing are some examples (Kearney and DeYoung (1995), Chan and Shaheen (2011)). However, strategies like carpooling are quite restrictive and are popular mostly among commuters sharing common origin and destination points. Another alternative is to properly design transit systems so that they can be readily available at the residential areas and provide easy connection to offices or a major transit stop for commuters. These are more appropriately addressed as problems associated with first/last mile connectivity in literatures (Xie et al. (2010), DeMaio (2009)). It is, therefore, essential to have a potential solution to first/last mile transport connectivity problems and further, design our street systems that could help transit systems to achieve optimum service levels.

In general, feeder transit services (whether fixed or flexible) provide the ultimate first/last mile connectivity solution for passengers and their performance is intuitively dependent upon the street network design and its connectivity, as vehicles are potentially required to reach every point within the service area to serve the demand. Intuitively, the higher the network connectivity, the faster and more efficiently vehicles are able to serve customers and the better the feeder transit service performance. A more informative and more detailed relationship between the road

network design (and its connectivity) and the expected transit performance would be very desirable information to have for properly planning the development of residential areas with the goal of enhancing their transportation mobility. However, the correlation between street connectivity and transit performance has yet to be scientifically investigated. Current street connectivity measures are not sufficiently accurate nor linked to transit performance.

Flexible transit systems such as DRT are the most obvious choice for first/last mile access and transport connectivity as they are specifically designed to serve customers door-to-door, thereby providing a quick and convenient connection to the main transit line (Koffman (2004), Cortes et al. (2005)). However, to make a DRT system operate optimally street connectivity of a community should complement its performance. It is natural to believe that a poor street connectivity naturally would mean more work by the shuttle to achieve optimum service standards, which, otherwise, is easily attained with a more connected network. However, quantifying the relationship between street connectivity and performance is not trivial. This is because of the complexity involved in modeling street networks that are often of varied patterns in reality. Grid street systems are slightly easier to model because of inherent symmetry in their structure and are the most preferred form of street network systems as they provide good connectivity with multiple route options for various transportation modes. However, any grid street system in itself does not guarantee the best connectivity. The connectivity is influenced by the existing block lengths. Subsequently, this dissertation also presents a simple methodology to assess optimum block lengths best suited for transit as well as other non-motorized transport modes such as walking for pedestrians to promote a livable community.

The performance indicators of the DRT services are also dependent on the street network topology. A good street connectivity is important for a good traveling experience by the travelers with reduced travel times which also indirectly enhances ridership for the transit. Measures are needed to assess the robustness of street

connectivity in case of link failures from plausible scenarios such as a planned maintenance leading to a detour, accidents or emergency evacuations for terrorist attacks or even flooding. Thus, quantifying criticality of each link in a given network by a ‘score’ would be quite useful to have for transit operators in detour purposes of a DRT shuttle.

A demand responsive feeder shuttle has to navigate over a flexible route and follow a scheduling strategy for serving passengers that are often complex. Over the recent years, these types of flexible transit services have experienced a surge in ridership among commuters. However, transit managers often discontinue operating these flexible DRT feeder services mainly for lack of proper strategies related to scheduling at different demands during the day or season. In fact, a recent survey conducted among 1,100 transit managers, representing public transit systems of different sizes and types, indicated that flexible transit services were discontinued mainly due to “Problems with scheduling—can’t make time points when demand for flexible trips is high or have too much extra time when demand for flexible is low.” (Potts et al. (2010)).

Our understanding from the literatures shows that an efficient feeder transit system (especially, flexible) has the potential to connect thousands more to the main transit line than at present and ultimately contribute towards greater goals like reducing traffic and mitigating related pollution and congestion problems. What stops this from happening is the lack of existing research and information for transit managers in improving the state-of-the-art practice in operating these flexible transit services, especially related to the ‘problems with street connectivity’ and ‘problems with scheduling’. This dissertation provides solutions to these two broad problems. More specifically, we propose a model to describe a street connectivity indicator and build solution methodologies for studying best street connectivity indicator values, thereby, also identifying critical links in a street network, and recommending optimal street block lengths. Further, investigations are done and models developed to

study the relationship between the terminal-to-terminal cycle length and the level of service provided to customers, allowing for an easy computation of the optimal cycle length that could otherwise be estimated only through extensive simulation analyses. Several sets of simulation experiments have been performed to validate these models. The dissertation results would allow planners, decision makers, and practitioners to use these models to identify the best feeder transit operating design within a given area and thus, enhance community livability.

## 2. LITERATURE REVIEW

### 2.1 Street Connectivity Indicators

It is important to understand that the success of a feeder transit to solve first/last mile transport connectivity problem is embedded in the built environment. In this dissertation, the first and foremost focus is to highlight the role of built environment through the types of streets existing within a community, which aids in transit operations *directly*. This is studied in greater detail as ‘street connectivity indicators’ through several literatures that were analyzed as part of this dissertation.

There have been a number of attempts from researchers and practitioners to identify a good way to properly measure street connectivity with ‘connectivity indices or indicators’. Block length, block size and block densities are used as some of the ways to measure street connectivity ( Handy et al. (2003), Frank et al. (2000), Cervero and Kockelman (1997) ). But the requirements for the block length, size or density for evaluating street connectivity are only restricted to pedestrian and bicycle connections. Some researchers use percent grid or percent four-way intersections (in Boarnet and Crane (2001) and Greenwald and Boarnet (2001)) as a proxy to street connectivity which are quite limited in use and cannot be used as a substitute to measure density, land use mix, and street geometry for urban design which are critical for studying potential passenger demand. The percent grid (or percent four-way intersections) is computed by calculating the percentage of the street grid (or four-way intersections) within a quarter-mile radius of the person’s residence. Boarnet and Sarmiento (1998) used digital planimeter to compute percent grid by including four-way intersections as measures of street network connectivity within each quarter-mile radius area. Cervero and Kockelman (1997) examine built environment influence on travel demand with respect to density, diversity and design for trip rates and mode choice of residents in the San Francisco Bay Area. As a connectivity measure for studying the built environment variables for street design,

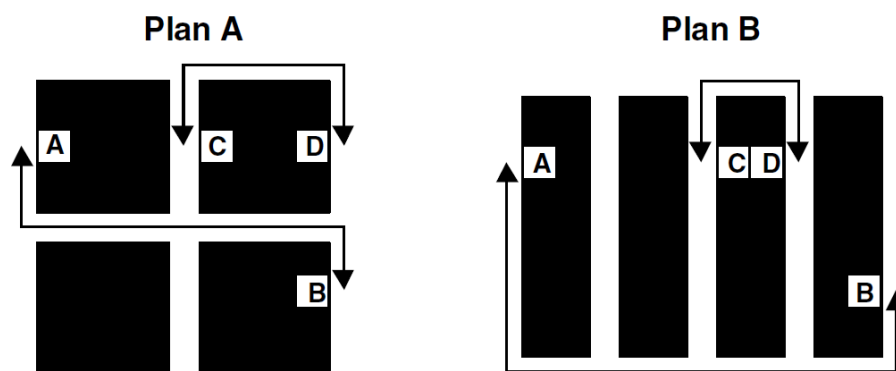
proportion of four-way intersections are used as a proxy for grid patterns. Cervero and Radisch (1995) investigate the effects of New Urbanism design principles on both non-work and commuting travel by comparing modal splits between two distinctly different neighborhoods in the San Francisco Bay Area. For this, number of intersections per square mile, blocks per square mile, four-way intersections, T-intersections and cul-de-sacs are used as a measure of urban street pattern. Crane and Crepeau (1998) use the concept of a ‘connected street’ network, a ‘cul-de-sac’ network, or a mixture of the two networks based on the type of neighborhood streets that are within 1/2 mile of the household. According to Frank et al. (2000), a gridiron, which is considered to be the most highly connected network pattern, increases route options for all modes of travel along with reducing route distances. Subsequently, as the street network increases in density, census block polygon decrease in size. Thus, block density could be directly related to street connectivity.

The term ‘connectivity’ has often been used for walking mode by various researchers in transportation planning. Randall and Baetz (2001) introduce the “pedestrian connectivity” as a measure of both the directness of route and the route distance for the pedestrian for each home–destination trip. Hess (1997) compares urban and suburban neighborhoods by examining the directness of pedestrian routes and thus, comparing their connectivity for pedestrians by selecting points that are one-eighth, one-quarter, three-eighths and one-half mile from the center of each neighborhood. However, pedestrian route directness is perhaps only suitable for connectivity measure in case of bicycling and walking as the distance traveled for a trip is a primary factor in determining whether a person walks or bikes (Dill (2004)).

Researchers have used difference in block sizes in terms of mean hectares to compare urban and suburban connectivity, as documented in Hess et al. (1999) and Reilly (2002). Dill (2004) suggests block size measured by area or perimeter as a standard may be more flexible than block length for each side and gives an example to illustrate block size as shown in Fig. 2.1. Consider two simple examples in Fig.



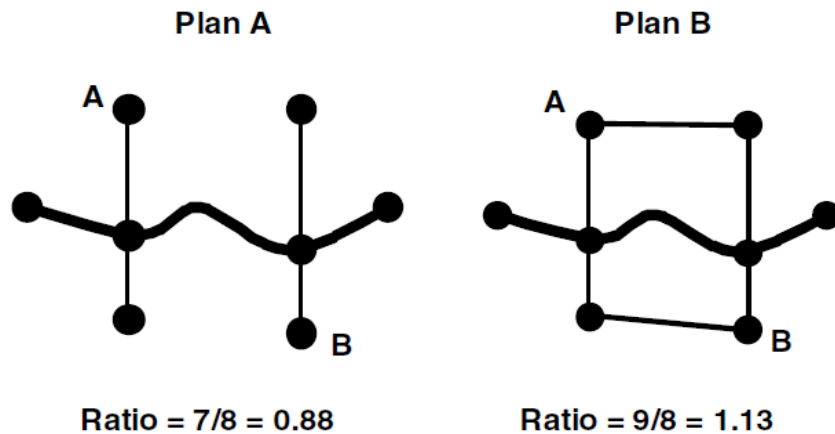
2.1. Under Plan A, each block face is the same length. Consider Plan A and Plan B where both have same perimeter and block area. Plan A has four blocks which are twice in width and half as long as compared to Plan B. The distance between points A and B, located on opposite sides of the development, for Plan A is shorter than Plan B. However, the distance between the two points is shorter when they are located on the same block as can be seen for points C and D.



**Figure 2.1 Block size illustration (Source: Dill (2004))**

Planners often use connectivity indicators to quantify street efficiency measured as the ratio of number of links (usually defined as the segment between two nodes or intersections) to the number of intersections (VDOT (2010), Handy et al. (2003), Allen (1997), Song (2003), Calgary (2010)). In a study by Ewing (1996), a link-node ratio of 1.4, is suggested as a good target for network planning purposes. Dill (2004) shows an example for connectivity measure using Plan A and Plan B in Fig. 2.2. Same numbers of nodes are present for both the plans and only differ in the number of links because of which resulting link-node ratio of Plan B is 1.13 and for Plan A is 0.88. There is an increased connectivity under Plan B for route between A and B (total of three possible routes) as compared to only one route between points A and B under Plan A. But the connectivity index defined using this ratio does not incorporate the link length information which intuitively affects connectivity. It is also quite easy to visualize that with the same connectivity index definition above,

two different streets could have the same connectivity index values depending on the way street link segments are counted (Steiner and Butler (2007)).



**Figure 2.2** Link-node ratio connectivity (Source: Dill (2004))

In some other literatures, street connectivity is often described as related to pedestrian accessibility. Aultman-Hall et al. (1997) use the average walking accessibility between alternative neighborhood designs consisting of three neighborhood plans – the development’s original layout, the original layout without pedestrian walkways, and a more “sustainable” redesign. For each of these plans schools, open space, and transit stops are considered as neighborhood destinations and difference in pedestrian accessibility is recorded. They find that pedestrian walkways are an excellent means to improve walking accessibility within neighborhoods. However, the results cannot be extended to connectivity as transit systems travel longer distances.

Ballou et al. (2002) present ‘circuitry factors’ useful in designing logistics networks, routing vehicles, and planning in other geographically based logistics applications, as a multiplier in order to approximate actual road travel distances for various countries and country regions throughout the world. The study can help in deriving street based connectivity index but is not capable in capturing the randomness involved in passenger demand distribution present in a flexible transit system.

Researchers Mately et al. (2001) define connectivity as the ability to move one place to another via street and sidewalk networks and other urban design elements. In their work, street network density as connectivity measure was calculated for each census tract done using simple geometric lengths of TIGER streets derived in the GIS in street kilometers per square kilometer (miles per square mile). Grid dummy variables are used by Messenger and Ewing (1996) as a substitute for street network variables representing connectivity for different types of network. Variable 1 is assigned to pure grids or near-grids were assigned and variable 0 is assigned to highly interrupted grids or curvilinear networks. Silva (2000) refers to connectivity as some percentage of households connected to services such as water, electricity and sewer which is again limited in use to predict transit performance based on connectivity. Haas et al. (2009) has used bus data to calculate the frequency and extent of transit for a given block group for total weekly route trips in both directions. The calculation is referred to as transit connectivity index (*TCI*) used for a quarter mile buffer area intersecting block groups and is defined by the equation (2.1). The equation, however, lacks information about distance travelled by transit in *TCI* computation.

$$TCI = \frac{\sum((0.25 \text{ miles buffer area intersecting block group}) \times (\text{route total weekly trips}))}{\text{total census block group area}} \quad (2.1)$$

There are several connectivity definitions which have been in use from biology and ecology too. Tischendorf and Fahrig (2000) use dispersal success or search time based on immigration into all habitat patches as a connectivity measure. Moilanen and Nieminen (2002) use three different connectivity measures - distance to all source population in exponential form, buffer measures and nearest neighbor measures – as

indicators of connectivity for colonization of spatial ecological habitats. The nearest neighbor measures are expressed in three different ways using the following equations,

$$I_i = d_{NN} \quad (2.2)$$

$$I_i = \frac{d_{NN}}{A_{NN}^b} \quad (2.3)$$

$$I_i = \frac{d_{NN}}{A_i^c A_{NN}^b} \quad (2.4)$$

where, the  $I_i$  is isolation of the empty focal patch  $i$ ,  $A_i$  is area of patch  $i$ , and  $d_{NN}$  and  $A_{NN}$  are the distance to and the area of the nearest occupied habitat patch. Two separate parameters  $b$  and  $c$  are used for area to consider the scaling of emigration and immigration as a function of patch area, respectively. The other connectivity measure is used with no distance effects as occupied patches are considered equally within a limited neighborhood of the focal patch. Thus,

$$S_i = \sum_{\substack{j \neq i \\ d_{ij} \leq r}} A_j^b \quad (2.5)$$

$$S_i = A_i^c \sum_{\substack{j \neq i \\ d_{ij} \leq r}} A_j^b \quad (2.6)$$

where,  $S_i$  is the connectivity of patch  $i$ ,  $r$  is the radius of the buffer area, and  $d_{ij}$  is the distance between patches  $i$  and  $j$ . The third connectivity measures use a negative exponential dispersal kernel, with parameter  $\alpha$  scaling the effect of distance to migration. These are,

$$S_i = \sum_{j \neq i} \exp(-\alpha d_{ij}) A_j^b \quad (2.7)$$

$$S_i = A_i^c \sum_{j \neq i} \exp(-\alpha d_{ij}) A_j^b \quad (2.8)$$

However, the above connectivity measures cannot be extended for use in measuring network connectivity as they are too local in use for nearest neighbors or lack distance factors and need parameter calibrations.

Peponis et al. (2007, 2008) introduced the concepts of ‘reach’ and ‘directional distance’ as the measures of connectivity applicable to GIS-based representations of street networks. However, this measure of connectivity lacks a closed form expression for defining the connectivity index for any general network. The Gamma index that exists in Kansky (1963) is particularly useful in quantifying connectivity for a particular street network but does not include provisions for ridership demands or any passenger utility. Derrible and Kennedy (2010c,b,a) studied the metro transit network system as graphs and in some sense there was a link between the connectivity and transit performance. However, metro rails have fixed tracks that they follow as a travel constraint and hence, do not bear very close resemblance to flexibility of other modes of transit (such as demand responsive transit) which use streets.

To assess network effects on transit performance, it is important to study the effect of street connectivity on transit performance – by using a quantified measure that is a good representation of street connectivity. A preliminary knowledge of the extent

of street connectedness can help transit operators design DRT efficiently within an area. The effects of street connectivity is not limited to just transit, in fact, street connectivity also affects the performances of other modes of transportation - such as biking and walking. Lam and Schuler (1981) developed and tested a methodology for measuring network connectivity for the purpose of evaluating transit system design and transit performance. Concepts from graph theory, urban transportation planning models, and statistical sampling were used in the study approach with considerations to different factors that influence the development of the transit network, routes and schedules, and the quality of services rendered. Further, Lam and Schuler (1982) also studied a methodology for determining the connectivity of the routes and schedules of an entire public transit system with the objective of using a connectivity indicator for quantitative tool in the evaluation of service-delivery strategies. They find that using the graph-theoretical connectivity by computer simulation, the mean of the reciprocals of the trip lengths of a representative sample of trips proved to be a good connectivity indicator. However, consideration for demand distribution that also accounts for transit ridership is missing in their work.

## 2.2 Link Criticality

A number of research articles can be found that are focused towards understanding a single link failure case by considering an increase in travel time or travel distance for the commuters as a vital component in the determination of critical link. Jenelius et al. (2006) derived several link importance indices and site exposure indices based on the increase in generalized travel cost when links are closed. The measures used were divided into two groups—the first one reflecting an “equal opportunities perspective”, and the second a “social efficiency perspective”. These measures were calculated for the road network of northern Sweden. Knoop et al. (2008) developed many indicators to determine vulnerable parts of a network. These were determined without simulating the network flows with an incident on each of the links. Further,

a list of indicators was proposed in literature and comparisons were made. It was observed that different indicators ranked links differently.

Taylor et al. (2006) performed vulnerability analysis on road networks by considering the socio-economic impacts of network degradation. Several standard indices of accessibility were considered, which included a generalized travel cost, the Hansen integral accessibility index, and the ARIA index used in Australia. However, the evaluation is not explicitly based on the impacts on vehicular performances for any given link failure. Often a solvable approximation is needed for identifying the most vital arc or link in a network using some algorithmic approach. Ball and Golden (1989) used the most vital arcs problem (MVAP) of finding a subset of arcs such that whose removal from the network results in the greatest increase in the shortest distance between two specified nodes. Corley and Sha (1982) used algorithms to identify the most vital links (or nodes) in a weighted network whose removal from the network resulted in the greatest increase in shortest distance between two specified nodes.

However, most past research work in identifying critical links in a given network need software to code the networks and thereby compute changes in travel time by deleting or adding new links. The process is often time consuming and would need high-end software for computational purposes. The methodology becomes complicated even for simple and symmetrical-looking grid street networks that are found in plenty all over the United States. This part of dissertation presents some closed form results that would help planners and engineers decide on the most critical link quickly without involving exhaustive computations or simulations. In this study, critical links of a grid-based network are identified as those that when removed/closed would cause the largest drop in performance for a general DRT. Later, simulation experiments are also performed to validate analytically determined critical street link(s) in the network.

### 2.3 Transit Performance

Transit performance measures are often related to mostly accessibility, mobility and economic development across all modes. Table 2.1 shows the compilation of performance measures for the above three categories (TCRP (1999), Cambridge Systematics (1999), Bertini and El-Geneidy (2004)).

It is generally difficult to identify a unique definition of performance of a transit system as priorities differ among stakeholders. Several authors have used measures such as passenger cost, passengers per vehicle hour, vehicle miles per operator, cost per vehicle mile, cost per vehicle hour, the ratio of cost to fare box revenue and fleet fuel efficiency for the urban public transit ( Gleason and Barnum (1986), Fielding et al. (1985), Badami and Haider (2007)), Quadrifoglio and Li (2009)). However, all seem to agree that transit performance can generally be identified as a combination of operating costs (roughly directly proportional to the traveled miles) and service quality, which can be expressed (for the most part) as passengers' disutility: a weighted sum of expected waiting time, expected in-vehicle travel time and walking time (Chandra et al. (2011)). Many other factors are certainly important, but generally considered less significant.

### 2.4 Transit Scheduling

There are different applied forms of DRT services in existence and each of the different applied kind plays an important role in improving the living standards for people even in areas which lack an acceptable means of transportation. Dial-a-ride (operate similar to demand responsive transit) used as door-to-door transportation services can be found in the form of ADA paratransit services (Diana and Dessouky (2004), Melachrinoudis et al. (2007)). Rural transit providers also rely on DRT systems as feeder for their operations, due to low population density not allowing traditional fixed-route service to be sufficiently efficient. These low-demand den-



**Table 2.1 List of transit performance measures**

Accessibility	Mobility	Economics
<ol style="list-style-type: none"> <li>1. Average travel time and trip length,</li> <li>2. Percent of population within <math>x</math> miles of employment,</li> <li>3. Percent of population that can reach services by transit, bicycle, or walking,</li> <li>4. Percent of transit dependent population and population within access to transit service,</li> <li>5. Percent of transfers between modes to be under <math>x</math> minutes and <math>n</math> feet,</li> <li>6. Transfer distance at passenger facility,</li> <li>7. Percent of urban and rural areas with direct access to passenger rail and bus service,</li> <li>8. Access time to passenger facility,</li> <li>9. Route miles of transit service, route spacing and total transit trip time spent out of vehicle,</li> <li>10. Existence of information services and ticketing,</li> <li>11. Availability of park and ride</li> </ol>	<ol style="list-style-type: none"> <li>1. Percent on-time performance,</li> <li>2. Percent of scheduled departures that do not leave within a specified time limit,</li> <li>3. Travel time contour,</li> <li>4. Minute variation in trip time,</li> <li>5. Fluctuations in traffic volumes,</li> <li>6. Average transfer time/delay,</li> <li>7. Dwell time at intermodal facilities,</li> <li>8. Proportion of persons delayed,</li> <li>9. In-vehicle travel time,</li> <li>10. Frequency of service,</li> <li>11. Averages wait time to board transit,</li> <li>12. Number of public transportation trips</li> </ol>	<ol style="list-style-type: none"> <li>1. Percent of region's unemployed or low income citizens that cite transportation access as a principal barrier to seeking employment</li> </ol>

sity areas especially those that often lack a reasonable transportation infrastructure are often considered as potential candidates for DRT services. A small community called El Cenizo along the US-Mexico border in Texas serves as a good example (Quadrifoglio et al. (2009)).

Demand responsive services operate according to either a static or a dynamic mode. Several related literatures can be found in this regard in Cordeau and Laporte (2007). From the perspective of vehicle routing problems, mathematical formulations are often carried out for optimizing and managing fleet size for demand responsive or dial-a-ride systems (Horn (2002), Diana et al. (2006) among others). However, due to low demand fleet size is not of a major concern. A transit operator would prefer to operate as fewer fleets as possible simply to minimize operating costs (Ahouissoussi and Wetzstein (1998)). Often, a single shuttle could suffice if the demand responsive is meant for residential areas and those in particular used among the elderly community (TriMet (2012)). With regard to this, single vehicle study for dial-a-ride can be found in the work of Psaraftis (1980) as an exact dynamic programming solution. The single vehicle case deals with mostly minimizing route duration, ride time, and waiting time of the passengers. As a follow-up to this, Chandra et al. (2011) studied a simulation based approach using a single vehicle case to estimate optimal cycle length for the feeder services within a residential community. There are other simulation based studies as well. These studies, however, require considerable data input a priori that often are not available in a new area.

Demand responsive systems and, in particular, dial-a-ride problems have often been mathematically modeled with different formulations with time window settings for passenger requests (Ropke et al. (2007), Cordeau (2006)). The time window constraints make it harder for transit operators to schedule pick-up/drop-off with less flexibility in operation. However, time windows are redundant when the cycle lengths are already small in length and demand low to serve passengers almost immediately in some instances. The challenge mostly lies in minimizing the waiting

time and improving service reliability without having to worry too much about the time window constraints. Literatures can be found that deal with a single cycle (or headway) optimization for performance, cost etc. of operating a ‘fixed’ feeder transit services (Chowdhury and Chien (2011), Zhao and Zeng (2008)). The same for flexible transit systems is still not properly addressed due to complex service request times and demand uncertainty. Surely, researchers have emphasized the importance of using an optimal bus dispatch policy by varying shuttle capacity and under stochastic lead times with fixed stepwise costs (Ignall and Kolesar (1974), Alp et al. (2003)). There are other models for transit bus dispatch at intermodal transfer stations using several techniques such as bus tracking technology, dynamic vehicle dispatch and using archived bus dispatch systems data (Chowdhury and Chien (2001), Dessouky et al. (1999), Bertini and El-Geneidy (2004)). These might hold true for demand responsive transit systems as well but most lack a closed form value for frequency setting required in operating a flexible transit system such as DRT.

Serving passengers with a shuttle in DRT operations can be treated to be a problem similar to those found in queuing theory, where the shuttles can be considered as dynamic service windows, passengers as service objects, and dispatch time from service windows as waiting times (Hongqi (2009), Daganzo (1990)). However, the influence of service area characteristics of DRT cannot be easily integrated with performance in these studies.

Linking passenger-waiting times with feeder frequency is very critical in designing an optimal schedule. Longer and unreliable feeder bus headways or cycle lengths lead to increased passenger waiting times (Chang and Hsu (2004), Ozekici (1987)). Best cycle lengths or frequencies occur for when the discomfort caused to the passengers in terms of waiting and in-vehicle travel times is the minimum. Each cycle length needs to be designed using an appropriate scheduling strategy to reduce individual passenger waiting time and travel time at least on an average. This is not much of an issue as several heuristic methods have been developed to solve prob-

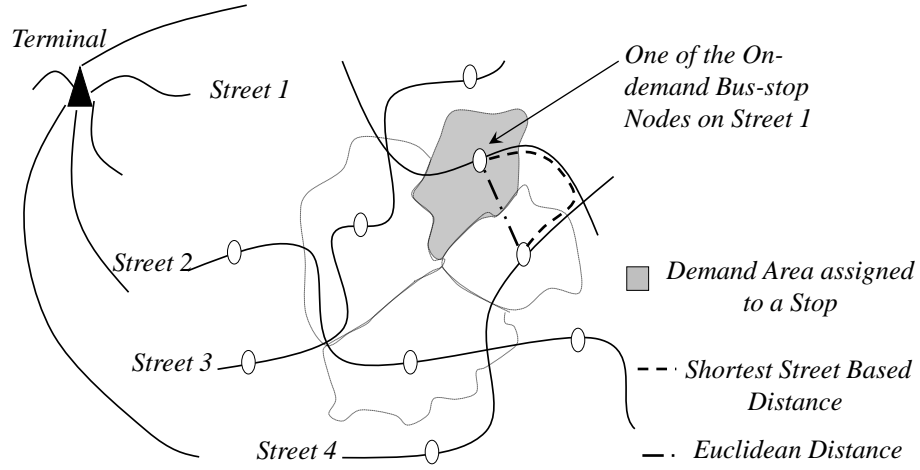
lems related to scheduling for obtaining smart solutions without much compromising on the optimality. Scheduling problems of flexible transit such as DRT or DART often fall in the category of TSP that are known to be NP-hard. Previously, Jaw et al. (1986) described a heuristic for a time-constrained version of the many-to-many DART Problem. The algorithm describes the Advanced Dial-a-Ride Problem with Time Windows (ADARTW) with service quality constraints and identifies feasible insertions of customers into vehicle work-schedules. As a test on the performance of the heuristic, Barr et al. (1995) has provided reporting guidelines for computational experiments performed using heuristic methods. Later, Campbell and Savelsbergh (2004) developed an efficient ‘insertion heuristics’ for vehicle routing and scheduling problems that was computationally fast and could easily handle complicated constraints.

The first goal of this dissertation is to identify and test a new Connectivity Indicator which is simply defined, easily computable, and properly able to capture the relationship between connectivity and feeder transit performance. A revised and expanded definition of the ‘connectivity indicator’ in Lam and Schuler (1982), which depends on certain number of given travel times between demand points, is reformulated taking into consideration the street network layout and the passenger demand density distribution. The new connectivity indicator uses the average distance traveled between two potential demand points on a network system. Further, strategies are adopted to work with a regular grid-street network system to estimate critical links and optimal block length needed for the largest connectivity indicator value. Lastly, an optimal shuttle scheduling strategy is suggested through mathematical formulations using approximations of street-based path for best transit performance.

### 3. A NEW STREET CONNECTIVITY INDICATOR

#### 3.1 Methodology

A residential area is considered that is served by an on-demand feeder bus service providing residents with transportation from/to their home to/from a major transit terminal. Passengers are able to book their rides by means of an internet/phone service. One or more ‘on-demand bus-stop’ node is assigned to each link of the road network. The maximum distance from any home to its closest on-demand stop is within the recommended walking capacity of the passengers which is usually 5 minutes of walk, corresponding to approximately 1,200 feet ( O’Sullivan and Morrall (1996)). Assigning ‘on-demand bus-stop’ nodes helps both the bus operators and the passengers in serving at designated points along the cross street link when there are multiple requests made for service at that link. The on-demand nodes bus stops are not placed at the intersections. This is because bus stops at mid-block streets are preferred for design as they minimize sight distance problems for the pedestrians and also help create less pedestrian congestion at the passenger waiting areas (Fitzpatrick et al. (1996)). Demand could arise anywhere within the service area following some spatial/temporal distributions and is assumed to be assigned to the closest stop (see Fig. 3.1). Passengers might be required to do some walking, but the overall service time is reduced when there are multiple requests made for service at that link. The shuttle departs from the terminal at pre-set intervals. Immediately before the beginning of each roundtrip, customers sequence is scheduled by some algorithm, so the route is constructed and the passengers served.



**Figure 3.1 Sketch of on-demand bus stop nodes on street links**

The aim is to define a new Connectivity Indicator (C.I.) as a good predictor of the on-demand transit performance, which is composed by a weighed combination of operator's objective (lesser total distance traveled) and level of service (shorter in-vehicle riding time and waiting time, assuming negligible walking time). Intuitively, all these terms are dependent on how quickly the shuttle is able to serve customers.

The expected in-vehicle riding time  $E(T_{rd})$  and waiting time  $E(T_{wt})$  for a feeder transit service can be related to the cycle length  $C$  using the following equations (Quadrifoglio and Li (2009)),

$$E(T_{rd}) = \frac{C}{2} \quad (3.1)$$

$$E(T_{wt}) = (1 + \alpha) \frac{C}{2} \quad (3.2)$$

where  $\alpha$  is the proportion of passengers going from home to terminal and  $(1 - \alpha)$  the portion traveling from terminal to home.

In a given service cycle, a set of  $n$  on-demand nodes (starting at the terminal  $i = 0$  and returning back at the terminal  $i = n + 1$ ) is scheduled for service and the

total distance traveled is  $D = \sum_{i=0}^n d_{i,i+1}$ , where  $d_{i,i+1}$  is the shortest path between any two consecutive stops  $i$  and  $i + 1$ . Thus, the cycle length  $C$  is expressed as

$$C = \left( \frac{D}{v} + nt \right) \quad (3.3)$$

where  $t$  is the average service time spent at each stop and  $v$  is the average velocity of the shuttle. If  $N$  is total number of potential on-demand stops within the service area (with  $n$  being a subset of  $N$ ), the sum of all the shortest paths among all potential  $N$  nodes is

$$T = \sum_{i=1}^N \sum_{j=1}^N d_{ij} \quad (3.4)$$

It can be easily seen that  $D$  is a fraction  $f$  of  $T$  ( $D = fT$ ), where  $f$  will be different every cycle.

The operator objective (total distance traveled) of the transit performance is obviously directly proportional to  $D$  and thus  $T$ . The level of service components are too; in fact, by using equation (3.1), (3.2) and (3.3) and knowing that  $D = fT$ ,

$$E(T_{rd}) = \frac{1}{2} \left( \frac{fT}{v} + nt \right) \quad (3.5)$$

$$E(T_{wt}) = \frac{(1 + \alpha)}{2} \left( \frac{fT}{v} + nt \right) \quad (3.6)$$

which are both directly proportional to  $T$ .

Hence, a desirable C.I. of a given network should logically also be proportional to  $T$  to be a good predictor of the transit performance.

### 3.1.1 Expected Street-based Shortest Path

When comparing different network configurations within a given service area for planning purposes, the simple use of  $T$  as C.I. would be good only if  $N$  is a constant among all options. However, it would be desirable to define a C.I. as general as possible and not necessarily dependent on  $N$ . Different network options might in fact have more or less potential stops and this should not influence their on-demand transit performance. Thus, it is necessary to remove the dependency from  $N$ , which is easily done by defining the average (expected) shortest path  $S$ . If demand is assumed to be distributed uniformly among all the stops, then it can be easily seen that  $S$  is given by

$$S = \frac{T}{N(N-1)} \quad (3.7)$$

It is fair to say that uniformly distributed demand is an acceptable assumption, as otherwise, modeling is not easy. However, in the more general case, demand might be unevenly distributed among stops, so that some links are more likely to be used in a cycle and therefore more critical than others for the overall transit performance. As an intuitive example, links connecting stops relatively far from the others but with little demands should not be considered as important as links connecting pairs of nodes with higher demands. Let  $\Lambda$  be the demand rate in the considered service area and let  $\lambda_i$  be the demand rate at the on-demand stop  $i$  ( $\Lambda = \sum_i \lambda_i$ ). The likelihood for a pair of nodes  $i$  and  $j$  to be consecutive in a cycle (and the shortest path  $d_{ij}$  between them to be actually driven by the vehicle) is proportional to the product of their demand rate  $\lambda_i$  and  $\lambda_j$ . Therefore, the expected shortest path between any two nodes in a network can be expressed as



$$S = \frac{1}{\Lambda} \sum_i \left( \lambda_i \frac{\sum_j \lambda_j d_{ij}}{\Lambda - \lambda_i} \right), \quad \forall i, j \in \{1, 2, \dots, N\}, j \neq i \quad (3.8)$$

which reduces to (3.7) for uniform demand. Thus, a good C.I. taking into account spatial demand distribution should be related to (3.8).

### 3.1.2 Ideal Network I

Most residential street patterns follow the grid-form of street networks as it is both pedestrian and vehicle friendly. Grid street patterns give plenty of route options for trips if covered by walking, transit or by using a private vehicle (Kostof (1991)). The maximum transit performance is reached as this layout provides multiple route options.

An example of a grid street pattern is shown in Fig. 3.2 from the town of Hempstead (with block length  $s \approx 350$  feet), a residential town fifty miles northwest of downtown Houston, TX, and there are several such grid networks as examples all around the cities and towns in the US.

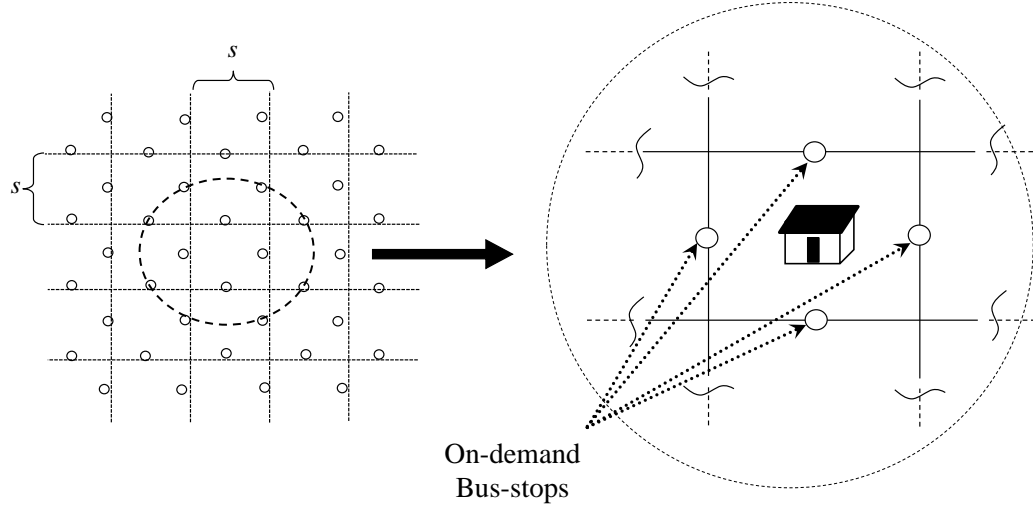


**Figure 3.2 A grid section of the street network system of the town of Hempstead, TX (Source: TNRIS (2011))**

Consider a grid form of residential street pattern with each ‘square-shaped’ units of block-size length  $s$  and spread infinitely across a very large area. The purpose of the perfect connectivity is to develop an ideal scenario (even though it might be ‘hypothetical’ but technically correct) when a given DRT shuttle would exhibit best service quality to its passengers and hence, would be superior to any other street network with any demand distribution found in reality. In general, the expressed CI is a ratio of ‘expected distances between two demand points’. The numerator is the ‘lower bound’ for expected distance between nodes that any street system with demands can have. Thus, a perfect connectivity would be the ‘perfect’ incorporating the fact that the shuttle should be able to pick-up customers quickly for the best connectivity of a given ‘hypothetical’ street network design. This is possible in two ways 1) the street itself should be so well laid out that the DRT shuttle has multiple options to move from one node to another and 2) the passengers also cross streets to hop into the shuttle not caring for the inconvenience caused in crossing the street

instead of waiting for the shuttle to make a round and pick them up from the stop where they request service. These two conditions might or might not exist in reality as there is discomfort involved in crossing the street (Hadas and Ceder (2010)). However, if in reality these two conditions exist together, we would have the best combination of shuttle service strategy for aforesaid perfect street connectivity in place.

Each single trip of DRT should be based on the smallest possible point-to-point distance traveled to show optimum performance. However, computing an optimal tour for serving passengers like this is similar to solving a Travelling Salesman Problem (TSP) which is considered to be  $NP$ -hard and hence, is computationally expensive each time DRT makes a departure from the terminal. If we assume that the DRT shuttle picks a certain number of passengers during a given cycle length, the average closest distance between two random pick-up/drop-off passengers would be close to the optimal tour. Using this average closest distance between mutual pick-up/drop-off demands would also give an average lowest shuttle travel distance than that obtained using any available scheduling algorithm. Hence, the next section this average closest between two random points is derived over the perfect grid network system. The sketch in Fig. 3.3 depicts a structural framework of an infinitely large grid network system.



**Figure 3.3 Model for a perfect street network system**

The expression is derived for the average closest street based distance between two uniformly distributed random demand points over an infinitely large perfect grid network. Consider grid street network system as shown in Fig. 3.3. Uniformly and randomly scattered demand points follow a spatial Poisson distribution (Quadrifoglio et al. (2006)). Assuming that the number of demand points  $\Omega_A$  within the area  $A$  is a Poisson random variable, its distribution is given by

$$P \{ \Omega_A = x \} = \frac{(\rho A)^x}{x!} e^{-\rho A} \quad (3.9)$$

where,  $x = 0, 1, 2, 3, \dots$

For a zero demand to occur within the area  $A$ , would imply  $x = 0$ , and the following expression is obtained,

$$P \{ \Omega_A = 0 \} = e^{-\rho A} \quad (3.10)$$

The passengers are expected to walk to the closest on-demand bus-stop to avail the DRT service. This also means that the DRT shuttle would prefer to pick the next closest passenger at the on-demand bus-stop. Thus, using simple geometry, at present if the DRT shuttle is at node  $Z$  which could also be the terminal itself (see Fig. 3.4), the occurrence of a request for service within an assigned area  $A_n$  decides how far the  $n^{\text{th}}$  closest on-demand point is located on the grid street system. For example, the first closest demand point from  $Z$  will be located at a street based distance of  $s$  if there is a request for service within the demand area of  $A_1$  as shown in Fig. 3.4. The second closest distance from the node  $Z$  is  $2s$  when a request pops up in the next demand area of  $A_2$  and so on. An example has been shown using area  $A_2$  in Fig. 3.4 for further explanation. The arrows show the direction of travel to all the closest nodes which are at a street based distance of  $(3s/2 + s/2 = 2s)$  from node  $Z$ . All demands that occur within the “un-shaded” square box around rightmost node labeled  $z$  are closest to latter than any other node (if we assume rectilinear travel from a demand within the square box to node  $z$ ). Similarly, all nodes which are a distance of  $2s$  from  $Z$  have demands enclosed within squares for which the respective nodes are closest. (Note, the area is analyzed for quarter section only as computation is easy.)

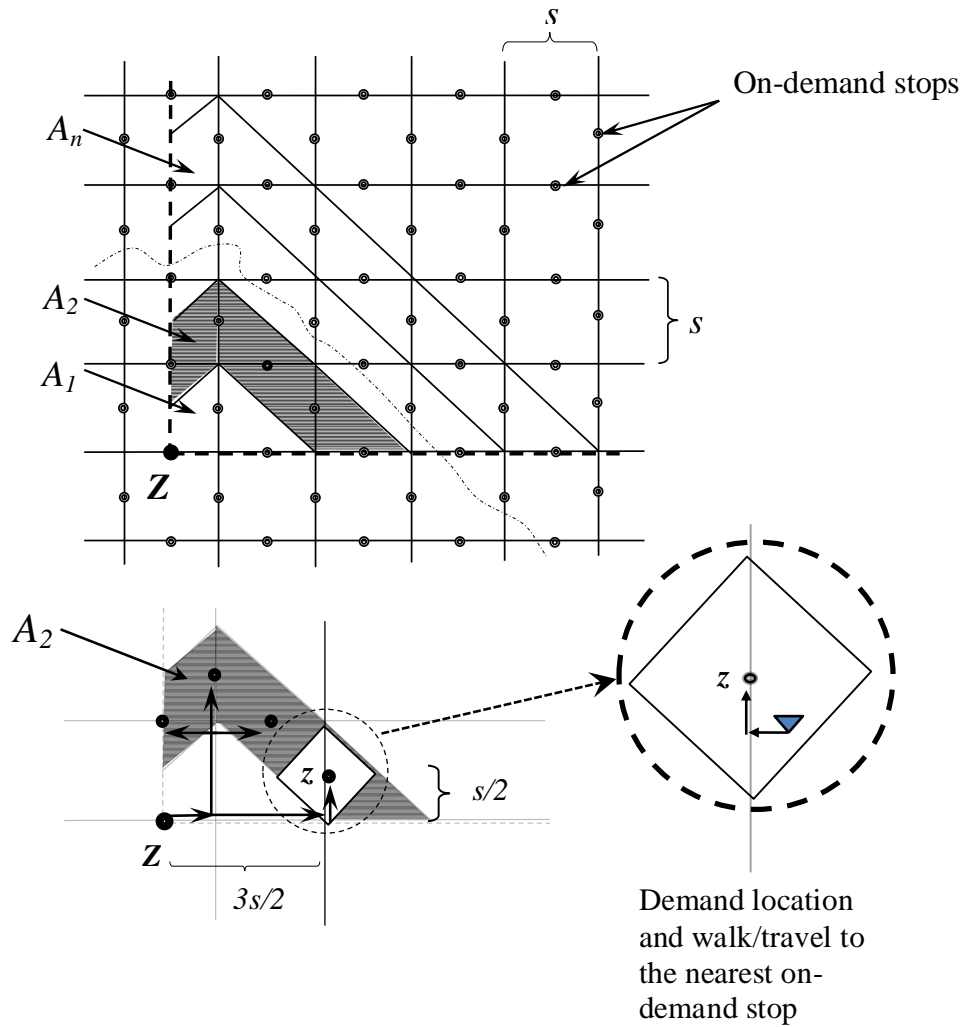


Figure 3.4 Location of the closest demand on a node from a known node ( $Z$ ) along the grid

Observing the geometry of each of the quarter sections in Fig. 3.4, the following expressions hold,  $A_1 = \frac{s^2}{2} + \frac{3s^2}{8}$ ,  $A_2 = \frac{(2s)^2}{2} + \frac{3s^2}{8} + \frac{s^2}{2}$ ; or, in general for the  $n^{\text{th}}$  demand area,

$$A_n = \frac{1}{2}(ns)^2 + \frac{3s^2}{8} + (n-1)\frac{s^2}{2} \quad (3.11)$$

Using the concept that more the number of cross streets the better the connectivity leading to a *perfect connectivity*, the variable  $n$  should be intuitively large. Thus, the expected closest distance between two random demands  $E[D]$  can be written using (3.10) as,

$$\begin{aligned}
E[D] &= \sum_{n=1}^{\infty} (ns)P\{\Omega_A = 0\} = s \sum_{n=1}^{\infty} (n)e^{-4\rho A_n} \\
&= s \sum_{n=1}^{\infty} (n)e^{-2\rho s^2(n^2+(n-1)+\frac{3}{4})} = s \sum_{n=1}^{\infty} (n)e^{-2\rho s^2(n^2+n-\frac{1}{4})} \\
&= (se^{\rho s^2}) \sum_{n=1}^{\infty} ne^{-2\rho s^2(n+\frac{1}{2})^2}
\end{aligned} \tag{3.12}$$

The effect of variable  $n$  is small compared to the exponential terms with second power of  $n$  (where,  $n \geq 1$ ) in (3.12), this makes the expression for  $E[D]$  controlled primarily by the behavior of the exponential term. For sufficiently large demand  $\rho$ , we can write,

$$E[D] \approx (se^{\rho s^2}) \sum_{n=1}^{\infty} e^{-2\rho s^2(n+\frac{1}{2})^2} \tag{3.13}$$

The entries in Table 3.1 shows some examples of values obtained using (3.12) and (3.13) for different values of  $\rho$  (per square mile) with  $n = 1$  to 100 and  $s = 350$  feet of the service area. It can be seen that for large demand density we can approximate (3.12) with 3.13).

For  $n \geq 1$ , (3.13) can be further approximated as,

$$E[D] \approx (se^{\rho s^2}) \sum_{n=1}^{\infty} e^{-2\rho s^2 n^2} = (se^{\rho s^2}) \sum_{n=1}^{\infty} \left(\frac{1}{e^{4\rho s^2}}\right)^{\frac{n^2}{2}} \tag{3.14}$$

**Table 3.1** Sample values of expected shortest street-based distance between two random points

$\rho$	$E[D]$ (in miles)	
	Eqn (3.12)	Eqn (3.13)
2	1.68	0.38
10	0.29	0.14
18	0.15	0.09
26	0.10	0.07
34	0.07	0.05
42	0.05	0.04
50	0.04	0.04



Using the simplified expression for discrete normal distribution summation from Szablowski (2001) that satisfy the following condition  $\left(\frac{1}{e^{4\rho s^2}}\right) \in (0, 1)$ .

The expression for  $E[D]$  can be written as,

$$E[D] \approx \left(se^{\rho s^2}\right) \sum_{n=1}^{\infty} \left(\frac{1}{e^{4\rho s^2}}\right)^{\frac{n^2}{2}} = \left(se^{\rho s^2}\right) \left\{ \frac{1}{2} \left[ \sqrt{\frac{\pi}{2\rho s^2}} \left( 1 + 2 \sum_{n \geq 1} e^{-\frac{\pi^2 n^2}{2\rho s^2}} \right) - 1 \right] \right\} \quad (3.15)$$

Ignoring the summation terms, since  $\left(2 \sum_{n \geq 1} e^{-\frac{\pi^2 n^2}{2\rho s^2}}\right) \ll 1$ ,  $E[D]$  can be further simplified as,

$$E[D] \approx \left( \frac{se^{\rho s^2}}{2} \left( \sqrt{\frac{\pi}{2\rho s^2}} - 1 \right) \right) \quad (3.16)$$

The expression for  $E[D]$  in ((3.16)) should hold only for  $\rho \leq \frac{1.57}{s^2}$  as right hand side should be a positive quantity. Typically, for a value of  $s = 350$  feet or less, the condition  $\rho \leq \frac{1.57}{s^2}$  will naturally be met for most demand responsive transit systems. Limits can be found for the right hand side of (3.16) by setting block length too small. Then,  $\lim_{s \rightarrow 0} E[D] \approx \frac{0.63}{\sqrt{\rho}}$  which can be verified with exactly similar result obtained for a rectilinear metric assumption used by Quadrifoglio et al. (2006).

### 3.1.3 Ideal Network II

The purpose of this section is to define another *relaxed* version of ideal network I with “perfect” connectivity, which would allow an on-demand feeder transit service to achieve the best possible performance and hence, would be superior to any other real street network, under the uniformly distributed demand assumption. Theoretically, in a given area of length  $L$  and width  $W$ , the smallest possible average expected

shortest path distance  $S_{min}$  is calculated by assuming Euclidean paths among all pair of points when calculating  $T$  and  $S$  and is given by Gaboune et al. (1993) and is

$$S_{min} = \frac{\sqrt{L^2 + W^2}}{3} + \frac{L^2}{6W} \ln \left( \frac{W + \sqrt{L^2 + W^2}}{L} \right) + \frac{W^2}{6L} \ln \left( \frac{L + \sqrt{L^2 + W^2}}{W} \right) + \frac{L^5 + W^5 - \sqrt{(L^2 + W^2)^5}}{15L^2W^2} \quad (3.17)$$

However, a slightly more realistic computation for  $S_{min}$  would consider rectilinear paths among demand points. Assuming an ideal infinitely dense grid network,  $S_{min}$  would more simply be expressed by (Gaboune et al. (1993))

$$S_{min} = \frac{(L + W)}{3} \quad (3.18)$$

which is, of course, higher with respect to (3.17). More rigorous values for  $S_{min}$  might be calculated, taking into account actual constraints, such as, for example, the minimum block length  $s$ , which would cause the grid not to be infinitely dense and  $S_{min}$  to increase, but would not be easy to compute. The purpose of defining  $S_{min}$ , computed with (3.17) or (3.18), allows us to have a value for it for an ideal network with “perfect” connectivity. Any other network serving the same area would have  $S > S_{min}$ .

### 3.1.4 Connectivity Indicator

Thus, in order to have the C.I. directly (not inversely) proportional to on-demand transit performance and to cause an ideal C.I. identifying a “perfect connectivity” to be equal to 1 (as most indicators are defined), the final definition of it is as follows,

$$\text{Connectivity Indicator} = \left( \frac{S_{\min}}{S} \right) \quad (3.19)$$

This definition ensures that ideal networks with “perfect” connectivity would have a C.I. = 1. Any real network with shortest paths calculated over actual available links would have C.I.  $\leq 1$ .

We’d like to emphasize that identifying a precise absolute  $S_{\min}$  instead of the ones proposed above would not be a crucial step for the purpose of improving this study, as  $S_{\min}$  behaves as a constant multiplier within the C.I. definition. Its value is important to evaluate how well a given network is doing with respect to an ideal case, but would not be crucial in comparing multiple network options among each other, as all would have  $S_{\min}$ .

The proposed C.I. is very easy to calculate for any street network system and should be a very good predictor of the on-demand transit performance: intuitively, the higher the C.I., the better the transit performance.

## 3.2 Other Connectivity Indicators

Most common currently available indicators to measure connectivity are summarized below. The comparison between proposed C.I. against these two are carried out in the next section.

### 3.2.1 Gamma Index

Graph theory measure of network connectivity for planar graphs, known as the Gamma index, is expressed as  $\left( \frac{e}{3(\nu-1)} \right)$ ; where  $\nu$  is the number of vertices present in the network and  $e$  is the number of edges connecting the vertices. A vertex is formed due to an intersection of two or more edges in the network. The end point of a free

edge such as that of cul-de-sac or a dead end is automatically counted as a vertex. Going by the definition of Gamma index, the higher the Gamma index, the greater connected should the network be and vice-versa.

### 3.2.2 Transportation Planning Indicator

The connectivity index in transportation planning is measured as the ratio of the total number of links to the total number of intersections in the network (for further reading see Street Connectivity - Zoning and Subdivision Model Ordinance, 2009). For this connectivity measure used in planning, the higher the connectivity index value the greater the connectivity of the network.

## 3.3 Simulation Results and Discussions

The aim of the simulation is to demonstrate the robustness and the applicability of proposed C.I. for some reasonably assumed data sets and parameters. The connectivity indicator represented by the ideal network II (3.17) is used as the only difference in proposed C.I. would be brought about by the constant numerator term in  $E[D]$  or  $S_{min}$ . A hypothetical on-demand feeder service that runs for a range of cycle lengths varying from 7.5 minutes to 40 minutes, serving a demand of 300 passenger per day within a rectangular area of  $L = 2,050$  feet,  $W = 1,750$  feet and  $s = 350$  feet (minimum block size), is put in operation in ten different street networks from different parts of Palm City, FL and Hempstead, TX (see Fig. 3.5). The street networks from these regions give ample examples of different forms of streets that could be used in simulation and could possibly cover any form of real street network one could find not only within the United States but also in any part of the world. Another reason for resorting to simulation experiments is a lack of real data that could be used for comparing the proposed C.I. with demand responsive transit performance data. The shuttle operational times are fixed from 6:30 am to 9

pm and the passengers make random service requests generated from a typical travel demand hours of US commuters as shown in Fig. 3.6 (Data source: NHTS (2009)). Since the actual cumulative probability density (which was derived from real travel time data) was difficult to invert for generating passenger request times, the assumed cumulative density in its linear form was used (see Fig. 3.6). By using the above assumptions one will get on an average demand of 20-22 passenger per hour. This is typically found in practice from call-n-ride systems operating as demand responsive service (Potts et al. (2010)). The value of  $S_{min}$  computed using (3.17) for the rectangular area dimension mentioned above assuming no street system is 0.151 miles. The requests for service are accepted between 6 am through 8:30 pm on phone or internet and are randomly assigned as pick-up (home to terminal) or drop-off (terminal to home) and are uniformly spatially distributed. The sequence at each cycle is computed by using insertion heuristic (Quadrioglio et al. (2007)). A brief summary of the steps involved in “insertion heuristic” are outlined below. The heuristic assumes that the passenger service order is pre-decided based on priority of service request time. The street based shortest path distance between any two nodes is computed using Dijkstra’s algorithm coded in MATLAB R2008b.

#### Insertion Heuristic

- Step 1) Select the shortest edge between passenger locations for a subtour.
- Step 2) Select a passenger from a pool of passengers not present in the subtour.
- Step 3) Find an edge in the subtour such that the increase in edge cost of inserting the selected passenger between the nodes or vertices will be minimal in new subtour.
- Step 4) Repeat step 2 until no more passengers remain to be served.

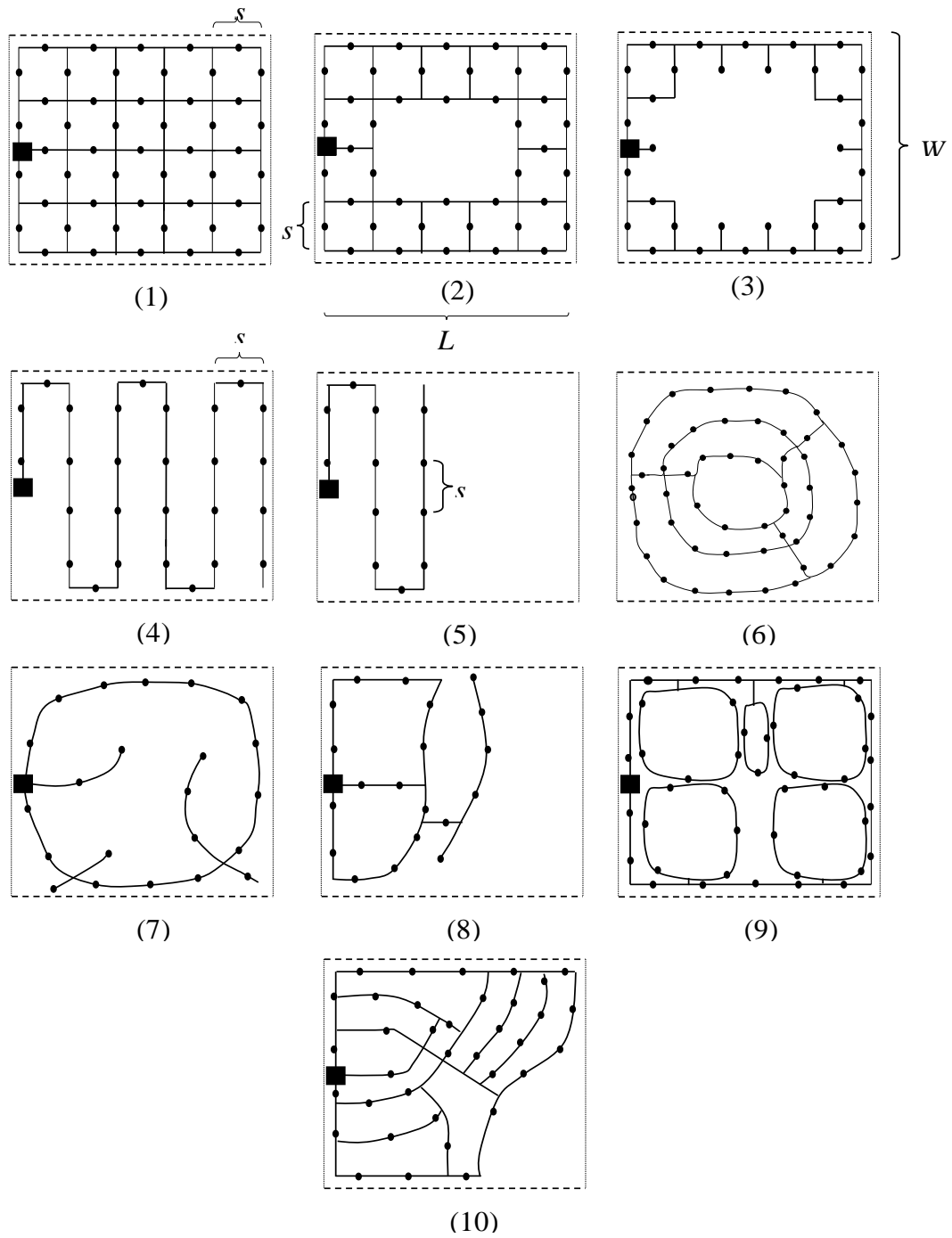
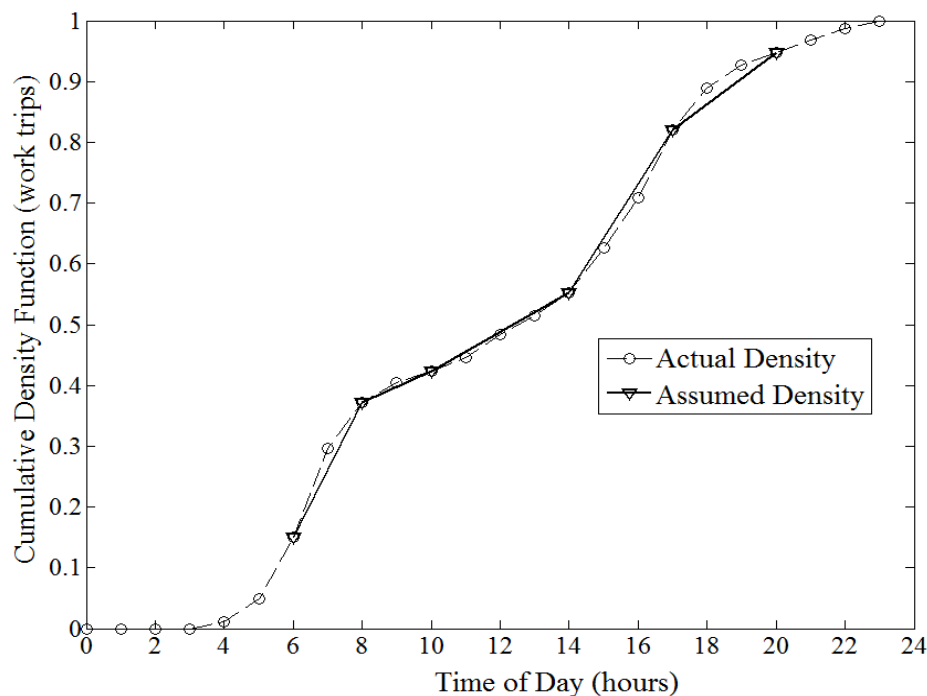


Figure 3.5 Examples of ten different real street networks from within the United States



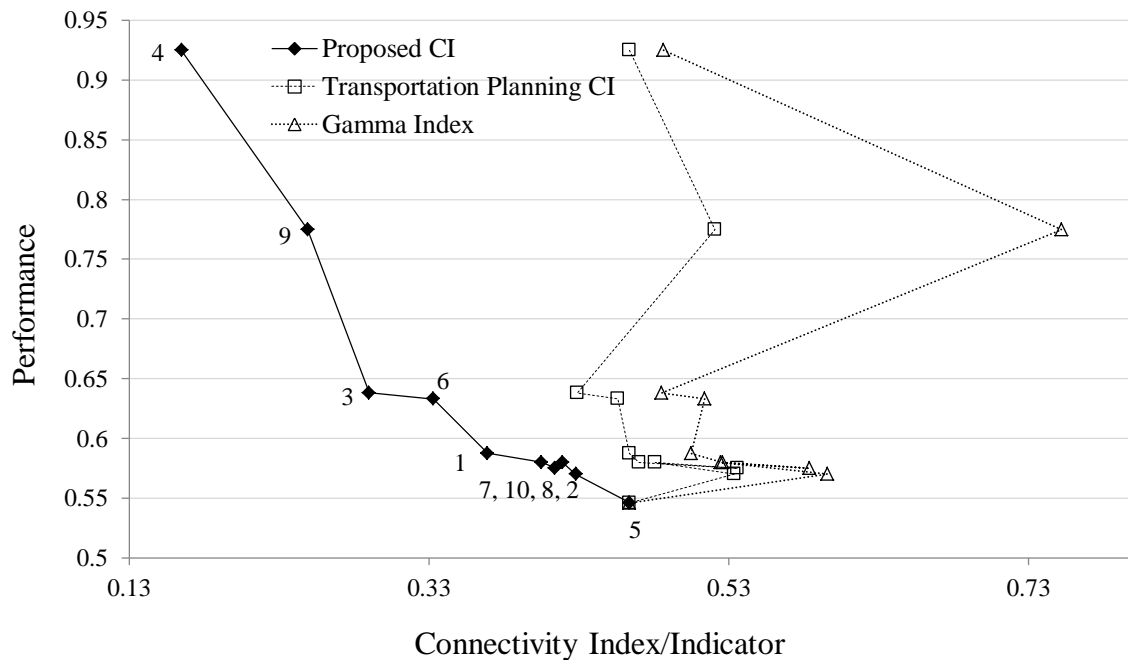
**Figure 3.6 Cumulative density functions for the US work-trips (NHTS (2009))**

In computing the transit performance, the assumption is that the service quality is the key factor as the operating costs are almost constant between the considered competing networks, all assumed to use the same vehicle type. As noted earlier, the service quality can be expressed as passengers' disutility: a weighted sum of expected waiting time and expected in-vehicle travel time, in the ratio of 1 ÷ 1.8 ( Wardman (2004)). The performance values were obtained from an average of ten replications for each of the ten networks shown before in Fig. 3.5. The resulting simulation output is tabulated in Table 3.2. The resulting performance reflects the disutility of an average passenger expressed in terms of "hours" followed by its standard deviation.

The scaled values represent the C.I. with respect to the network (5) to make comparisons easier in Fig. 3.7. The network numbers are displayed beside the data points.

**Table 3.2 Connectivity indicators evaluated for ten selected real street networks**

Network	Proposed	Planning		Gamma		DRT Disutility (Performance)	Std. Dev.
	CI	CI		Index			
	Cal.	Cal.	Scaled	Cal.	Scaled		
1	0.428	1.150	0.534	0.393	0.596	0.570	0.053
2	0.405	1.013	0.470	0.347	0.526	0.580	0.054
3	0.290	0.925	0.429	0.320	0.485	0.638	0.085
4	0.165	1.000	0.464	0.321	0.487	0.925	0.057
5	0.464	1.000	0.464	0.306	0.464	0.546	0.033
6	0.333	0.983	0.456	0.339	0.514	0.633	0.049
7	0.369	1.000	0.464	0.333	0.505	0.587	0.064
8	0.419	1.037	0.481	0.346	0.525	0.575	0.039
9	0.249	1.123	0.521	0.496	0.752	0.775	0.050
10	0.414	1.155	0.536	0.385	0.584	0.580	0.049



**Figure 3.7 Variation of DRT performances versus different connectivity indicators values**



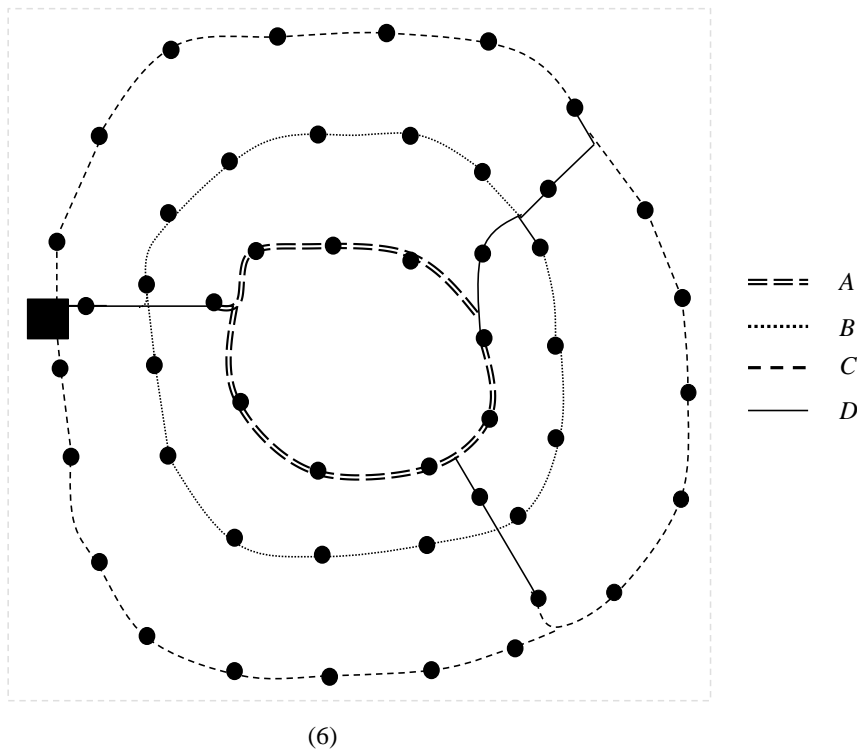
Next, it was essential to identify which and whether the proposed C.I. and the other two follow the logical expected relationship “higher connectivity  $\rightarrow$  better performance”. It can be deduced from Fig. 3.7 that as the transportation planning index and the Gamma index increase along the horizontal x-axis, the disutility does not follow with the expected and intuitive decrease (corresponding to a better performance). Gamma index does better than the planning connectivity index in validating a general increasing trend in disutility for networks (6), (3), (9) and (4) (see Fig. 3.5) the connectivity decreases. However, the relationship between the performance of other networks and their Gamma index is extremely erratic. This clearly shows that performance cannot be very well related if the measure of connectivity is used from the graph theory concepts or in particular that obtained by transportation planning index.

On the other hand, Fig. 3.7 shows that our proposed C.I. does pretty well in expressing the monotonic relationship of the disutility with the networks’ connectivity. Higher C.I.s correspond to lower disutility values (and higher performance). This information would be quite useful for the transit agencies to assess a transit system’s performance for a given network before it is even set-up or put in operation. The C.I. is easily computable for a given demand and approximate geometry of the service area and street layout options can be evaluated with respect to their related transit performance without extensive simulation analyses.

### 3.3.1 Effect of Demand Distribution

While in the earlier simulation analyses the demand distribution was assumed to be ‘uniform’ within the rectangular area, the purpose of this section is to capture and validate out proposed C.I. with respect to uneven demand distributions. Network (6) is further analyzed for performance with four different sets of demand patterns. The street link connections are maintained as the one used earlier over network (6). However, demand is distributed differently at the on-demand nodes depending on

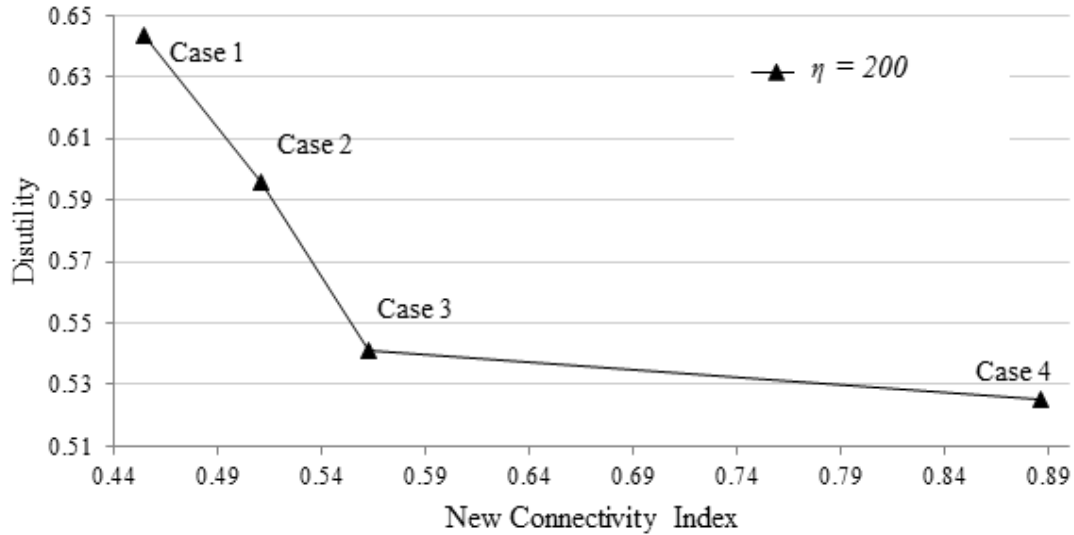
their location. The image in Fig. 3.8 shows four different portions of the network identified as loops - (A), (B), (C) and, radially placed nodes on three street segments (counted together as a group) denoted by (D).



**Figure 3.8 Different demand distributions within selected street network (6)**

The demand distribution is varied by assuming all demands concentrated at nodes belonging to one of the loops (or segments) and none on the rest. Nodes from a given loop (or segments) have an even demand distribution among themselves. These are identified as four different cases from 1 to 4, where Case (1) corresponds to all the demands concentrated uniformly only over the nodes in loop (A) and none on any of the other loops or segments. Similarly, Case (2) has demands only over nodes in loop (B) and none on other loops (or, segments) and so on. The simulation results

for these cases are represented through the charts in Fig. 3.9 for different total daily demands of  $\eta = 200$ .



**Figure 3.9 Disutility versus Connectivity Index variation for different demand distributions**

Different demand distributions within a given network (6) correspond to different values of the connectivity indicator, calculated using equation (3.19) for  $S$ . An increase in the proposed C.I. corresponds to a decrease in disutility, as one would have wished to observe. This further validates the versatility and applicability of the proposed C.I. for planning and design purposes over a given street network system.

### 3.4 Summary and Research Contribution

This study defines a novel Connectivity Indicator (C.I.) to predict transit performance by identifying the role that street network connectivity plays in influencing the service quality of demand responsive feeder transit services. The new C.I. definition is easily computable and dependent upon the expected shortest path between any two nodes in the network, includes spatial features and transit demand distribution information. Simulation analyses over a range of networks have been conducted to

validate the new definition. Comparisons performed by simulation vs. other current indicators demonstrate the validity of the proposed C.I., which is also shown to work properly when varying demand distributions within the same network. Results also show a desirable monotonic relationship between transit performance and the proposed C.I., whose values are directly proportional and therefore good predictors of the transit performance, outperforming other available indicators, typically used by planners.

Feeder transit services have been identified as one of the possible solutions of the first/last mile issue for improving transit performance. A new street Connectivity Indicator (C.I.) is proposed that is able to predict on-demand transit performance, as there is a need of such tools. The proposed C.I. is defined to be between 0 (worst connectivity) and 1 (ideal “perfect” connectivity) and its values are higher for better connected networks which also have better transit performance. Other dimensions that could form the future study based on this section will be in fine tuning C.I. definition to include variability in travel distance between two demand points. The basis for the variability in distance traveled between two points occurs due to auto-congestion, differences in pavement types etc.

In practice, planners may use the proposed C.I. to evaluate alternative street network configurations in competition to be implemented in a given residential area and predict how well they would allow an on-demand transit service to perform within the area.

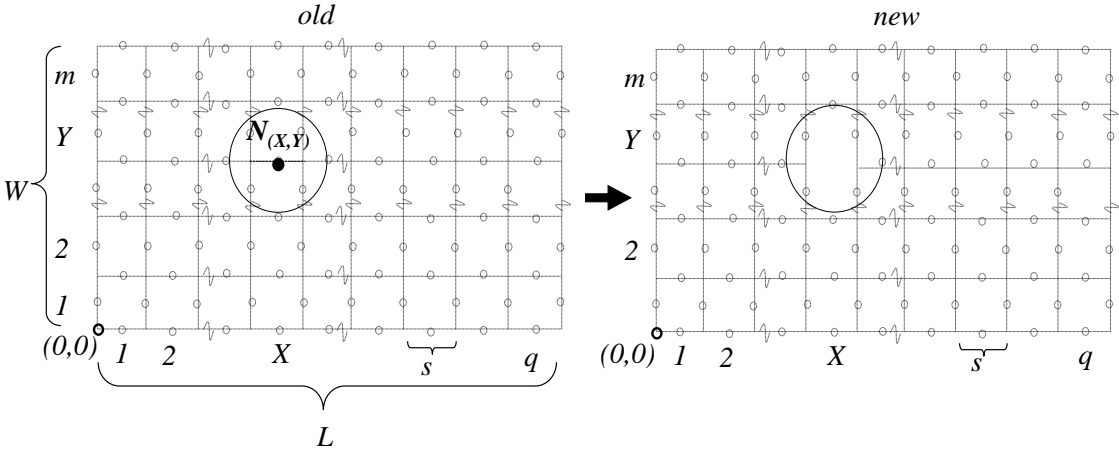
## 4. CRITICAL LINKS IN STREET NETWORKS

### 4.1 Modelling – Street Network Set-up

A general grid street network system is selected with square shaped block size. This choice of a street network would be ideal to analyze as several other forms of street networks such as the rectangular, cul-de-sacs etc. can be constructed by eliminating or adding new links to this uniform grid street network system. Each of the links are identified using different sets of on-demand nodes  $N_{(X,Y)}$  as is shown for one of the horizontal links in Fig. 4.1 (using solid circles in the ‘old’ network while other links are marked as nodes using empty circles). These nodes are such that they represent the pick-up/drop-off points for the passengers in a random demand distribution setting. Mid-block locations are selected for possible shuttle stops, as unnecessary interference with the upstream traffic at the intersections is avoided (Fitzpatrick et al. (1996)). These mid-block stops are called on-demand stops in this study, as the shuttle would only visit these nodes if a service request is made at these nodes. On-demand stop designations at street mid-blocks can also be understood to be average locations of demand on a street.

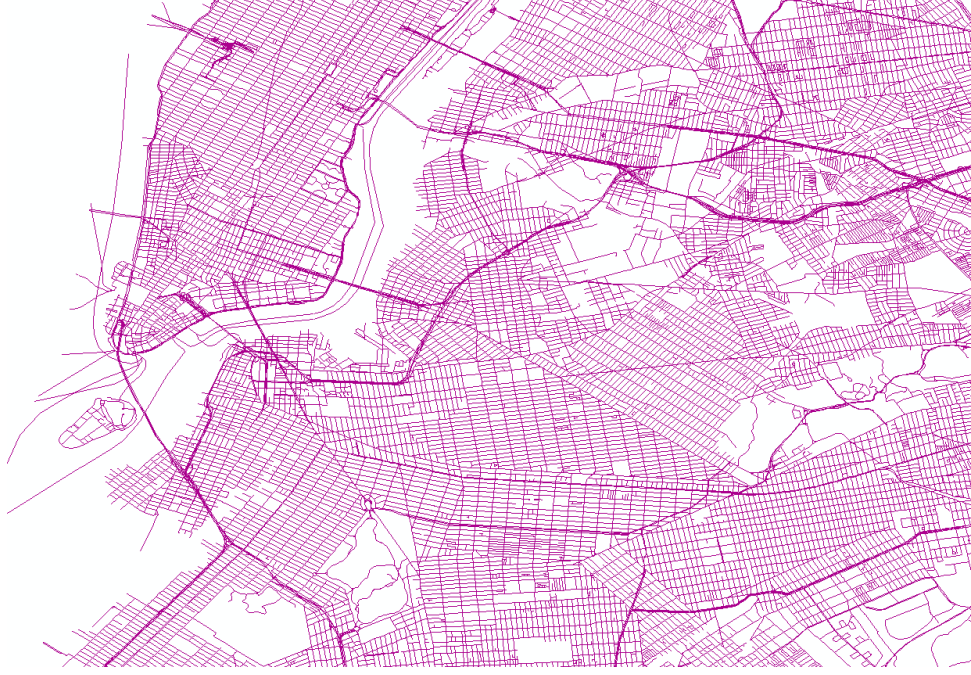
The block size  $s$  of the grid street is such that it is within the desired walking capacity of the passengers to a transit stop. Suitable values of block sizes that could be within a pedestrian walking capacity can be decided based on research results from O’Sullivan and Morrall (1996).

The ‘new’ network in Fig. 4.1 is formed by eliminating one of the horizontal links designated as  $N_{(X,Y)}$  from the ‘old’ network. The notation  $N_{(X,Y)}$  is such that it is located at an horizontal distance of  $(X - 0.5)s$  and a vertical distance of  $(Y - 0.5)s$  from the origin  $(0,0)$  where  $s$  stands for the block length of the network. Thus, we say,  $X \in 1, 2, \dots, q = \left(\frac{L}{s}\right)$  and  $Y \in 1, 2, \dots, m = \left(\frac{W}{s}\right)$ , where,  $L$  and  $W$  are the length and width of the networks.



**Figure 4.1** Removal of a link to create a ‘new’ network from an ‘old’ network

The demand is assumed to be evenly distributed over the street network. Thus, each on-demand node has equal probability of being selected for a demand popping over it. The choice of the grid network shown in Fig. 4.1 is quite a popular pattern of street network found in the United States. The streets of Manhattan serve as a good example for grid streets (see Fig. 4.2).



**Figure 4.2 Grid street system of Manhattan, NY (Source: StreetMap (2011) )**

For a given DRT system, using the concepts introduced in Section 3 – A New Street Connectivity Indicator, the change in  $T$  (which is the sum of total distance among all nodes) is computed using single link removal from the network. A single link removal in this manner causes an elimination of an on-demand node from the network. The change in average distance between remaining on-demand nodes is given by,

$$\Delta = \frac{T_f}{(N-1)(N-2)} - \frac{T_i}{N(N-1)} \quad (4.1)$$

where,  $T_f$  and  $T_i$  are the final and original  $T$ , obtained after the link removal, respectively. Rewriting (4.1), we have,

$$\Delta = \frac{1}{N(N-1)} \left( T_f - \frac{T_i}{\left(1 - \frac{2}{N}\right)} \right) \quad (4.2)$$

For  $N \gg 2$ , the term  $\Delta$  can be approximated as,

$$\Delta \approx \frac{1}{N(N-1)} (T_f - T_i) \quad (4.3)$$

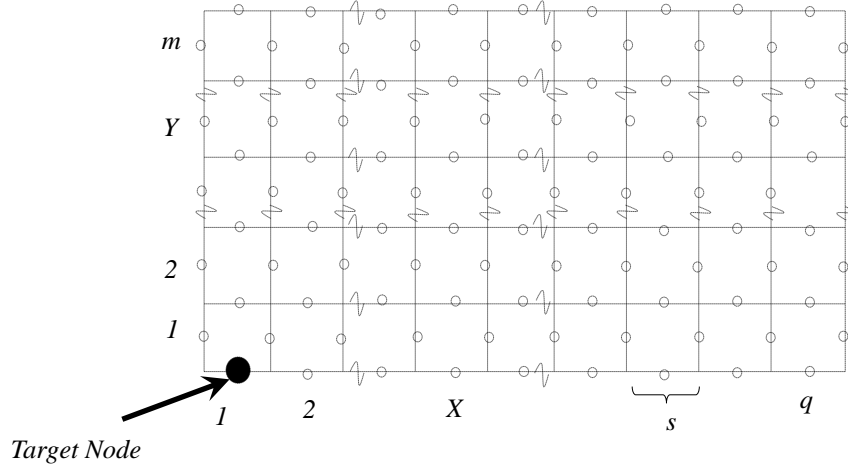
The expression in (4.3) shows that, with number of nodes kept constant, average change in distance between two on-demand nodes in a grid network structure of Fig. 4.1 is directly dependent on change in total distance among all nodes.

There are two ways in which a link can be removed in a grid street network set-up of Fig. 4.1 - a link placed horizontally is removed or a link placed vertically is removed. Now, consider a node labeled as  $N_{(X,Y)}$  is removed from the network. The change in  $T$  consisting of all street based shortest path distances from node  $N_{(X,Y)}$  can be derived. The change is average traveled distance between two on-demand nodes consist of two components decrease in  $T$  (say  $S_{(X,Y)}$ ) and increase in  $T$  ( say,  $R_{(X,Y)}$ ). These are derived in the next sections.

#### 4.1.1 Link Removal – Decrease in Average Travel Distance

Let us define a ‘target’ node to which we compute the sum of total distances from all on-demand nodes. This target node (shown as a solid circle; empty circles are on-demand nodes or just ‘nodes’) is located at the lower horizontal line of the bottom corner grid of the street network system as shown in Fig. 4.3.





**Figure 4.3 Sketch depicting the ‘target’ node in the street network system**

In the sketch of Fig. 4.3, there are a total of  $(2m + 1)$  series of nodes that are distributed horizontally and  $(2q + 1)$  series of nodes distributed vertically. Let  $T_{(2m+1-2k)}$  denote the sum of distances from the target node to a series of ‘unnumbered’ horizontal nodes just above a ‘numbered’ horizontal series  $k$  ( $k \in 0, 1, 2, \dots, m$ ). The last sum being  $T_{(2m+1)}$  for  $k = 0$ . Also, let  $T_{(2m+2-2p)}$  stand for the sum of distances to the target node from ‘numbered’ horizontal nodes  $p$  ( $p \in 1, 2, \dots, m$ ). Thus, the last sum is  $T_{(2m)}$  for  $p = 1$ . Thus, in terms of constant  $m$ , we have,

$$T_1 = \left\langle \frac{q(q-1)s}{2} + s + qms \right\rangle \quad (4.4)$$

$$T_2 = \left\langle \frac{q^2s}{2} + \frac{s}{2} + (q+1)\left(ms - \frac{s}{2}\right) \right\rangle \quad (4.5)$$

:

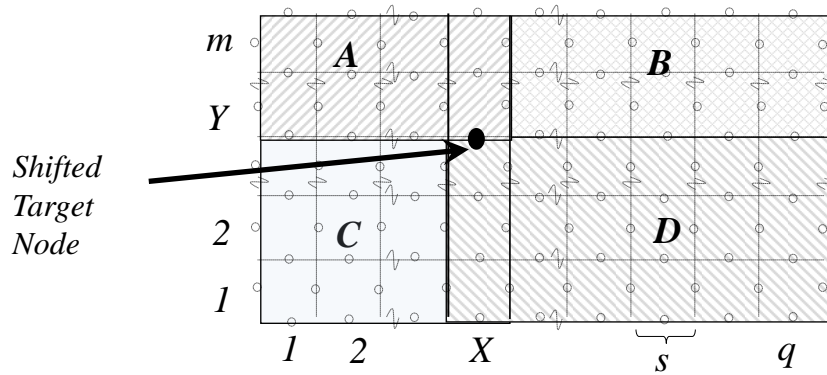
$$T_{2m} = \left\langle \left( \frac{q^2s}{2} + \frac{s}{2} \right) + (q+1) \left( ms - \frac{(2m-1)s}{2} \right) \right\rangle \quad (4.6)$$

$$T_{2m+1} = \left\langle \left( \frac{q(q-1)s}{2} + s \right) + q \left( ms - \frac{2ms}{2} \right) - s \right\rangle \quad (4.7)$$

Thus, summation of all the above terms in  $T_e$  with  $e = 1, 2, \dots, 2m+1$  would give us the sum of all distances from all the nodes of the street network system to the target node. It can be easily computed using some rearrangement of terms as an arithmetic progression series and we can write,

$$\begin{aligned}
 & \sum_{k=0}^m T_{2m+1-2k} + \sum_{p=1}^m T_{2m+2-2p} \\
 &= \sum_{i=1}^{2m+1} T_i \\
 &= \left\langle qm^2s + (m^2s/2) + mq^2s + \frac{3ms}{2} + \frac{q(q-1)s}{2} \right\rangle \quad (4.8)
 \end{aligned}$$

Using the above result for sum of the distances from all nodes of the network to the target node, we can derive a similar expression for the sum of distances from a general on-demand node to all other on-demand nodes. First we notice that we can treat any intermediate node in the network system as a ‘shifted target node’ with the total area divided into four regions such as  $A, B, C$  and  $D$  as shown in Fig. 4.4.



**Figure 4.4** Split regions to create target node for any intermediate node

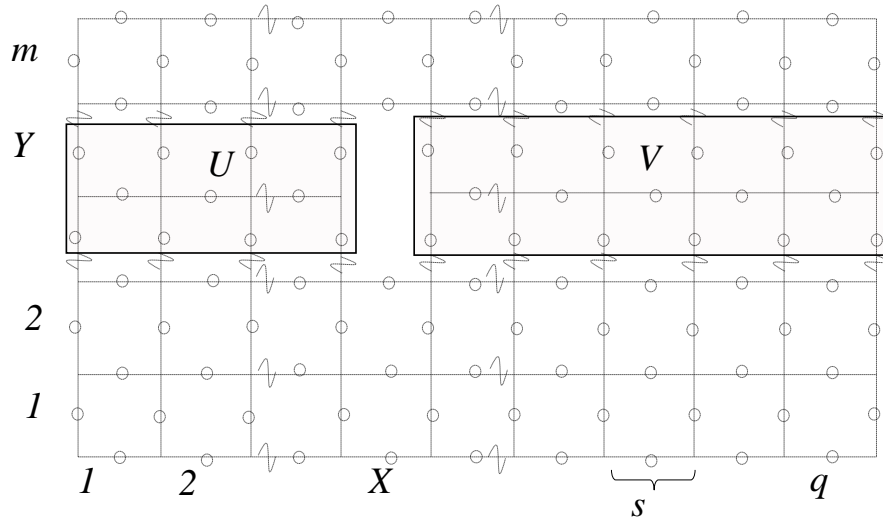
The shifted target node lies such that there is an overlapping area of  $A, B, C$  and  $D$  that needs to be accounted for (see Fig. 4.4). Thus, the sum of distances from all

the nodes of each of the respective four regions (say  $S_{(X,Y)}$ ) to this target node has been derived and written in final form as,

$$\begin{aligned}
S_{(X,Y)} &= (q+2)(m-Y+1)^2s + (m)(q-X+1)^2s \\
&+ (3m+2)s + \frac{(q-X)(q-X+1)s}{2} \\
&+ (q+2)(Y-1)^2s + (m)(X)^2s + \frac{(X-1)Xs}{2} \\
&- \frac{Y(3Y-1)}{2}s - \frac{(3m-3Y+5)}{2}(m-Y+2)s
\end{aligned} \tag{4.9}$$

#### 4.1.2 Link Removal – Increase in Average Travel Distance

Elimination of a link results in increase in total distance for some of the nodes in the network. The sketch in Fig. 4.5 is used to derive the expression for the increase in distance  $R_{(X,Y)}$ .



**Figure 4.5 Identification of nodes for computing  $R_{(X,Y)}$**

Each of the bottommost and topmost nodes aligned horizontally in region  $U$  of Fig. 4.5 is at an increased distance of  $2s$  with the nodes in region  $V$  after the link removal. Thus, there is an overall increase of total distance of  $2X(2s)(q - X) + s$ . For the middle layer of nodes, we have a total increase of  $s$ ,  $2s$  and  $s$  with the top, middle and bottom horizontal aligned nodes of region  $V$  respectively. Thus, there is an overall increase of total distance of  $(X - 1)(s + s)(q - X + 1) + 2s(q - X)$  for the middle horizontal aligned nodes of  $U$ . Similarly, we find the total an increase in distance of nodes of region  $V$ . Using the above discussion,  $R_{(X,Y)}$  (i.e. increase in  $T$  due to a link and on-demand node removal) can be written as,

$$\begin{aligned}
R_{(X,Y)} &= 2X \{2(q - X) + 1\} s \\
&+ 2(X - 1) \{(q - X) + 1\} s \\
&+ 2(X - 1)(q - X) s \\
&+ 2(q - X + 1) \{2(X - 1) + 1\} s \\
&+ 2X(q - X) s + 2(q - X)(X - 1) s \\
&= 4(4qX - 4X^2 + 4X - 2q - 1) s
\end{aligned} \tag{4.10}$$

### 4.1.3 Determination of Critical Link

This section describes the methodology of locating the critical links in the grid network by minimizing net change in distance due to both link and node removal. The net increase in  $T$ ,  $\Delta_d$ , can be written as,

$$\begin{aligned}
\Delta_d &= R_{(X,Y)} - 2S_{(X,Y)} \\
&= 4(4qX - 4X^2 + 4X - 2q - 1)s \\
&\quad - 2(q+2)(m-Y+1)^2s - 2(m)(q-X+1)^2s - 2(3m+2)s \\
&\quad - (q-X)(q-X+1)s - 2(q+2)(Y-1)^2s \\
&\quad - 2(m)(X)^2s - (X-1)Xs \\
&\quad + (Y(3Y-1)s - (3m-3Y+5)(m-Y+2)s)
\end{aligned} \tag{4.11}$$

The multiplier term 2 in equation (4.11) is the back and forth distance which is to be counted twice between the removed node and any other node. For a given constant  $Y$ , the derivative of  $\Delta_d$  with respect to  $X$  gives,

$$\begin{aligned}
\frac{\partial \Delta_d}{\partial X} &= 16qs - 32Xs + 16s + 4(m)(q-X+1)s \\
&\quad + (q-X+1)s + (q-X)s - 4msX - Xs - (X-1)s \\
&= (18q + 4mq + 4m + 18 - 36X - 8mX)s
\end{aligned} \tag{4.12}$$

$$\frac{\partial \Delta_d}{\partial X} = 0 \text{ when } X = \left(\frac{q+1}{2}\right) \text{ and}$$

$$\frac{\partial^2 \Delta_d}{\partial X^2} = -8m - 36 < 0.$$

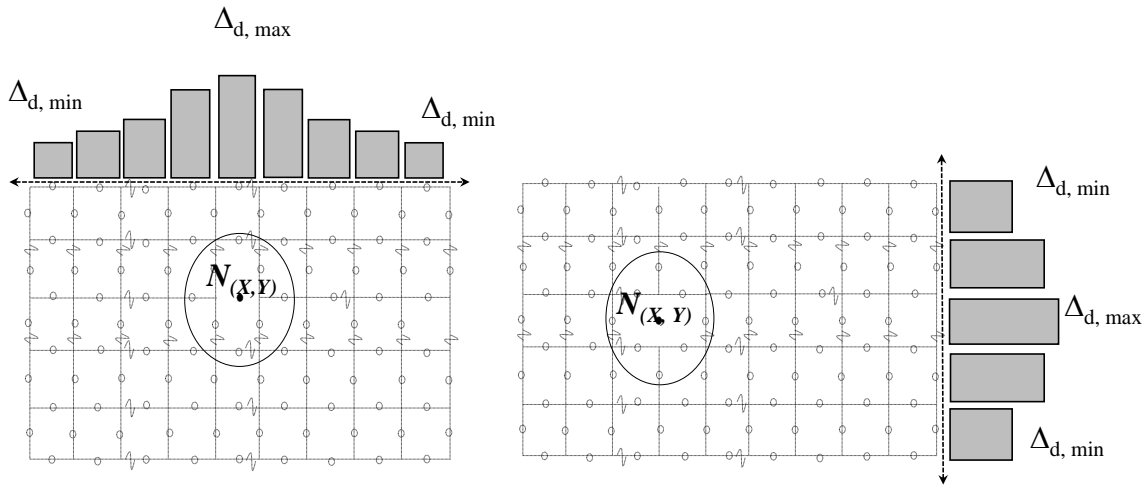
Thus, for a given row (i.e.  $Y$ )  $\Delta_d$  attains a maximum for  $X = \left(\frac{q+1}{2}\right)$ . It can also be noted that the above result holds for an odd  $q$ . Since,  $\left(\frac{q+1}{2}\right)$  is a non-negative integer for any odd number  $q$ . For an even number  $q$ , we carry out the analysis in slightly different manner. It can be observed that for a continuous discrete variable  $X$ , the expression for  $\Delta_d$  is a discrete convex function and has a maximum at  $X = \left(\frac{q+1}{2}\right)$ . Thus,  $\Delta_d$  would attain a maximum for an even  $q$  at  $X = \left(\frac{q}{2}\right)$  or  $X = \left(\frac{q}{2} + 1\right)$  or both. Denoting the terms in  $Y$  and other constant terms as  $f(Y)$  in expression

(4.11), a quick check can be done for one of the two values of  $X$  that would give a maximum . Observe that both for  $X = \left(\frac{q}{2}\right)$  and  $X = \left(\frac{q}{2} + 1\right)$  equal expressions of  $\Delta_d$  are obtained as

$$\begin{aligned}\Delta_d &= 4(q^2 - 1)s - 2m\left(\frac{q}{2}\right)^2 s - \left(\frac{q}{2}\right)^2 \\ &\quad - \left(2m\left(\frac{q}{2}\right)^2 + 2mq + 2m\right)s - \left(\frac{q}{2}\right)^2 + f(Y) \\ &= \left(\frac{7q^2}{2} - mq^2 - 2mq - 2m - 4\right)s + f(Y)\end{aligned}\tag{4.13}$$

Further, if we fix  $X$  as constant and find the derivative of  $\Delta_d$  with respect to  $Y$  in (4.11),  $\Delta_d$  attains a maximum at  $Y = \left(\frac{m}{2} + 1\right)$  and  $Y = \left(\frac{m}{2}\right)$  for even  $m$  and at  $Y = \left(\frac{m+1}{2}\right)$  for odd  $m$ . This result follows from the symmetry of the street network structure along with the positions of the on-demand nodes.

For a given row in the network system of Fig. 4.1 (i.e. given  $Y$ ), attains a maximum for  $X = \left(\frac{q+1}{2}\right)$  and for an odd  $q$ . For an even number  $q$ , would attain a maximum both for  $X = \left(\frac{q}{2}\right)$  and  $X = \left(\frac{q}{2} + 1\right)$ . Further, if we fix  $X$  as constant,  $\Delta_d$  attains a maximum at  $Y = \left(\frac{m}{2} + 1\right)$  and  $Y = \left(\frac{m}{2}\right)$  for even  $m$  and at  $Y = \left(\frac{m+1}{2}\right)$  for odd  $m$ . This result also follows from the symmetry of the street network structure. For illustration , the solid bars (not to scale) in Fig. 4.6 represent an approximate magnitude of the variation of  $\Delta_d$  from  $\Delta_{d,\max}$  to  $\Delta_{d,\min}$  individual link closure along the cross-section (both horizontal and vertical) of the network for an odd  $q$  and odd  $m$ .

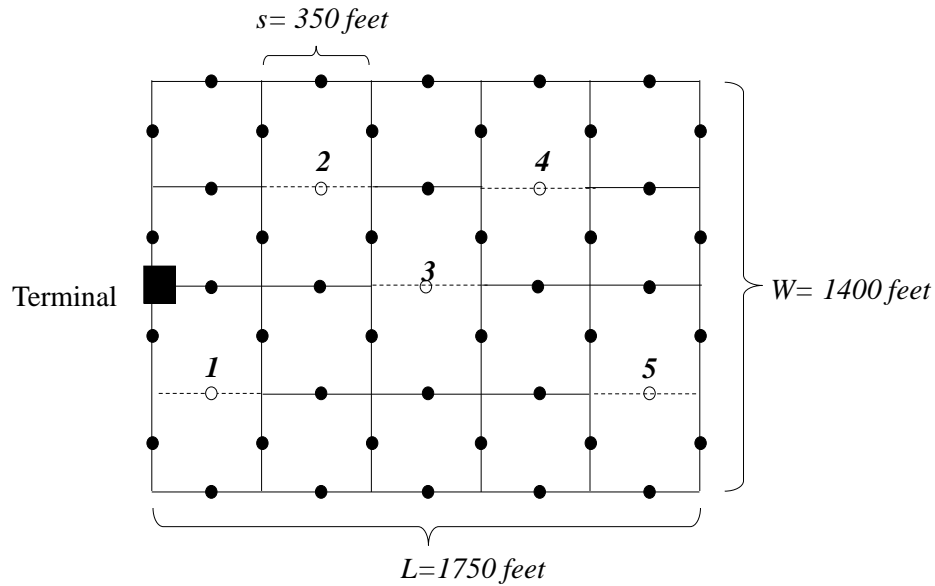


**Figure 4.6 Variation of  $\Delta_d$  along the cross-section of the street network**

It can also be observed that in situations when two or more combination of links are simultaneously eliminated from the ‘old’ network of Fig. 4.1, the resulting reduction in vehicular performance would be maximum when most of the central links are removed. However, we leave this discussion as our future research area.

## 4.2 Simulation Experiments

We present some simulation results that validate the determination of critical links as shown above. A finite size grid street network with identical blocks (as the old network of Fig. 4.1) is selected with some random links being removed in a sequence each time 1-2-3-4-5 (see Fig. 4.7). Hence, five different networks (in each a link missing) were used in the simulation.



**Figure 4.7 Sequential link closures/removals 1-2-3-4-5 to create five different sets of street networks**

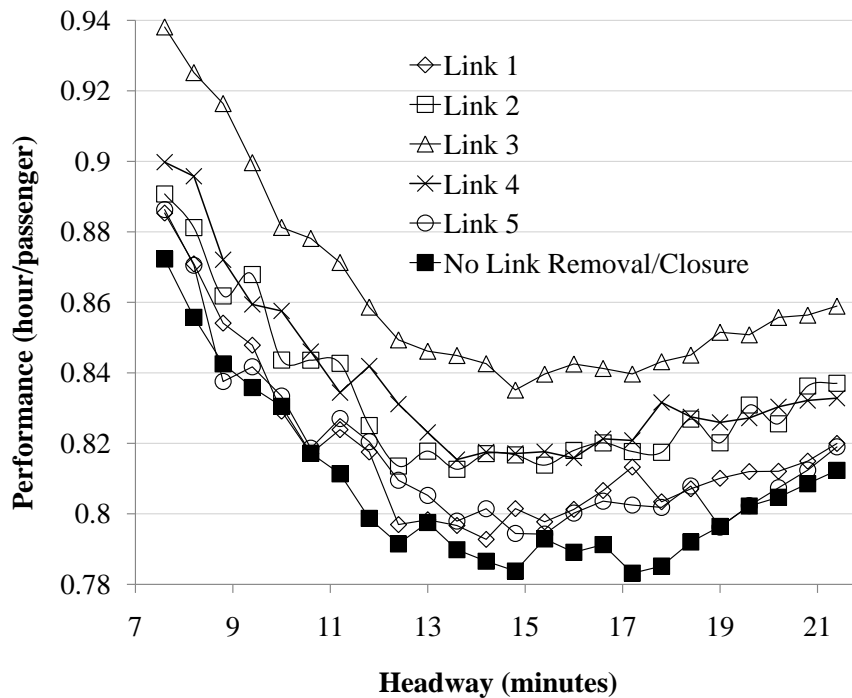
A hypothetical DRT service that runs for a variable headway of 7 minutes to 21 minutes (assumed), serving a daily passenger demand of 350 (assumed) within a rectangular area of  $L = 1750$  feet,  $W = 1400$  feet and  $s = 350$  feet (block size for Hempstead street network), is put in operation in all the five different grid networks (see Fig. 4.7). The DRT service operation times are fixed from 6:30 am to 9 pm, generally found for most demand responsive transit systems. The passengers make random service requests generated from a typical travel demand hours of US commuters as used in Section 3.3 under Simulation Results and Discussion section.

The requests for service usage are accepted between 6 am through 8:30 pm on phone or internet. These requests are randomly assigned as pick-up or drop-off requests. The requests for service usage are accepted on phone or internet. The spatially random service requests (within a given headway) are distributed uniformly over the on-demand nodes. These requests for service are either pick-up or drop-off with a fixed DRT terminal. The order of pick-up/drop-off of passengers, within each of the headways, is carried out using insertion heuristic (Quadrifoglio et al.



(2007)). The street based shortest path distance between two nodes is computed using Dijkstra's algorithm coded in MATLAB R2008b ( MATLAB (2009)).

The DRT performance can generally be identified as a combination of operating costs and service quality. The service quality is expressed as passengers' disutility: a weighted sum of expected waiting time and expected in-vehicle travel time (in the ratio of 1:1.8) typically used for any DRT service (Wardman (2004)). The performance values were obtained from an average of ten numbers of replications for each of the five networks for different links removed and is shown below in Fig. 4.8.



**Figure 4.8 Performance effects on DRT for the sequential link closures/removals**

The chart in Fig. 4.8 shows that the removal of Link 3 results in an increase in the average waiting and riding time of the passengers the most. Link 1 and Link 2 case removal conditions show a very close resemblance in performance with Link 4 and Link 5 case removals, respectively; while for a 'no link removal/closure' condition

the performance of the transit shuttle is the best. Thus, simulation results validate our analytical modeling of the critical link(s) identification when  $q$  (or  $m$ ) is odd.

### 4.3 Summary and Research Contribution

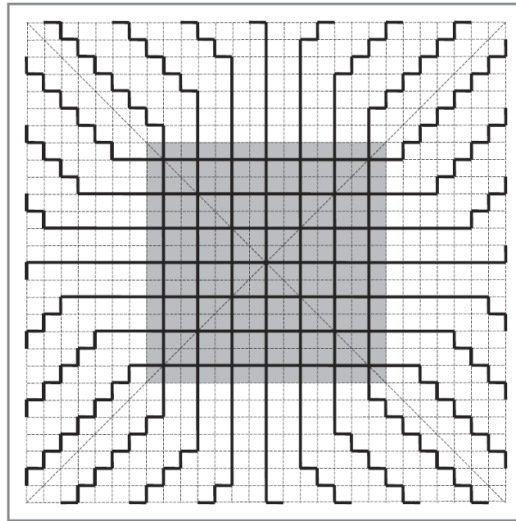
This part of the dissertation presents a simple, yet profound, methodology to identify and locate critical links in a grid street network system (of any size) for feeder transit services. A ‘critical’ link can be defined as that link which when eliminated from, or appended to, an existing network would cause the largest change in the network connectivity and consequently change in the transit performance. This study does away with exhaustive computations or approximations that have been carried out for similar research on networks over the years. Easily computable formulas have been provided and validated by simulation analysis. Useful insights indicate a monotonic decrease in link criticality as we depart from the centrally located links to those located at boundaries. The above findings have been validated by simulation experiments for the street network from the town of Hempstead, Texas. Though, this work mainly focuses on studying a grid network system, a large form of other network structures such as cul-de-sacs, rectangular etc. can be analyzed using a similar logic presented in this study.

## 5. OPTIMAL GRID STREET NETWORKS

### 5.1 Background

Studies related to grid network optimization are plenty as they are particularly useful for many cities in North America and also other parts of the world. Terms like efficient and optimal spacings have already been described and investigated with respect to square and rectangular grid networks in several literatures (Fawaz and Newell (1976a,b), Miyagawa (2009)). The basic methodology involved the minimization of the sum of travel and construction costs.

Hybrid network models have been developed by Aldaihani et al. (2004) integrating a flexible demand responsive service with a fixed route service. Using the model an optimal number of zones are decided that are served by the flexible on-demand vehicles. From connectivity point, mathematical programming has often been used in network design generating sets of feasible routes connecting nodes (Ceder and Israeli (1998)). Current et al. (1986) have analyzed hierarchical networks by formulating the problem as integer programming. Besides, several heuristic methods have been developed for computing optimal values for network design problems (Balakrishnan et al. (1994), Baaj and Mahmassani (1995)). An iterative procedure by Lee and Vuchic (2005) used set of routes composed by the shortest paths for all the origin–destination pairs over the network by eliminating the less efficient ones. Several researchers have propose that having a hybrid street systems consisting of hub-spoke and grids are the most efficient transit networks (Daganzo (2010), Nourbakhsh and Ouyang (2012), Estrada et al. (2011)). The image in Fig. 5.1 shows the proposed hybrid network. However, the sensitivity on the variability of street spacing on performance measure is not discussed.



**Figure 5.1** A hybrid network structure (adapted from Nourbakhsh and Ouyang (2012), and Daganzo (2010))

## 5.2 DRT Operational Challenges

Transit shuttles, which also move from point to point for passenger pick-up/drop-off, rely on good accessibility and connectivity of the street network. Often transit operators try to offset unfavorable street configurations by use of best scheduling algorithms to maximize chances of a timely passenger pick-up/drop-off. However, the most challenging part is selecting an appropriate algorithm to carry out the scheduling for passenger pick-up/drop-off in a most efficient manner. Decisions regarding the sequence of pick-up/drop-off of passengers for DRT becomes challenging as the problem is similar to a TSP-known to be NP-hard.

Wiransinghe and Liu (1995) showed that the optimal design of a schedule is very sensitive to the passenger demand patterns along the route. Several heuristic methods exist for scheduling passenger pick-up/drop-offs (Jaw et al. (1986); Quadrifoglio et al. (2007)). Barr et al. (1995) has provided reporting guidelines for computational experiments to test some of the heuristic methods. Quadrifoglio and Li (2009) pro-

vided a strategy of scheduling pick-up/drop-off passengers using rectilinear metric closely representing streets.

In this part of research, we use insertion heuristics to demonstrate passenger pick-up/drop off for scheduling in the simulations used Insertion heuristic is easy to code and understand and the results can be validated with certain accuracy by manual calculations as well (Campbell and Savelsbergh (2004)). Insertion heuristic outputs for lower demands are quite comparable to optimal values obtained from CPLEX or any other optimization software. This will be demonstrated in more detail under Section 6.

### 5.3 Design Framework

Among all modes that could find using a given grid street systems, the primary focus of this study is in giving priority to facilitating street designs for transit. This is simply because other than walking and biking, which are mostly promoted in planning for a livable community, transit is always the prime focus of study popularly in the form of a transit oriented development.

The model framework consists of using connectivity indicator (CI) introduced by Chandra and Quadrifoglio (2012) and designed especially to reflect performance measure of a demand responsive transit system. The performance measure of a DRT operating within a residential area was shown to be proportional to the CI. The choice of the connectivity indicator is justified as it considers, besides node-to-node distance, the existing demand density at each node and makes it of superior choice to most others that exist in literature. The connectivity indicator for a total of  $N$  on-demand nodes or DRT stops each placed at the mid-street block is expressed as having the following relationship,

$$CI \propto \left( \sum_i \left[ \frac{\lambda_i}{\sum_i \lambda_i} \left( \frac{\sum_j \lambda_j d_{ij}}{\sum_j \lambda_j} \right) \right] \right)^{-1} \quad (5.1)$$

where,  $\lambda_i$  is the demand per day or demand rate at  $i^{th}$  node and  $d_{ij}$  is the shortest path between  $i$  and  $j$  with  $d_{ij} = d_{ji} \forall i, j \in \{1, 2, \dots, N\}, j \neq i$ .

In this study, we restrict our analysis to a DRT service operating within a residential area especially with mixed-use where traffic signals are rarely encountered but the vehicle would need to stop for pedestrians often at an intersection required by law. Most residential street patterns follow the grid-form of street networks simply as they are both pedestrian and vehicle friendly. As it has been mentioned earlier under Section (3.1.2), it is noted again that grid street patterns give plenty of route options for trips if covered by walking, transit or by using a private vehicle (Kostof (1991)). The maximum transit performance is reached as this layout provides multiple route options.

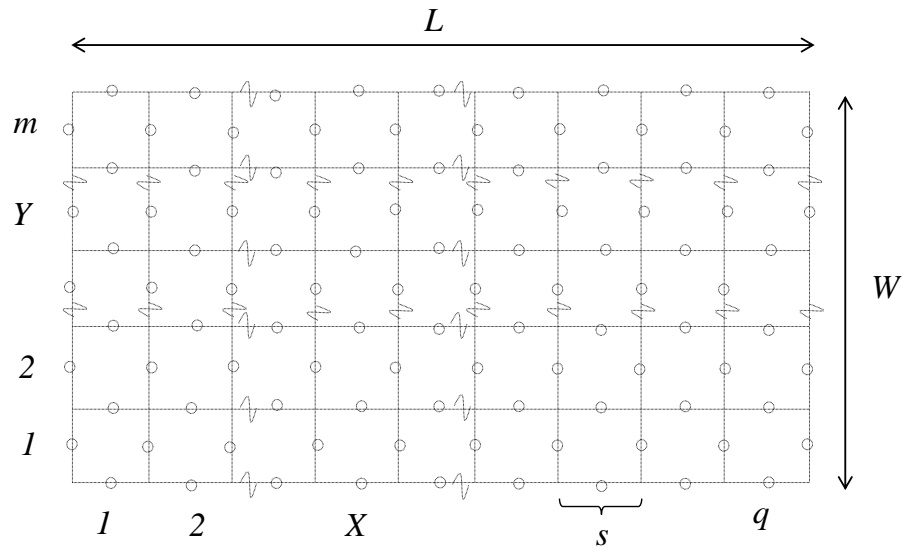
Siksna (1997) did a comparative study of block size. Twelve North American and Australian city centers were studied to analyze the effect of subsequent urban development. Performance evaluation for each of the block and layout pattern was reported in which certain block forms and dimensions performed better than the others. Performance was primarily based on the circulation provided by different block sizes. In this regard, the smaller blocks function better as compared to larger blocks, because a greater circulation is produced by finer-mesh resulting from smaller blocks. Table 5.1 lists some of the different street lengths from different parts of the world (Cardillo et al. (2006))

A prototype of grid network is considered having block length  $s$  with on-demand nodes as shown in Fig. 5.2. Variables  $q \approx \left(\frac{L}{s}\right)$  and  $m \approx \left(\frac{W}{s}\right)$ . These on-demand nodes are located on an average at the middle of each street and serve as potential stops for the DRT shuttle. Besides this, a mid-block stop is considered safest for

**Table 5.1 Average street length from different cities of the world**

	City	Average street length (feet)
1	Ahmedabad	90.50
2	Barcelona	367.39
3	Bologna	217.33
4	Brasilia	440.80
5	Cairo	122.90
6	Irvine1	1023.59
7	Irvine2	420.69
8	Los Angeles	373.49
9	London	237.24
10	New Delhi	316.72
11	New York	283.16
12	Paris	292.87
13	Richmond	189.09
14	Savannah	212.45
15	Seoul	170.95
16	San Francisco	462.18
17	Venice	102.50
18	Vienna	236.68
19	Washington	393.40
20	Walnut Creek	418.43

passengers/pedestrians and does not involve DRT vehicle's interference with the nearby intersection.



**Figure 5.2 Grid street system with on-demand stops.**

## 5.4 Modeling

### 5.4.1 Street Design for DRT Shuttle

The relationship in (5.1) can be simplified by assuming a spatially uniform and independent demand distribution over the service area for a grid street system. Under the assumption when  $\lambda_i = \lambda_j$  the right hand side of (5.1) expresses ‘impedance’ in terms of distance cost experienced by the DRT feeder shuttle in travelling between  $i$  and  $j$ . Alternatively, we can also write (5.1) as,

$$CI \propto (I_{imp})^{-1} \quad (5.2)$$

The impedance ( $I_{imp}$ ) is composed of geographical distance traversed between an origin and destination points, number of intersections encountered, congestion etc. during shuttle travel. In fact, the best representation of impedance in such cases is by measuring the total ‘travel time’ during the shuttle service. This is because



travel time can be directly related to headway which can be linked directly to DRT performance (Quadrifoglio and Li (2009)). With each intersection encountered, there is always some time lost in traveling between two points on a network. The vehicle is expected to halt at the ‘stop’ sign required by law and in some instances the DRT shuttle might even has to wait for ‘green time’ if a traffic signal is present. Therefore, the average impedance ( $I_{imp}$ ) should exhibit the following relationship,

$$I_{imp} \propto \left( \frac{1}{N(N-1)} \sum_i \sum_j \left( d_{ij} + \frac{tVd_{ij}}{s} \right) \right) \quad (5.3)$$

where,  $t$  is the stop time at an intersection (or stop) and  $V$  is the average speed of the shuttle. This simply means that the DRT performance is also directly proportional to  $I_{imp}$ .

Accessibility to a transit stop, which is related to average distance walked by passengers, also plays a crucial in determining the success of DRT and hence, is also a proxy for performance. Accessibility can be used as an indicator of transit performance. A good accessibility becomes important especially for other modes of transportation as well such as walking and biking by ordinary pedestrians. Irrespective of the kind of street pattern present in a community, accessible origin and destination points by walking for pedestrian/passenger should not be more than a quarter-mile (Song and Knaap (2004)). Although a DRT, ideally, aims to provide a door-to-door service, streets having longer block lengths often pose constraints to how closest the shuttle can reach a passenger’s origin/destination points. Thus, streets that have longer block lengths, on an average, would require greater passenger walking than those with shorter block lengths. Thus, to appropriately account for the restrictions imposed by streets to passenger walking, a penalty function can be used to revise impedance associated with DRT operations in (5.3). This is achieved by using a “penalty-function” expression in (5.4) which shows that with every quarter-

mile of distance that a passenger could walk along the streets, a steady decline in DRT service standards (performance) would occur.

$$\text{Penalty Function} = \left( \frac{1}{0.25 - A_W} \right)^\theta \quad (5.4)$$

where,  $\theta$  is parameter that needs to be calibrated and  $A_W (< 0.25)$  is the average walking distance to the closest on-demand stop within a quarter-mile walking distance. The sketch in Fig. 5.3 shows a passenger's average value of walking distance to an on-demand stop i.e.  $A_W = \left(\frac{s}{4}\right)$

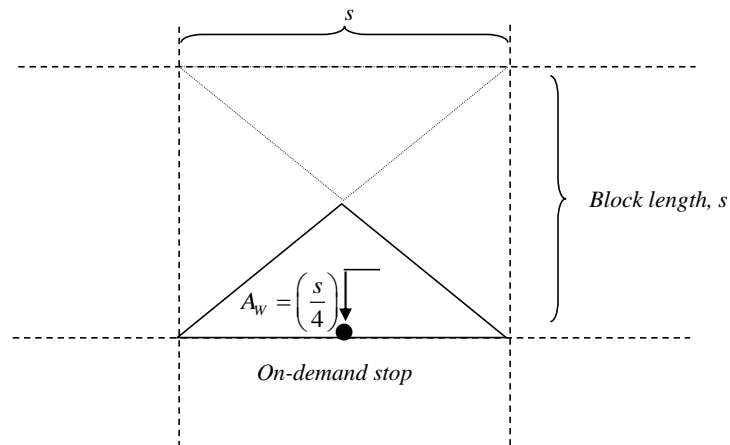


Figure 5.3 Computation of  $A_W$  within a block

#### 5.4.2 Street Design for Pedestrians

Livability standards of a community cannot be fully achieved without considering the built environment suitable for pedestrian comfort. This amounts to incorporating reasonable walking distances that would be associated with the selected block size in street designs. Research findings by Hess et al. (1999) showed that the urban sites with small blocks had, on average, three times the pedestrian volumes than the suburban sites with large blocks. Moudon et al. (1997) also support this in an-

other study for urban versus suburban difference in pedestrian facilities provided due to block size and sidewalk length affects pedestrian volumes. There are studies that demonstrate statistically significant relationships between types and extent of infrastructure and the total vehicles mile traveled (Cervero and Gorham (1995), Cervero and Kockelman (1997)). These studies also highlight the effect of neighborhood designs on travel mode choice.

Unfavorable walking scenarios such as adverse weather conditions, too many streets to cross or having to climb stairs along the walk path can often be unpleasant. Quantification of these unpleasant and unfavorable scenarios is not easy in travel modeling. Wibowo and Olszewski (2005) use the concept of equivalent walking distance to precisely address this discomfort in walking between origin and destination. The equivalent distance is expressed as the weighted sum of the actual walking distance and number of street crossings that a pedestrian has to do within. Equivalent walking distance ( $E_w$  in miles) at an intersection can be written as,

$$E_w = 0.25 + 0.00062(N_C) \quad (5.5)$$

where,  $N_C$  is the number of crossings whose average value within a grid street network is approximately  $\left(\frac{0.25}{s}\right)$ .

## 5.5 Block Design – Objective Function

A grid street system with longer block lengths and having limited street connections would cause too much of DRT shuttle driving to serve passengers that are spread far apart. Longer block length also causes an increase in passenger walking distance to reach a transit stop. Too short block lengths, on the other hand, result in an increase in the number of intersections encountered with large number of stops acting as impedance for the DRT shuttle. For shorter block lengths pedestrians have

to watch for any vehicle they might encounter at an intersection, which add to pedestrian discomfort. Intuitively there must be an optimal block length that causes a minimal discomfort, disutility or under performance to a DRT shuttle, passengers or pedestrians. Therefore, the factors that are directly related to transit performance and pedestrian comfort can be expressed as an objective function consisting of minimizing the total impedance. Thus, the objective function (minimization of  $Z_1$ ) can be written in a general form as,

Min  $Z_1 =$  DRT shuttle performance (in terms of cycle time) + Passenger comfort + Pedestrian comfort

Specifically, using various expressions for the general minimization function, we can write

$$\begin{aligned} Min(Z_1) = & \beta_1 \left( \frac{1}{V} \right) \left( \frac{1}{N(N-1)} \sum_{i=1}^N \sum_{j=1}^N \left( d_{ij} + \frac{tVd_{ij}}{s} \right) \right) \\ & + \beta_2 \left( \frac{1}{0.25 - A_W} \right)^\theta \\ & + \beta_3 \left( \frac{1}{V_w} \right) (0.25 + 0.00062N_C) \end{aligned} \quad (5.6)$$

where,  $V_w$  is the average walking speed of a pedestrian. The terms  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  are the respective weights/costs associated with the DRT's travel time impedance, passenger discomfort in walking used as a penalty function to the nearest on-demand stop and a pedestrian's equivalent walking distance. The value of parameter  $\theta$  is assumed to be 1 in this study. The decision variable for (5.6) is the block length  $s$ . The constraints are embedded into the objective function (5.6) itself as it's easier to derive a closed form expression for an optimal block length as shown later in the subsequent sections.

### 5.5.1 Rigorous Solution

For a grid street network (as shown in Fig. 5.2), it is possible to obtain a closed form expression for the impedance. The result follows from the work of Chandra et al. (2011) where a closed form expression for the total distance from a ‘target node’ (say, located at  $((X - \frac{1}{2})s, (Y - \frac{1}{2})s)$ ) to all other nodes in a network has been derived (see Fig. 5.3). Thus, the expression for the total sum of all distances  $S_{(X,Y)}$  from the target node to all other nodes is,

$$\begin{aligned}
S_{(X,Y)} &= (q+2)(m-Y+1)^2s + m(q-X+1)^2s + (3m+2)s \\
&+ \frac{(q-X)(q-X+1)s}{2} + (q+2)(Y-1)^2s + (mX)^2s \\
&+ \frac{(X-1)Xs}{2} - \frac{Y(3Y-1)}{2}s - \frac{(3m-3Y+5)}{2}(m-Y+2)s \quad (5.7)
\end{aligned}$$

To compute a closed form of the right hand side of impedance in (5.3), we need to treat every on-demand node in the network as a target node and compute the sum. Let  $S_{(m,n)}$  be the total sum of all distance impedance from all on-demand nodes of networks shown in Fig. 5.2. Therefore,

$$S_{m,n} = \sum_i \sum_j \left( d_{ij} + \frac{tVd_{ij}}{s} \right) \quad (5.8)$$

$$= \left( 1 + \frac{tV}{s} \right) \sum_i \sum_j d_{ij} \quad (5.9)$$

$$= \left( 1 + \frac{tV}{s} \right) S_H \quad (5.10)$$

Writing  $S_H$  as,

$$\begin{aligned}
S_H = \sum_{Y=1}^{m+1} \sum_{X=1}^q & \left( (q+2)(m-Y+1)^2 s + m(q-X+1)^2 s + (3m+2)s \right. \\
& + \frac{(q-X)(q-X+1)s}{2} + (q+2)(Y-1)^2 s \\
& + (mX)^2 s + \frac{(X-1)Xs}{2} - \frac{Y(3Y-1)}{2} s \\
& \left. - \frac{(3m-3Y+5)}{2} (m-Y+2)s \right)
\end{aligned} \tag{5.11}$$

$$\begin{aligned}
= \sum_{Y=1}^{m+1} & \left( (q+2)(m-Y+1)^2 sq + (m) \frac{(q)(q+1)(2q+1)}{3} s + 3msq \right. \\
& + \left( \frac{(q)(q+1)(2q+1)s}{6} \right) - \frac{(q)(q+1)s}{2} \\
& + (q+2)(Y-1)^2 sq \\
& - (Y^2 - Y)sq - \frac{(Y^2 + Y)sq}{2} - (m-Y+1)(m-Y+1+1)sq \\
& \left. - \frac{(m-Y+2)(m-Y+2+1)sq}{2} + 2sq \right)
\end{aligned} \tag{5.12}$$

$$\begin{aligned}
&= \left( \frac{(q+2)(m)(m+1)(2m+1)sq}{6} + \frac{(m)(m+1)(q)(q+1)(2q+1)s}{3} \right. \\
&\quad + 3(m)(m+1)sq + \frac{(q)(q+1)(2q+1)(m+1)s}{6} - \frac{(q)(q+1)(m+1)s}{2} \\
&\quad + \frac{(q+2)(m)(m+1)(2m+1)sq}{6} - \frac{(m+1)(m+2)(2m+3)sq}{6} \\
&\quad + \frac{(m+1)(m+2)sq}{2} - \frac{(m+1)(m+2)(2m+3)sq}{12} \\
&\quad - \frac{(m+1)(m+2)sq}{4} - \frac{(m)(m+1)(2m+1)sq}{6} - \frac{(m)(m+1)sq}{2} \\
&\quad \left. - \frac{(m+1)(m+2)(2m+3)sq}{12} - \frac{(m+1)(m+2)sq}{4} + 2sq(m+1) \right)
\end{aligned} \tag{5.13}$$

On simplifying (5.13), we get,

$$\begin{aligned}
S_H = (m+1) &\left( \frac{(2q+3)(m)(2m+1)sq}{6} + \frac{(2m+1)(q)(q+1)(2q+1)s}{6} \right. \\
&\quad \left. + \frac{(5m+4)sq}{2} - \frac{(q)(q+1)s}{2} - \frac{(m+2)(2m+3)sq}{3} \right)
\end{aligned} \tag{5.14}$$

The expression in (5.14) holds true for all nodes which are on horizontally placed street links in Fig. 5.2, the sum of total distances for nodes placed in the vertical links (say,  $S_V$ ), obtained by replacing  $q$  with  $m$  and  $m$  with  $q$  respectively in (5.14). Thus,

$$S_V = (q+1) \left( \frac{(2m+3)(q)(2q+1)sm}{6} + \frac{(2q+1)(m)(m+1)(2m+1)s}{6} \right. \\ \left. + \frac{(5q+4)sm}{2} - \frac{(m)(m+1)s}{2} - \frac{(q+2)(2q+3)sm}{3} \right) \quad (5.15)$$

Rewriting the term  $S_{(m,n)}$  as  $s \left(1 + \frac{tV}{s}\right) (S_H + S_V)$ , and we have,

$$S_{(m,n)} = s \left( 1 + \frac{tV}{s} \right) \left[ \frac{mq}{6} ((2m+3)(2q+1)(q+1) + (2q+3)(2m+1)(m+1)) \right. \\ + \frac{(m+1)(q+1)}{6} ((2q+1)(m)(2m+1) + (2m+1)(q)(2q+1)) \\ + \frac{1}{2} ((5q+4)(q+1)m + (5m+4)(m+1)q) \\ - \frac{(q+1)(m+1)(m+q)}{2} - \frac{1}{3} ((q+2)(2q+3)(q+1)m \\ \left. + (m+2)(2m+3)(m+1)q) \right] \quad (5.16)$$

The correctness of the expression in (5.16) has been verified with several variables of  $m$  and  $n$ . Besides the expression for  $(S_H + S_V)$  reduces to With  $N_C = \left(\frac{0.25}{s}\right)$ ,  $A_W = \left(\frac{s}{4}\right)$ , and  $N = \frac{L(W+s)+(L+s)W}{s^2}$  the expression for  $Z_1$  in (5.6) can be rewritten as,

$$\min Z_1 = \beta_1 \left( \frac{1}{V} \right) \left( \frac{S_{(m,n)}}{\left( \frac{L(W+s)+(L+s)W}{s^2} \right) \left( \frac{L(W+s)+(L+s)W-s^2}{s^2} \right)} \right) \\ + \beta_2 \left( \frac{4}{1-s} \right) + \beta_3 \left( \frac{1}{V_w} \right) \left( 0.25 + \frac{0.00015}{s} \right) \quad (5.17)$$



On substituting for  $S_{(m,n)}$  from (5.16) into (5.17), yields

$$\begin{aligned} \min Z_1 = & \beta_1 \left( \frac{1}{V} \right) \left( 1 + \frac{tV}{s} \right) \left[ \frac{s}{3} + \frac{(L+W)}{3} \right. \\ & \left. + \frac{(s^2 LW(L+W) + 2LW s^3)}{(4L^2 W^2 + s(4L^2 W + 4LW^2) + s^2(L^2 + W^2) - s^3(L+W))} \right] \\ & + \beta_2 \left( \frac{4}{1-s} \right) + \beta_3 \left( \frac{1}{V_w} \right) \left( 0.25 + \frac{0.00015}{s} \right) \end{aligned} \quad (5.18)$$

A graphical solution can be obtained for (5.18) to estimate optimal block length for a minimum  $Z_1$ . For an extreme case when  $s \rightarrow 0$  and also using  $t = 0$ , the  $\left( \frac{S_H + S_V}{\left( \frac{L(W+s) + (L+s)W}{s^2} \right) \left( \frac{L(W+s) + (L+s)W - s^2}{s^2} \right)} \right)$  term in (5.18) reduces to finding an average Euclidean distance between two uniformly random distributed demands in a rectangle which is  $(L+W)/3$ . This serves as a quick check on the derivation of the average distance that the DRT shuttle would travel in an ideal situation with using Euclidean distance metric with no stops at intersections.

### 5.5.2 Approximation to Rigorous Solution

Obtaining a closed form for an optimal block length from (5.18) is not trivial due to an improper fraction present in the first term. However, approximations can be made for the terms in (5.18) with some reasonable assumptions. Therefore, we assume  $\left( \frac{s}{3} + \frac{(L+W)}{3} \gg \frac{(s^2 LW(L+W) + 2LW s^3)}{(4L^2 W^2 + s(4L^2 W + 4LW^2) + s^2(L^2 + W^2) - s^3(L+W))} \right)$  since the right hand side fraction of the inequality is smaller due to denominator being large in magnitude with high powers of  $L$  and  $W$ . Thus, (5.18) can be approximated as,

$$\begin{aligned} \min Z_1 = & \beta_1 \left( \frac{1}{V} \right) \left( 1 + \frac{tV}{s} \right) \left[ \frac{s}{3} + \frac{(L+W)}{3} \right] \\ & + \beta_2 \left( \frac{4}{1-s} \right) + \beta_3 \left( \frac{1}{V_w} \right) \left( 0.25 + \frac{0.00015}{s} \right) \end{aligned} \quad (5.19)$$

The chart in Fig. 5.4 shows a negligible difference between the rigorous expression from (5.18)

$$\left( \text{where, } A = \left( \frac{1}{V} \right) \left( 1 + \frac{tV}{s} \right) \left( \frac{s}{3} + \frac{(L+W)}{3} + \frac{(s^2 LW(L+W) + 2LW s^3)}{(4L^2 W^2 + s(4L^2 W + 4LW^2) + s^2(L^2 + W^2) - s^3(L+W))} \right) \right)$$

and approximate relationship from (5.19)

$$\left( \text{where, } B = \left( \frac{1}{V} \right) \left( 1 + \frac{tV}{s} \right) \left( \frac{s}{3} + \frac{(L+W)}{3} \right) \right)$$

for the first term representing shuttle performance in  $Z_1$ . The dimension of the rectangular service area used in Fig. 5.4 have (lengths, widths) with four example cases – *Case1*: (8000 feet, 4000 feet), *Case2*: (9000 feet, 5000 feet), *Case3*: (10000 feet, 6000 feet) and *Case3*: (11000 feet, 7000 feet). The intersection stop time is assumed to be  $t = 2$  seconds and  $V = 20$  mph.

Differentiating (5.19) with respect to  $s$  gives,

$$\frac{dZ_1}{ds} \approx \beta_1 \left( \left( \frac{1}{3} \right) - \frac{(L+W)}{3} \left( \frac{tV}{s^2} \right) \right) - \beta_2 \frac{4}{(1-s)^2} - \beta_3 \left( \frac{1}{V_w} \right) \left( \frac{0.00015}{s^2} \right) \quad (5.20)$$

With assumption that  $s \ll 1$  mile, the minimum for  $Z_1$  occurs at

$$s \approx \sqrt{\frac{(\beta_1 (L+W) tV + 0.00045\beta_3)}{\beta_1 - 12\beta_2}} \quad (5.21)$$

Note that for the optimal block length expression in (5.21) is valid only when denominator is a positive quantity i.e.  $\beta_1 > 12\beta_2$ . Further, it is obvious that

$$\frac{d^2 Z_1}{ds^2} = \left( \frac{2\beta_1 (L+W) tV}{3s^3} \right) + \beta_2 \frac{8}{(1-s)^3} + \left( \frac{0.00030}{s^3} \beta_3 \right) > 0 \quad (5.22)$$

Thus, approximate expression for block length given in (5.21) is the optimal block length considering DRT shuttle performance and passenger and pedestrian comfort. The optimal cycle length is also estimated for a sample case scenario using simulations in the next section.

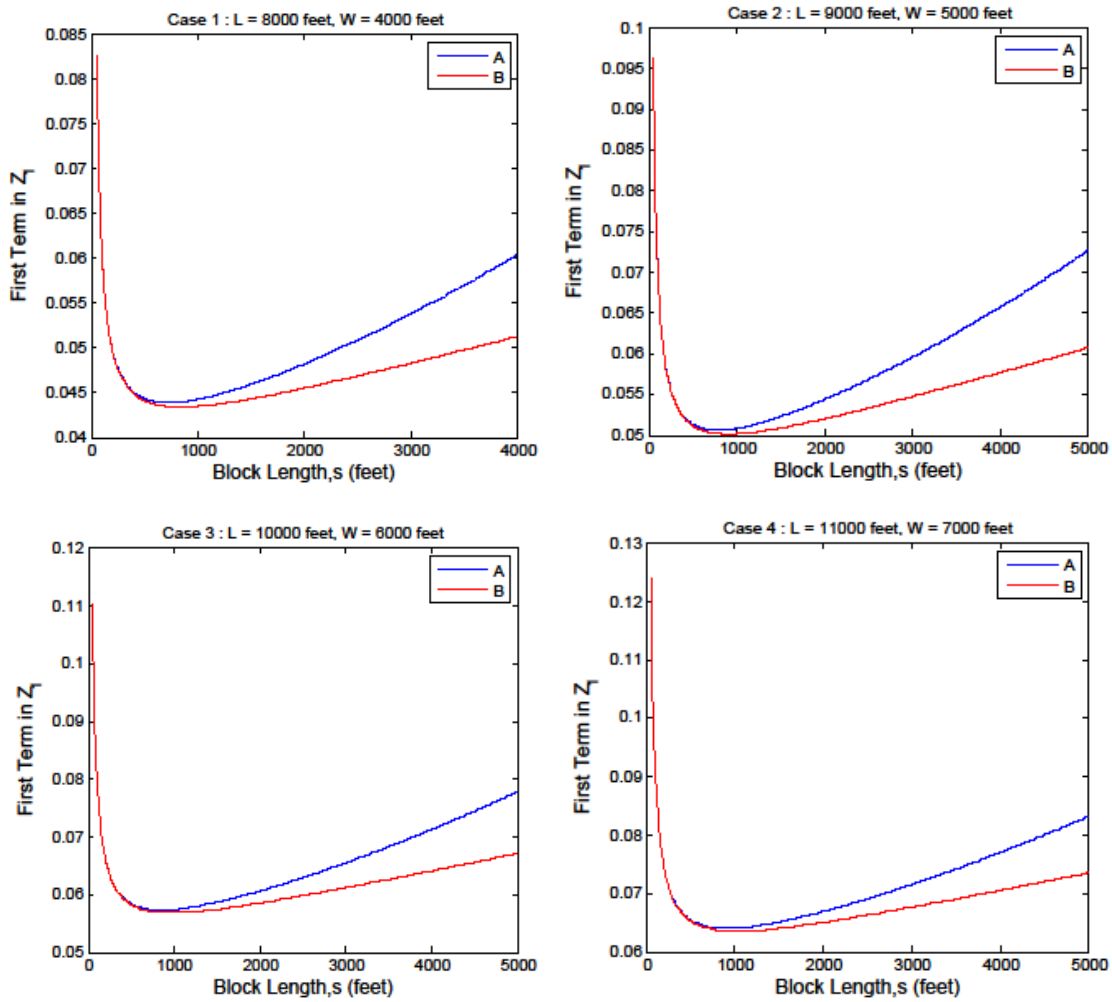
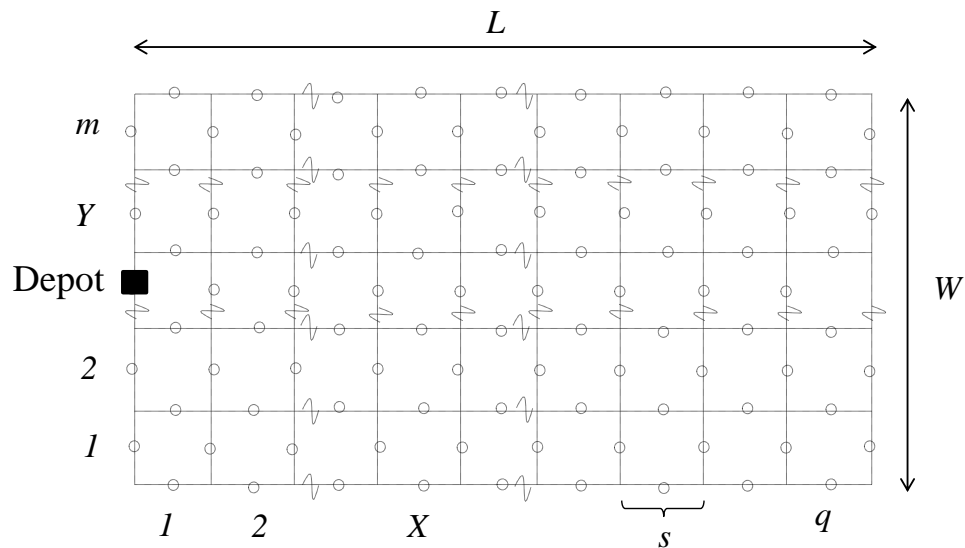


Figure 5.4 Comparison of the rigorous term,  $A$ , and the approximate term,  $B$ , in  $\min(Z_1)$

## 5.6 Simulation Results and Discussions

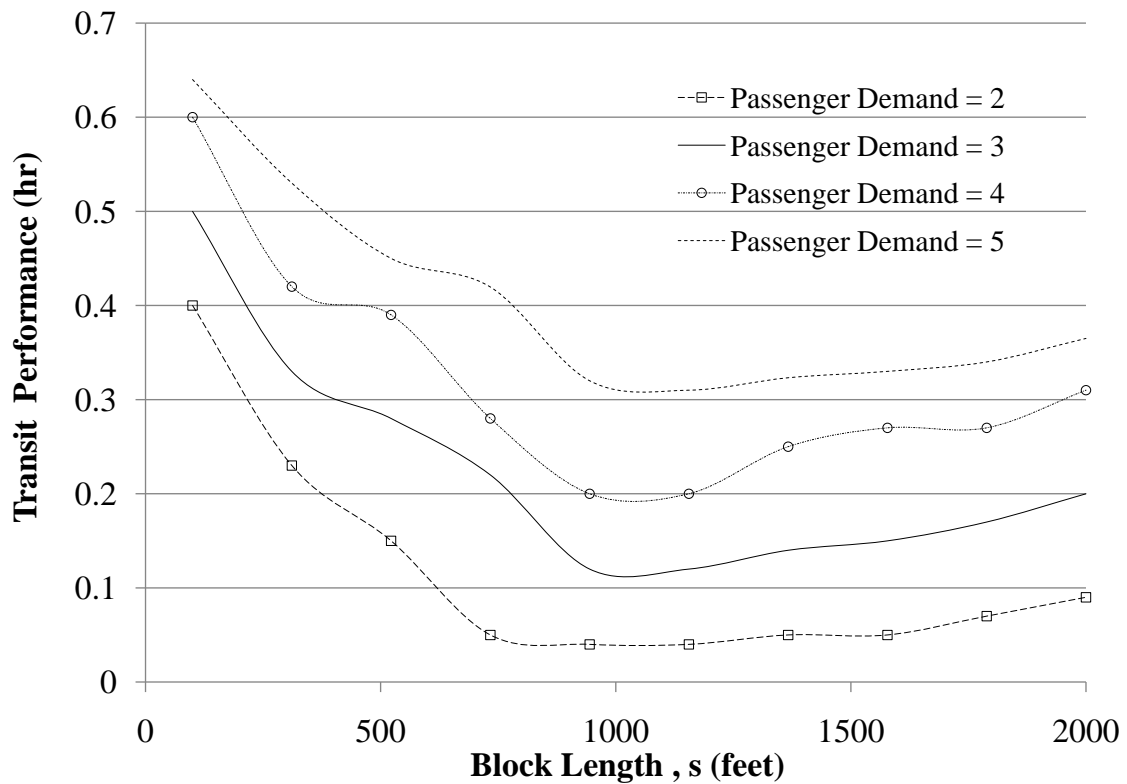
Simulation experiments are performed to validate results for optimal block length obtained using analytical modeling in the previous sections. The simulation set-up consists of coding 10 different networks with varying block sizes of  $s = 100$  feet to 2000 feet at regular intervals of 211 feet within a rectangular grid street system of length,  $L = 8000$  feet and width,  $W = 4000$  feet. A hypothetical DRT system is used with varying demands from 2 to 5 passengers with an increment of 1 passenger

each time. Each demand shows up randomly within the area and is assigned to the nearest on-demand stop located on the street. This low demand is usually found for a general demand responsive transit operating in a residential community (Potts et al. (2010)). The service durations are assumed to be large enough to serve all demands in a single cycle. The depot is located at the middle left edge of the service area (see Fig. 5.5). The DRT shuttle departs from the depot and serves available demand in an order with an almost near-optimal path decided by the insertion heuristic approach. Subsequently, the time taken by the shuttle to serve all available demand is recorded. The simulations are carried out with 20 replications for every demand considered and each of the 10 different grid street systems. The average speed  $V$  of the DRT shuttle is assumed to be 20 mph with an intersection stop time  $t = 2$  seconds. These values are consistent with those found in a residential community. For the values of the parameters  $\beta_1$ ,  $\beta_2$  and  $\beta_3$ , a sensitivity analysis could be carried out for different weights of the parameters which form the future research work of the author.



**Figure 5.5 Grid street system set-up for simulation**

The DRT operation is coded in MATLAB R2008b and the average time taken by the shuttle to pick-up all passengers is recorded for each demand. The results are displayed in Fig. 5.6. The shuttle performance is in ‘time’ units of hours taken by shuttle to serve a given number of demands. For demands higher than 5 passengers per cycle and with block length less than 200 feet, the computational times are noted to be very high and not considered in the simulations. With assumed values of parameters, the value of optimal block length from simulation for transit performance is found to be roughly in the range of 800 feet to 1100 feet ( as can be noted from Fig. 5.6) which is close to the approximate analytical optimal of 839 feet obtained using (5.21) for  $\beta_2 = 0$  and  $\beta_3 = 0$ . It must be noted that the shuttle performance is directly proportional to the first term of the objective function  $Z_1$  and this causes all 4 curves of shuttle performance in Fig. 5.6 to either be scaled up or down depending on  $\beta_1$ . Other outputs that are obtained consist of average passenger walking distance to a transit stop and the average number of crossings within a quarter mile distance for a pedestrian (see Fig. 5.7 and Fig. 5.8, respectively). The y-axis labels are not mentioned in these figures since the emphasis is made only to showcase the trend in variation of disutility versus the block lengths.



**Figure 5.6 Simulation output for transit performance with varying block length**

Observing the outputs from the charts in Fig. 5.6, it can be deduced that lower the demand the lower the cycle length (in hours) and better the performance. The variation in magnitude of passenger comfort versus block length shows that with larger block length values the passenger discomfort increases (see Fig. 5.7). The curve for pedestrian comfort remains flat almost for the entire set of block lengths used in analysis (see Fig. 5.8). However, for ridiculously small block lengths the curve for pedestrian comfort would rise.

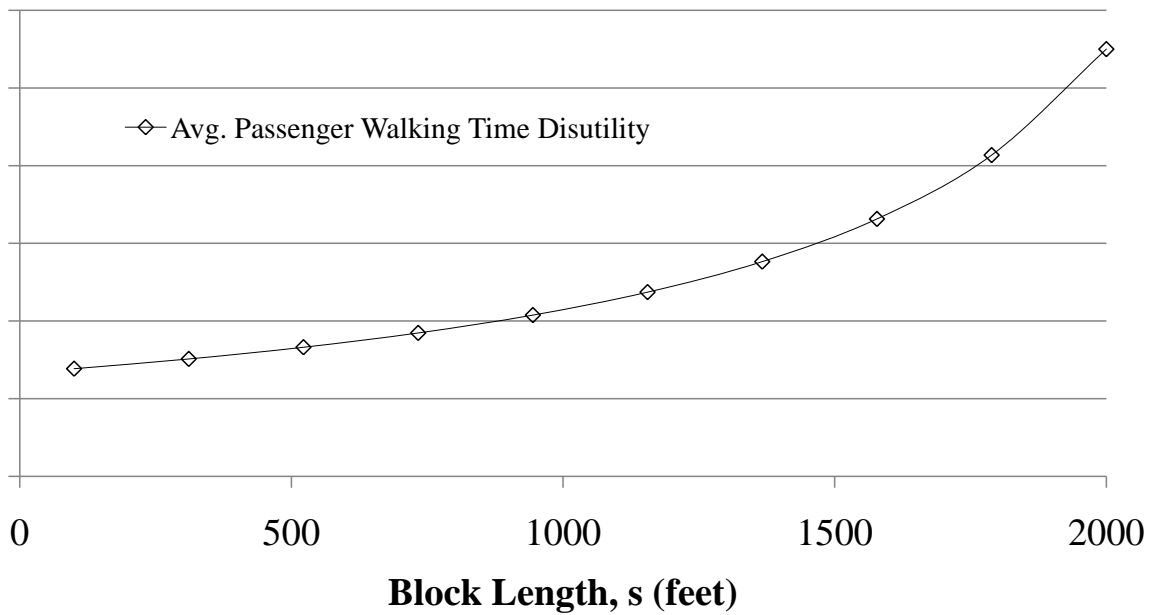


Figure 5.7 Passenger disutility/discomfort variation with block length (penalty-function)

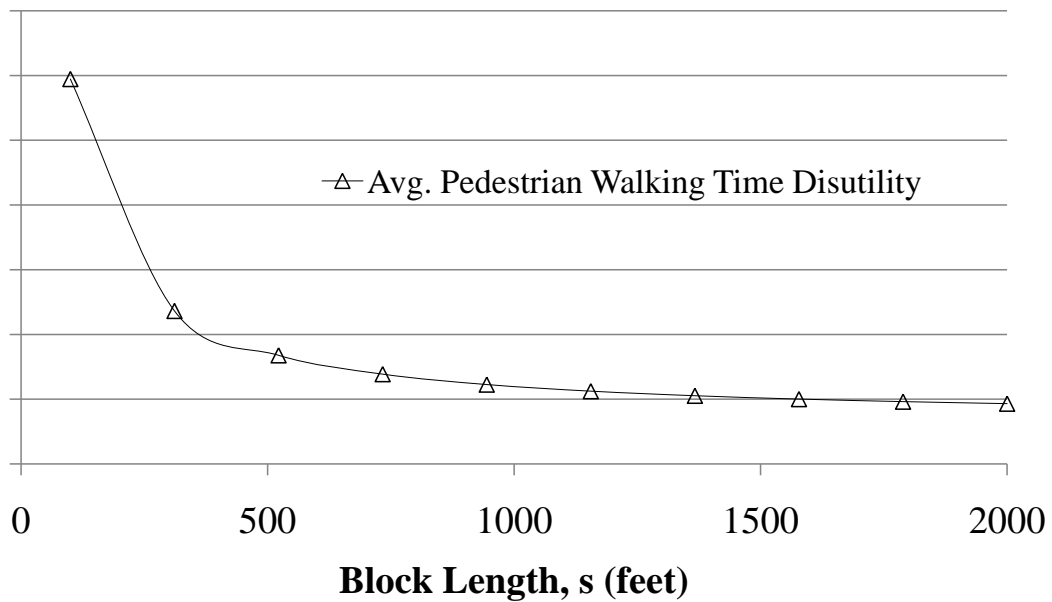


Figure 5.8 Pedestrian disutility/discomfort variation with block length

## 5.7 Summary and Research Contribution

The number of four-way intersections over a given street network inadvertently affects shuttle performance. The higher the number of 4-way intersections or stops, higher the travel times for DRT shuttles in each cycle. A large number of stops or intersections results from having smaller block lengths and vice-versa.

Consequently, as street connectivity is linked to block length, an optimal value for latter could certainly help planners in design of a transit-oriented community and simultaneously ensure pedestrian walking comfort. From this part of the dissertation, which also evaluates the best demand responsive transit performance, the approximate value of the optimal block length is found to be 839 feet for a model residential community having a grid street system with rectangular service area of length 8000 feet and width 4000 feet. The future research consists of analyzing the value of optimal block lengths for different weight settings of this study.

The analysis performed in this study systematically lays out several crucial interrelationships between streets and their users. The analytical model presented in this study would form a good starting point to dig into missing elements that often thwart community livability.



## 6. OPTIMAL TRANSIT SCHEDULING STRATEGY

### 6.1 Methodology

A generic residential area of rectangular shape with length  $L$  and width  $W$  is considered for analysis. The terminal (designated as  $D$ ) with coordinates  $(0,0)$  is located in the middle of an edge (see Fig. 6.1). Vehicles are departing from  $D$  at constant time intervals (cycle) to serve customers. Demand is assumed to be spatially uniformly distributed as well as temporally uniformly distributed within a target time interval of the day.

The methodology consists of building the analytical model for optimal cycle length in two steps. The first step consists of deriving an average number of passengers  $n$  that can be served by the shuttle within a given cycle length  $C$  and the second part consists of building the model for average waiting and in-vehicle travel time of the passengers.

#### 6.1.1 DRT Service Design

Designing DRT service would require models that can precisely describe the relationship between  $C$  and  $n$  to be used to maintain an optimum service standard. Further, a switch from one model to another should be possible depending on the demand and service area characteristics to represent the most accurate model matched with reality. In general, the expressions for cycle lengths serving  $n$  passengers can be split into two travel times. The first part consists of the time taken by the shuttle to serve the first/last spatially located closest passenger in the service loop as it departs from the depot and returns to the depot. And the second part consists of the travel time taken to serve the remaining  $(n - 2)$  passengers in the same loop. If the cycle lengths are too short in duration, the shuttle has to make too many frequent departures back and forth to the depot just to serve one passenger in the service

loop. Short cycle lengths will cause the feeder shuttle to make too frequent visits at the terminal resulting in too much of extra driving. This progressively increases the likelihood of causing increase in waiting times of the passengers (and thus, resulting in lower service levels). Similarly, an increase in passenger waiting and riding will also result due to longer cycle lengths simply because the shuttle would be too ambitious to serve a very large number of passengers in one single loop. Intuitively, a minimum delay in terms of lowest average waiting and riding must occur for certain cycle lengths between two extremes of too short and too long cycle lengths. Thus models that use scheduling strategies to serve  $n$  passengers within a given  $C$  should play a crucial role in deriving that *optimal* cycle length. We are summarizing four such models that are can be potentially used to describe the relationship between  $C$  and  $n$  with a scheduling strategy used for each. These are labeled as Design (I), (II), (III) and (IV). For each of these designs, for given cycle length  $C$ , the first part of the travel time (denoted by (i)) and second part of the travel time (denoted by (ii)) of the service loop are identified and highlighted.

Design (I). *Nearest-neighbor approach*: The average closest distance between two uniformly distributed passenger demands as developed by Quadrifoglio et al. (2006) for a very high demand density  $\rho$ , can be used for this approach. In addition to this, we also derive the average closest distance between the terminal and a passenger. The derivation is using an example case shown in Fig. 6.1.

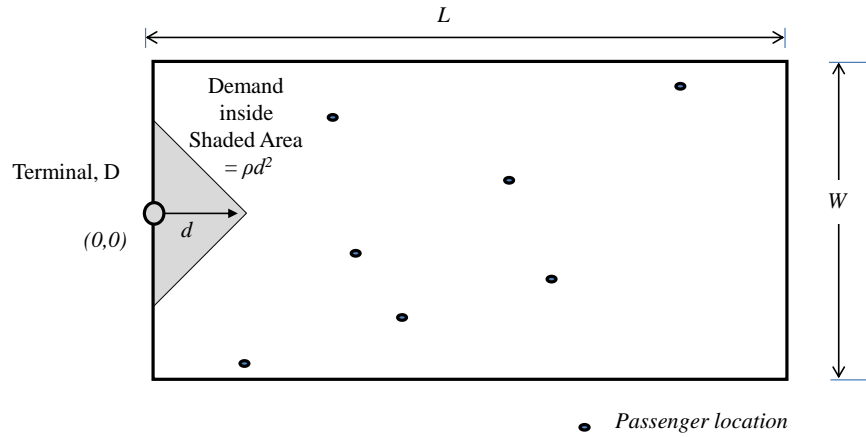
Within a rectangular service area with length,  $L$  and width,  $W$ , spatial-temporal *uniform* demand distribution of passenger requests follow a Poisson distribution having expected value of  $\rho A_R$ , with the probability of finding a given number of points ( $A_n$ ) within an area  $A_R$  as,

$$P(A_n = q) = \frac{(\rho A_R)^q}{q!} e^{-\rho A_R} \quad (6.1)$$

where,  $\rho$  = demand density and  $q = 1, 2, 3, \dots$

The expected closest distance  $E[D]$  between the terminal and a passenger can be obtained for  $q = 0$  and  $A_R = d^2$  (see Fig. 6.1), where  $d$  is the variable rectilinear distance between the terminal and the closest passenger.

$$E[D] = \int_0^{\infty} e^{-\rho d^2} dd = \frac{1}{2} \sqrt{\frac{\pi}{\rho}} \approx \frac{0.89}{\sqrt{\rho}} \quad (6.2)$$



**Figure 6.1** Illustration of expected closest distance between terminal and a passenger

Thus, the average time taken (i.e.  $C$ ) to serve  $n$  passengers can be approximated as

$$C = \underbrace{\frac{1.78}{V\sqrt{\rho}}}_{(i)} + 2t_s + \underbrace{(n-1) \frac{0.63}{V\sqrt{\rho}}}_{(ii)} + (n-1)t_s \quad (6.3)$$

where,  $t_s$  is the time taken at each stop or terminal to pick-up/drop-off of a passenger, and  $V$  is the average speed of the feeder bus. For a very high demand density, the following approximation for  $C$  can be made,

$$C \approx \frac{0.63\sqrt{n}\sqrt{LW}}{V} + (n+1)t_s \quad (6.4)$$

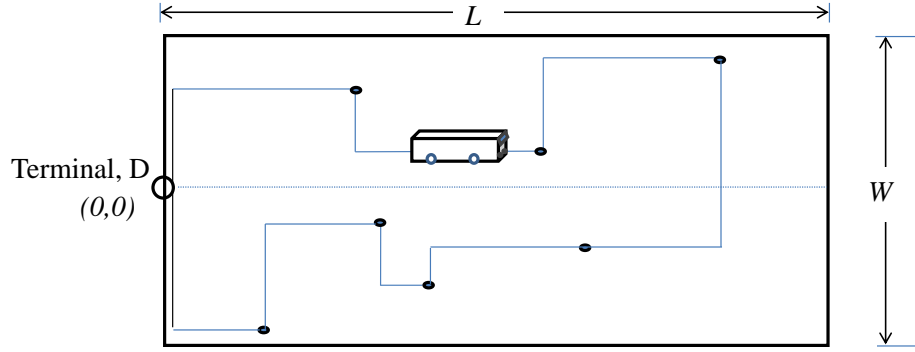
Design (II). *Approximate TSP solution approach:* Results from work of Beardwood et al. (1959) and Jaillet (1988) can also be used to express another approximate relationship between  $C$  and very large  $n$ , with

$$C = \underbrace{\frac{\sqrt{nLW}}{V}}_{(ii)} + (n+1)t_s \quad (6.5)$$

In this design, for a very large  $n$  the cycle length is long enough to outweigh the first part of the travel time of the service loop and thus, is not noted.

Design (III). *No-backtracking approach:* Exploiting the scheduling guideline as proposed by Daganzo (2004) and Quadrioglio and Li (2009) a strategy can be set for serving passengers for a lower passenger demand (low  $n$ ) and a high length-to-width ratio of service area (see Fig. 6.2). In this case, the DRT vehicle would move through the upper half of the region in a no-backtracking policy left-to-right, and move through the bottom half in a no-backtracking policy right-to-left. The relationship between  $C$  and  $n$  is expressed in this case by the following,

$$C = \underbrace{\frac{W}{2V} + 2t_s}_{(i)} + \underbrace{\frac{2Ln}{(n+1)V} + \frac{Wn}{6V} + \frac{W}{6V}}_{(ii)} + (n-1)t_s \quad (6.6)$$



**Figure 6.2 Shuttle pick-up/drop-off strategy**

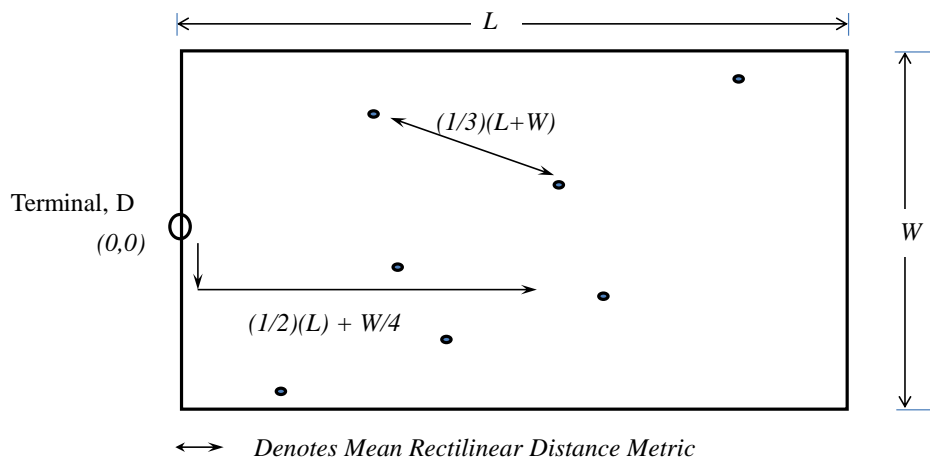
With the further assumption  $\left(\frac{n}{n+1}\right) \approx 1$ , the relationship between  $C$  and  $n$  in (6.6) becomes linear and can be expressed as

$$C \approx \frac{2L + \frac{2W}{3} + \frac{Wn}{6}}{V} + (n + 1)t_s \quad (6.7)$$

Using (6.7) for computing  $C$  does not change its value significantly with respect to (6.6), especially for higher values of  $n$  (Quadrifoglio and Li (2009)).

Design (IV). Random approach: This service strategy is mostly adopted when the demand is extremely low with not more than three passengers in each cycle. The DRT shuttles serves passengers as demands occur without using any optimization algorithm (see illustration in Fig. 6.3). Using an average rectilinear distance traveled between uniformly random distributed demand within a rectangle as  $(L + W)/3$  (Gaboune et al. (1993)), the cycle length for this case is,

$$C = \underbrace{\frac{L}{V} + \frac{W}{2V} + 2t_s}_{(i)} + \underbrace{\frac{(n-1)(L+W)}{3V} + (n-1)t_s}_{(ii)} \quad (6.8)$$



**Figure 6.3 Shuttle service operated using random pick-up/drop-off strategy**

### 6.1.2 Model Comparison

It is important to compare the relative applications of each of the design methodologies discussed above to select the best  $C$  and  $n$  relationship according to the service area and demand available. The four different forms of relationships are compared to outputs obtained from a well-known heuristic in the area of TSP, known as *insertionheuristic* (Jaw et al. (1986), Quadrifoglio et al. (2007)). Insertion heuristic can be preferred for good solutions as compared to optimality obtained using any well-known optimization software such as CPLEX 12.1. In fact, as the demand becomes higher, it is quite impractical to use CPLEX to obtain optimal solutions, simply because of unreasonable computational times involved in the process (for further explanation see Li and Quadrifoglio (2010)). Besides, insertion heuristic is widely used in practice for most scheduling problems and is quite easy to understand.

Cycle length values are computed for different demands and service area dimensions consisting of a rectangle with quite high length-to-width ratio and a square (shown in Table 6.1). An average of 1000 replications performed in MATLAB R2010b for each value of  $C$  and the values of  $n$  vary between 1 (too low) to 20 (too high)

to cover any variability in demand within each cycle. The average feeder speed is assumed to be 20 mile per hour, posted speed limit found in most residential areas where DRTs operate and the value for average time  $s$  spent at a passenger stop is assumed to be 30 seconds. Optimal cycle lengths are obtained using a TSP code in MATLAB and computing optimal using CPLEX 12.1. The optimal cycle lengths are denoted as  $Opt$  in Table 6.1–6.4. Following the values in table, a close match between the insertion heuristic and the optimal  $C$  is found. We did not report optimal  $C$  for  $n > 11$  as the software was taking unrealistic times for the number of replications desired. Thus, insertion heuristic was the most preferred benchmark for all the four design methodologies.

The results in Table 6.1–6.4 clearly show that the relationship in from design method (*III*) matches well with insertion heuristic (which is denoted by numeral  $V$ ) cycle lengths for higher length- to-width ratios and lower demands (i.e. lower  $n$ ). The cycle length values from design method (*II*) are closer to insertion heuristic outputs for the square shaped area for almost all values of  $n$ . The values for  $C$  using design method (*I*) appear to match more closely with insertion heuristic cycle lengths as  $n$  increases as compared to other design methods. This match is further improved as the demand density becomes higher (observe identical cycle length values for ( $L=2.5$  mile,  $W=0.5$  mile) with ( $L=1$  mile,  $W=1$  mile) for same  $n$ ). Similarly, the values of  $C$  from design method (*II*) are closer to the insertion heuristic results for higher  $n$  and demand density. Cycle lengths from insertion heuristic and design method (*IV*) match only for low demands ( $n < 5$ ) and for higher  $n$  the cycle length values are not close.

The cycle length values obtained in Table 6.1–6.4 can also be interpreted differently to quantify number of passengers that can be served comfortably by adopting one of the four scheduling design methods discussed above. As an example, say for a given cycle length  $C = 17$  min,  $L = 1.5$  mile and  $W = 0.5$  mile, the maximum number of passengers that can be served approximately by each of the four design

methods (I), (II), (III), and (IV), are 18, 13, 10 and 6 respectively. With insertion heuristic as the benchmark, the maximum number of passengers comfortably served would be approximately 11. In general, it is observed that for the different lengths and widths setting used in Table 6.1–6.4, design methods (I) and (II) recommend serving greater number of passengers for any given cycle length as compared to design methods (III) and (IV). It is therefore obvious to believe that employing methods (I) and (II) would result in higher performance of the DRT system as compared to using design methods (III) and (IV) for scheduling. These results set the stage for building our analytical model, as they are useful in estimating cycle lengths for any given service area geometry and demand.

Not all demands might be served by the single feeder bus system operating throughout the day. When an extremely high daily demand occurs, the transit agencies would need to account for any non-served customer to retain the popularity of the feeder transit. Thus, extra buses might be employed for service. If the transit attempts to serve an extremely high demand above its daily serving capacity with a single bus/shuttle, saturation in performance is reached beyond which there is an exceptionally high average waiting times and in-vehicle travel times of the passengers. Too low passenger demands, on the other hand, would not generate enough revenues for operating the transit service. Thus, the relationship between the cycle length and the number of demands served is critical in building up the model for estimating the optimal cycle length and hence, the design methodologies from (I) through (IV) are extremely useful. Note : the following notations have been used in Table 6.1–6.4, *a*–Nearestneighbor Eqn. (6.4), *b*–Approx TSP Eqn. (6.5), *c*–No-backtrack Eqn (6.7), *d*–Random Eqn. (6.8), *e*–Insertion heuristic, Opt-Optimal

### 6.1.3 Modeling DRT Operations and Optimal Cycle Length

The DRT *feeder* is assumed to operate daily for a fixed duration of time. Assuming, that a single DRT feeder bus operates for  $T$  hours on a given day, with



**Table 6.1 Cycle lengths for different demands with L=2.0 mile, W = 0.5 mile**

n	a	b	c	d	e	Opt
1	6.3	4.0	8.2	7	7.5	7.4
2	6.6	5.7	11.0	10	10.4	10.1
3	7.3	7.2	12.7	13	12.1	11.9
4	8.0	8.5	14.1	16	13.5	13.4
5	8.8	9.7	15.2	19	14.5	14.3
6	9.5	10.8	16.3	22	15.6	15.4
7	10.3	11.9	17.2	25	16.4	16.3
8	11.0	13.0	18.1	28	17.6	17.5
9	11.8	14.0	19.0	31	18.2	18.1
10	12.5	15.0	19.9	34	18.9	18.9
11	13.3	15.9	20.7	37	19.7	–
12	14.0	16.9	21.6	40	20.5	–
13	14.7	17.8	22.4	43	21.3	–
14	15.5	18.7	23.2	46	22.4	–
15	16.2	19.6	24.0	49	22.4	–
16	16.9	20.5	24.8	52	23.0	–
17	17.6	21.3	25.5	55	24.5	–
18	18.3	22.2	26.3	58	25.7	–
19	19.0	23.0	27.1	61	26.0	–
20	19.7	23.9	27.9	64	26.8	–

**Table 6.2** Cycle lengths for different demands with  $L=1.5$  mile,  $W = 0.5$  mile

n	a	b	c	d	e	Opt
1	5.6	3.6	6.7	5.5	5.9	5.9
2	5.9	5.2	9.0	8.0	8.2	8.1
3	6.6	6.5	10.5	10.5	9.8	9.5
4	7.3	7.7	11.7	13.0	11.1	10.8
5	8.0	8.8	12.7	15.5	12.1	11.8
6	8.7	9.8	13.7	18.0	12.9	12.7
7	9.4	10.9	14.6	20.5	13.8	13.7
8	10.2	11.8	15.5	23.0	14.6	14.2
9	10.9	12.8	16.3	25.5	15.4	15.4
10	11.6	13.7	17.2	28.0	16.2	15.7
11	12.3	14.6	18.0	30.5	17.0	–
12	13.0	15.5	18.8	33.0	17.7	–
13	13.7	16.3	19.6	35.5	18.5	–
14	14.4	17.2	20.4	38.0	19.2	–
15	15.1	18.0	21.2	40.5	19.9	–
16	15.8	18.9	21.9	43.0	20.7	–
17	16.4	19.7	22.7	45.5	21.4	–
18	17.1	20.5	23.5	48.0	22.1	–
19	17.8	21.3	24.3	50.5	22.8	–
20	18.4	22.1	25.0	53.0	23.5	–

**Table 6.3** Cycle lengths for different demands with  $L=1.0$  mile,  $W = 0.5$  mile

n	a	b	c	d	e	Opt
1	4.8	3.1	5.2	4	4.4	4.3
2	5.1	4.5	7.0	6	6.3	5.5
3	5.7	5.7	8.2	8	7.6	7.4
4	6.4	6.7	9.3	10	8.5	8.2
5	7.1	7.7	10.2	12	9.5	9.4
6	7.8	8.7	11.1	14	10.4	10.1
7	8.4	9.6	12.0	16	11.2	10.7
8	9.1	10.5	12.8	18	12.0	11.3
9	9.8	11.3	13.6	20	12.7	12.2
10	10.5	12.2	14.4	22	13.5	13.1
11	11.1	13.0	15.2	24	14.2	–
12	11.8	13.8	16.0	26	14.9	–
13	12.5	14.6	16.8	28	15.7	–
14	13.1	15.4	17.6	30	16.3	–
15	13.8	16.2	18.3	32	17.1	–
16	14.4	17.0	19.1	34	17.8	–
17	15.1	17.7	19.9	36	18.5	–
18	15.7	18.5	20.6	38	19.2	–
19	16.3	19.2	21.4	40	19.9	–
20	17.0	19.9	22.2	42	20.5	–

**Table 6.4 Cycle lengths for different demands with L=1.0 mile, W = 1.0 mile**

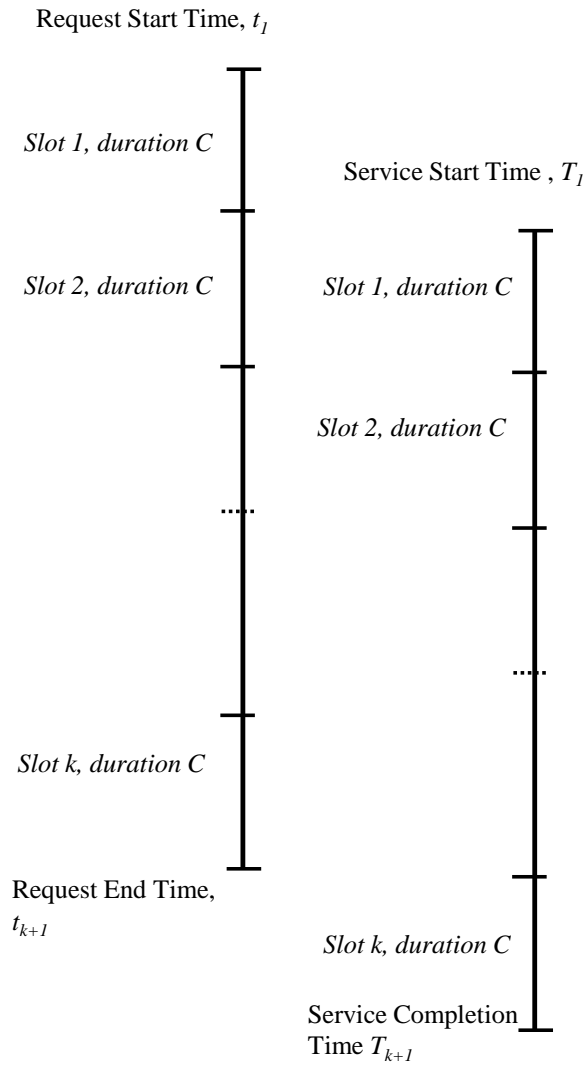
n	a	b	c	d	e	Opt
1	6.3	4.0	6.5	4.0	5.1	5.0
2	6.6	5.7	8.5	6.5	7.2	6.5
3	7.3	7.2	10.0	9.0	8.6	8.1
4	8.0	8.5	11.3	11.5	10.0	9.6
5	8.8	9.7	12.5	14.0	11.0	10.4
6	9.5	10.8	13.6	16.5	12.1	11.8
7	10.3	11.9	14.7	19.0	13.0	12.8
8	11.0	13.0	15.8	21.5	14.0	13.3
9	11.8	14.0	16.9	24.0	14.9	14.6
10	12.5	15.0	17.9	26.5	15.8	15.3
11	13.3	15.9	19.0	29.0	16.8	–
12	14.0	16.9	20.0	31.5	17.7	–
13	14.7	17.8	21.0	34.0	18.5	–
14	15.5	18.7	22.1	36.5	19.4	–
15	16.2	19.6	23.1	39.0	20.2	–
16	16.9	20.5	24.1	41.5	21.0	–
17	17.6	21.3	25.1	44.0	21.8	–
18	18.3	22.2	26.1	46.5	22.7	–
19	19.0	23.0	27.2	49.0	23.5	–
20	19.7	23.9	28.2	51.5	24.4	–

a constant cycle length  $C$ , the number of times the feeder bus is dispatched from the terminal  $\lceil \frac{T}{C} \rceil = \lceil \tau \rceil$  where,  $\lceil \tau \rceil$  stands for the nearest integer value for  $\tau$ . The cycle length is decided such that maximum number of passengers is served without compromising on their comfort. A priori information about the cycle length for a given demand is extremely useful for the transit operator in delivering an optimized service outputs (in the form of minimum waiting time and in-vehicle travel time) to passengers. Note in this study, we do not consider real time DRT operations that are certainly possible to improve the service quality of the picked-up passenger. This strategy, however, would worsen the service quality of the passengers already on-board. Moreover, with real time DRT operations the overall performance is hard to evaluate it a priori.

An advance knowledge of the most appropriate cycle length to use is especially crucial for passenger demands during peak hours of commuting. Thus, if there are  $N$  numbers of passengers that need to be served during a given period of DRT operation, the system should ideally be capable of serving  $\lceil \frac{N}{\tau} \rceil = l$  passengers in each cycle. Otherwise, when only  $n$  numbers of passengers are comfortably served on an average in a cycle, the residual  $(l - n)$  passengers would need to be served in the next cycle.

Further, if some of the residual passengers that do not get served in the next cycle, they would be scheduled to be served in next to the next cycle and this process continues for all the residual passengers in each cycle. As an example, there could be an instance when some of the residual passengers from the very first cycle (when the DRT shuttle starts its service) might never get served at all during the service durations of the DRT service or would refuse to ride due to extraordinary long waiting times. This will naturally happen when the cycle lengths are too small or the number of passengers that request for service within the first starting cycle length is overwhelmingly large.

Thus, in situations, when the number of residual passengers is very high such that in a given cycle  $(l - n) > n$ , the residual passengers are served in the next cycle otherwise fresh sets of passengers from the next immediate cycle are served. In this manner, the DRT service procedure follows the First-in-first-out (FIFO) policy, where the first request for service in terms of request time is given the priority to those making service requests for a later time. The FIFO policy also holds between two passengers and the passenger who makes a request earlier in the queue will always get served before or within the same cycle. The above situation is explained through sets of slots (each of duration  $C$ ) corresponding to each of the dispatch times of the feeder bus in the sketch of Fig. 6.4.



Average passengers served in a slot =  $n$ ,  
 Average number of passenger requests in a slot =  $l$

**Figure 6.4** Illustration of passenger requests and service times using slots of duration  $C$

The variables  $t_1$  and  $T_1$  are the start time of the passenger request times and the feeder bus service times, respectively. Similarly,  $t_{k+1}$  and  $T_{k+1}$  are the end times of the passenger request times and the feeder bus service times, respectively, for a total

of  $k$  slots in a day formed equal to  $[\tau]$ . Note that  $(T_1 - t_1) = C$  (and  $(T_{k+1} - t_{k+1}) = C$ ) with  $(t_{k+1} - t_1) = T$  and  $(T_{k+1} - T_1) = T$ .

#### 6.1.4 Service Disutility

It is generally difficult to identify a unique definition of performance for a transit system as priorities differ among stakeholders. Several authors have used measures such as passenger cost, passengers per vehicle hour, vehicle miles per operator, cost per vehicle mile, cost per vehicle hour, the ratio of cost to fare box revenue and fleet fuel efficiency for the urban public transit (Gleason and Barnum (1986), Fielding et al. (1985), Badami and Haider (2007)). However, all seem to agree that transit performance can generally be identified as a combination of operating costs and service quality. The service quality is expressed as passenger's disutility: a weighted sum of expected waiting time and the expected in-vehicle travel time of passengers. Thus, the performance measure or disutility  $U$  can be expressed as piecewise disutility for  $N$  number of passengers and hence, can be written as,

$$U = \begin{cases} Q_1 & \text{if } l > n, \\ Q_2 & \text{if } l \leq n. \end{cases} \quad (6.9)$$

where,  $Q_1 = \gamma_1 w_t + \gamma_2 r_t$  ( $w_t$  = expected waiting time and  $r_t$  = expected riding time;  $\gamma_1$  and  $\gamma_2$  are the weight factors for the waiting time and riding time respectively). The values for  $Q_1$  and  $Q_2$  can be appropriately calibrated using empirical results. Waiting at a stop near a residential area might have different values than waiting at a transit stop at a terminal.

The term  $Q_1$  is the disutility when the demand within a given cycle is greater than the demand that the DRT system can handle, and  $Q_2$  is the disutility when the demand for service is below the threshold demand that the system can serve easily within a given cycle.



Derivation of  $Q_1$  involves careful accounting for passenger requests served in a cycle or a slot. A passenger being picked-up by the feeder bus needs to wait an average of  $C$  from his/her show-up time at the stop. In the event that he/she does not get served within the requested service cycle length, he/she would need to wait for an average time of  $C(= C/2 + C/2)$  for next cycle of pick-up.

In situations when passengers are served in their requested slot, the derivation for  $Q_1$  (written as,  $Q_1 = \frac{1}{N} (Q_1^{ns} + Q_1^s)$ ) is easy with  $Q_1^{ns}$  in (6.10) (which shows the relationship for the total expected waiting time for the non-spillover case) for different served number of passengers  $n = n_i$  and demand  $l = l_i$  in slot  $i$ , respectively ( where,  $i = 1, 2, 3, \dots, \tau$  ). Another portion of  $Q_1$  is from the spillover case ( $Q_1^s$ ) when some left over passengers ( $l - n$ ) are not served in their request slots. In the spillover case, we assume that un-served sets of passengers are served in the slot immediately after their request slot. The modeling equations for this situation is shown in (6.11) by assuming that the DRT shuttle is able to serve all passenger demands during the peak periods within the duration  $T$  of service with just an extra slot in case of a spillover. If  $\alpha$  is the fraction of pick-up passengers, the expressions for  $Q_1^{ns}$  and  $Q_1^s$  are obtained as,

$$\begin{aligned}
Q_1^{ns} = & n_1 \alpha C + n_1 \frac{(1 - \alpha) C}{2} \\
& + (n_2 - (l_1 - n_1)) \alpha C + (n_2 - (l_1 - n_1)) \frac{(1 - \alpha) C}{2} + \dots \\
& \dots + (n_\tau - (l_{\tau-1} - \dots (n_2 - (l_1 - n_1)))) \alpha C \\
& + (n_\tau - (l_{\tau-1} - \dots (n_2 - (l_1 - n_1)))) \frac{(1 - \alpha) C}{2} \quad (6.10)
\end{aligned}$$

$$\begin{aligned}
Q_1^s = & (l_1 - n_1) 2\alpha C + (l_1 - n_1) \frac{3(1 - \alpha) C}{2} \\
& + (l_2 - (n_2 - (l_1 - n_1))) 2\alpha C + (l_2 - (n_2 - (l_1 - n_1))) \frac{3(1 - \alpha) C}{2} + \dots \\
& \dots + (l_\tau - (n_\tau - \dots (l_1 - n_1))) 2\alpha C \\
& + (l_\tau - (n_\tau - \dots (l_1 - n_1))) \frac{3(1 - \alpha) C}{2} \quad (6.11)
\end{aligned}$$

The right hand side terms in (6.10) and (6.11) are reduced to arithmetic progression summations by using  $l_1 = l_2 = \dots = l_n = l$  and  $n_1 = n_2 = \dots = n_\tau = n$ . Therefore, the final expression for  $Q_1$  is stated as,

$$Q_1 = \frac{\gamma_1 C}{N} \left( \frac{\tau(1 + \tau)(l - n)}{2} + \tau l \left( \frac{1 + \alpha}{2} \right) \right) + \gamma_2 \left( \frac{C}{2} \right) \quad (6.12)$$

And for  $l \leq n$ ,

$$Q_2 = \gamma_1 \left( \frac{C}{2} \right) + \alpha \gamma_2 \left( \frac{t}{2} \right) \quad (6.13)$$

where,  $t$  is defined earlier in 6.1 under the section of methodology. If the cycle length in any of the above relationships between  $C$  and  $n$  is too high, there is an associated unused slack time. In such a case, the correct relationship for the average travel time  $t$  taken to service  $n$  passengers is obtained by simply replacing  $C$  with  $t$  and  $n$  with  $(NC/T)$ , for all four design methodologies (I), (II), (III) and (IV) discussed earlier.

We can obtain a minimum disutility using  $\frac{dU}{dC} = 0$ . Thus, the following needs to be computed,

$$\frac{dU}{dC} = \begin{cases} \frac{dQ_1}{dC} & \text{if } l > n, \\ \frac{dQ_2}{dC} & \text{if } l \leq n. \end{cases} \quad (6.14)$$

Using the reverse expressions for estimating  $n$  with respect to  $C$  (see methods (I)–(IV) in 6.1 under the section of methodology), we can write  $n \approx (hC + f\sqrt{C} + g)$  with the values of  $h$ ,  $f$  and  $g$  listed in Table 6.5.

**Table 6.5 Expressions for  $h$ ,  $f$  and  $g$**

Design Method	$h$	$f$	$g$
(I)	$\frac{1}{t_s}$	$-\sqrt{\left(\frac{0.63LW}{t_s^3V^2}\right)}$	$-1 + \frac{0.31LW}{t_s^2V^2}$
(II)	$\frac{1}{t_s}$	$-\sqrt{\left(\frac{LW}{t_s^3V^2}\right)}$	$-1 + \frac{0.5LW}{t_s^2V^2}$
(III)	$\frac{1}{\left(\frac{W}{6V} + t_s\right)}$	0	$-\left(\frac{12L+4W+6Vt_s}{W+6Vt_s}\right)$
(IV)	$\frac{1}{\left(\frac{L+W}{3V} + t_s\right)}$	0	$-\left(\frac{\frac{2L}{3V} + \frac{W}{6V} + t_s}{\left(\frac{L+W}{3V} + t_s\right)}\right)$

It is difficult to work with non-linear expressions (due to square root of  $C$  involved) if design methods used are from (I) and (II) as  $f \neq 0$ . This also makes it hard to derive closed form expressions as roots of cubic polynomials are not trivial to estimate. Thus, we proceed to give some closed form results only for design methods (III) and (IV) when  $f = 0$  and only report optimal cycle lengths obtained graphically for the other two methods along with simulation results later. From now on, unless specified, assume we are only working with design methods (III) and (IV). Thus, writing  $Q_1$  in (6.12) for  $f = 0$  for design methods (III) and (IV), we get

$$Q_1 = \frac{\gamma_1}{2} \left( (2 + \alpha)C - \frac{(hC + g)T}{N} + T - \frac{(hC + g)T^2}{NC} \right) + \gamma_2 \left( \frac{C}{2} \right) \quad (6.15)$$

which is a convex quadratic function for  $C > 0$  and has a positive root

$$C \approx \sqrt{\frac{-gT^2}{N \left( (2 + \alpha) - \left( \frac{hT}{N} \right) + \left( \frac{\gamma_2}{\gamma_1} \right) \right)}} \quad (6.16)$$

Examining the expression of  $Q_2$  in (6.13) clearly shows that it is monotonically increasing function with respect to  $C$ . Subsequently, since we are looking for a minimum  $U$  and a continuous  $U$  at  $l = n$ , both  $Q_1$  and  $Q_2$  should intersect and the common cycle length which gives the lowest minimum should be the optimal cycle length. A minimum disutility at one of the intersecting points would mean that the passenger spillover has ended and the cycle lengths are long enough to serve all passengers with the lowest average passenger waiting and riding times. Using the linear expression for  $Q_2$ , the equality  $Q_1 = Q_2$ , would be a quadratic equation of the following form

$$\left( \frac{u}{C} + vC + r \right) = (mC + b) \quad (6.17)$$

where,  $u = \frac{\gamma_1}{2} \left( -\frac{gT^2}{N} \right)$ ,  $v = \frac{\gamma_1}{2} \left( (2 + \alpha) - \frac{hT}{N} \right) + \left( \frac{\gamma_2}{2} \right)$ ,  $r = \frac{\gamma_1}{2} \left( T - \frac{hT^2}{N} - \frac{gT}{N} \right)$ , with  $h$  and  $g$  as defined in Table 6.5 for methods (III) and (IV).

Depending on the relationship between  $C$  and  $n$  from design methods (III) and (IV) derived earlier, the expressions for  $m$  and  $b$  are as shown in Table 6.6.

Solving (6.17) gives the smallest value of cycle length which is  $C$  optimal ( $C_{opt}$ ),

**Table 6.6 Expression for right hand side coefficients of equation (6.17)**

Design Method	$m$	$b$
(III)	$\frac{\gamma_1}{2} + \frac{\alpha\gamma_2}{2} \left( \frac{NW}{6VT} + \frac{Nt_s}{T} \right)$	$\frac{\alpha\gamma_2}{2} \left( \frac{6L+2W}{3V} + t_s \right)$
(IV)	$\frac{\gamma_1}{2} + \frac{\alpha\gamma_2}{2} \left( \frac{N(L+W)}{3VT} + \frac{Nt_s}{T} \right)$	$\frac{\alpha\gamma_2}{2} \left( \frac{2L}{3V} + \frac{W}{6V} + t_s \right)$

$$C_{opt} = \frac{(b-r) - \sqrt{(b-r)^2 - 4u(v-m)}}{2(v-m)} \quad (6.18)$$

with all variables defined earlier. For (6.18) to hold true, it is essential that  $(b-r)^2 - 4u(v-m) \geq 0$  and if this condition is not satisfied it would mean that the spillover has not stopped. The  $C_{opt}$  in the latter case will be as obtained in (6.16).

We, further, validate the computed optimal cycle length in (6.18) using several simulation experiments shown in the next section.

## 6.2 Simulation Experiments

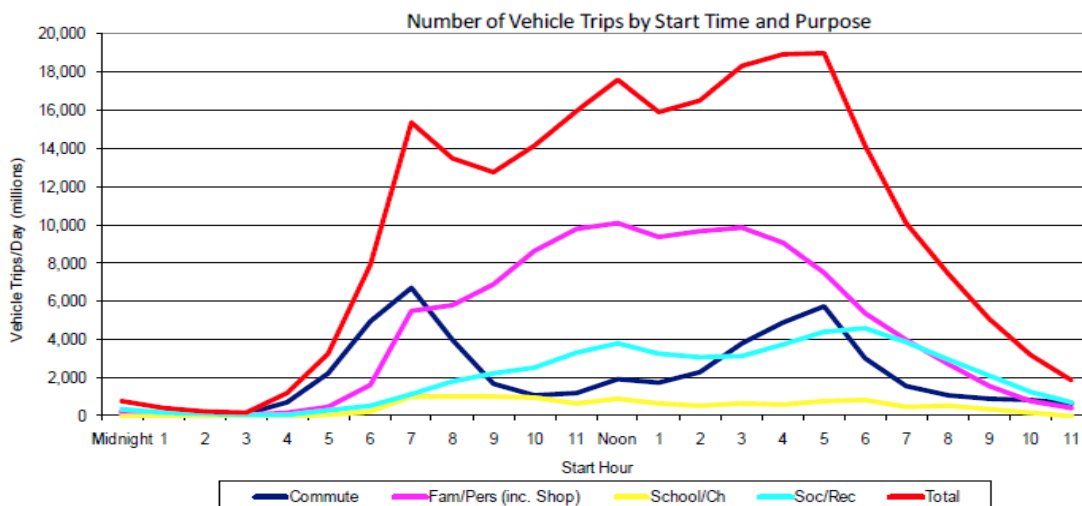
The purpose of the simulation exercise was to validate the derived analytical expressions for optimal cycle length estimation. Performance or the disutility values are obtained for different cycle lengths with two different assumptions of dimensions for DRT rectangular service area, denoted by Case 1 and Case 2.

*Case 1:  $L = 2$  mile,  $W = 0.5$  mile*

*Case 2:  $L = 1$  mile,  $W = 1$  mile*

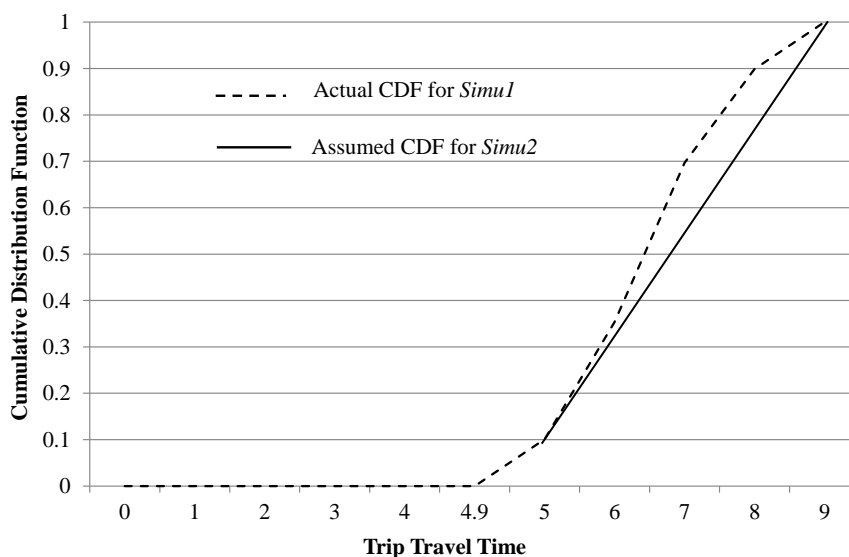
The simulation is performed by coding the DRT operations in MATLAB R2010b. The shortest street based path between any two demand points is computed using the Dijkstra's algorithm using the rectilinear distance between the points. The rectilinear distance is also a good approximation for street based distances between two demand points (Quadrifoglio and Li (2009)). There were 20 replications used for each simulation.

The primary data needed for simulation are the information or some guess of the travel times of the passengers who might use the DRT service. The commuters' trip departure times obtained from the National Household Travel Survey 2009 (NHTS (2009)) were considered to be ideal for choice of potential passengers (assuming the DRT service standards are good). The curves in Fig. 6.5 show different types of trips by start and purpose. It is quite rational to believe that DRT dispatch timings would be the most critical during the peak hours of travel. This is because a number of passengers would be requesting service at too close time intervals (as can be seen during the two peak hour trips from 5 am to 9 am and from 2 pm to 6 pm in Fig. 6.5). For the remaining times of the day the trips are comparatively negligible. Thus, in this study, we focus our analysis for computing optimal cycle lengths for best DRT performance during the peak travel times of the commuters. In this light, we just focus on simulating DRT service during the morning peak hour periods of 5 am to 9 am and estimating the optimal dispatch cycle length for the selected period. A similar simulation analysis can also be carried out separately for the other peak hour trips from 2 pm to 6 pm.



**Figure 6.5** Trip data for the entire United States. (Source: NHTS (2009))

For simplification, the trip data for the commuters are converted to cumulative distribution functions (CDF) as shown in Fig. 6.6. The actual obtained CDF (a polynomial of higher degree and hence, difficult to invert) is modified into an easily invertible piecewise linear function for random generation of travel times for passengers. In simulation, this is achieved by generating random real numbers between 0 and 1, and simply computing the corresponding travel request times using the linear function. A linear CDF is obtained that expresses the uniform random generation of passengers between 5 am to 9 am and this is in tune with a constant demand generated within each of the cycle lengths for analytical model discussed under the section of DRT Service Design methodology earlier. The CDFs are shown through charts in Fig. 6.6.



**Figure 6.6 CDF representing trip travel time for commuting**

Note that the service requests consist of only pick-ups as the passengers would be very likely to depart from their respective homes/locations to the terminal or the nearest transit station during the peak hour of commuting (i.e. 5 am – 9 am) selected for the simulation. However, one could simulate a combination of passenger types: pick-up and drop-off passengers- by choosing appropriately the value of  $\alpha$  as included in the analytical modeling earlier. During the other commuting peak hours for 2 pm to 6 pm, the opposite trend would be quite likely as most passengers would be requesting drop-offs to their respective homes/destinations.

In reality, every passenger would be expected to book a reservation for DRT shuttle service either on Internet or by a phone call to the agency at least half-an-hour in advance before the shuttle dispatch, so that the number of passengers to be picked-up/dropped-off can be decided. Thus, the first dispatch of the shuttle/feeder bus starts at 5:30 am and its service hypothetically assumed to cease after an extra half-an hour time of last service until 9:30 am. This condition (used as a penalty) creates an extra constraint on the service times of the shuttle and the decision on presetting cycle length becomes extremely critical to serve as many passengers as



possible without an extra-ordinary increase in the waiting times. This is crucial in the analysis as most passengers would not wait for too long for pick-up or drop-off. We will show later in results that simulation automatically selects optimum cycle lengths that causes almost negligible passenger spillover.

The service would stop at each pick-up location just once and in a manner to cover all the required nodes obtained using scheduling algorithms on its way back to the terminal. This is similar to the Travelling Salesman Problem (TSP) with an additional time constraint that the vehicle needs to be back at the terminal at the end of each given headway (or cycle length). This is hard to achieve for obtaining an optimal scheduling scheme. Thus, we use well known trip scheduling algorithm 'insertion heuristics' which evaluates and computes a sequence in which the requests are served for using the DRT bus service for a given headway. The simulation model needs bus cycle length as an input to schedule the pick-up in the best possible manner.

The passenger demands used are 50, 80, 100, and 250 for the DRT operation periods between 5:30 am and 9:30 am. The first three demands fall within those that are found in practice from several call-n-ride systems from the Denver Regional Transportation District (RTD) (Potts et al. (2010)) and were checked to be well below the saturation demand for cycle length of 30 minutes.

### 6.3 Results and Discussions

It is obvious that transit operators would prefer to operate DRT services at optimal cycle lengths that will result in minimum passenger disutility. To emphasize this, we analyze the simulation outputs for the two case scenarios discussed earlier with two different lengths and widths and other simulation settings used as outlined in Table 6.7.

The resulting minimum disutility from simulation outputs have been marked using circles in the charts of Fig. 6.7–Fig. 6.8. These charts are only shown for passenger demand = 100 with other optimal cycles and minimum disutility values

**Table 6.7 Input settings for the simulation model**

Parameter	Input Numerical Values
$V$	20 miles per hour (i.e. the average speed in a residential area)
$\frac{\gamma_1}{\gamma_2}$	1.8 Wardman (2004)
Fleet size	1 (A single feeder is assumed to be sufficient due to cost considerations)
Shuttle Capacity	<i>Infinite</i> (or large enough) to accommodate all passengers within a given cycle
Dwell Time	<i>30 seconds</i> (at the depot as well as at the passenger pick-up/drop-off location)
Headway/Cycle Length	<i>Minimum</i> : $(2L + W)/V + 2t_s$ time units (time needed to pick a passenger located at an extreme end of the rectangular area) <i>Maximum</i> : Long enough to capture lowest disutility for each simulation case.

for rest of the demands being tabulated in Table 6.8 – 6.17. The term  $C_m$  stands for the minimum cycle length needed to serve the extreme most passenger located in the area and as suggested for minimum headway/cycle length of Table 6.7. An entry such as 17–18 minutes in the tables means that the minimum disutility is flat over the range of 17 to 18 minutes and any cycle length value in between the range can be regarded as the optimal cycle length.

Four of the curves are used in the charts of Fig. 6.7–Fig. 6.8 for disutility from four different design methodologies adopted for relationship between  $C$  and  $n$  - *Nearest Neighbor* uses method (I), *Approximate TSP* uses method (II), *No-backtracking* uses method (III) and *Random* uses method (IV). The curves *Simu1* consists of the simulation with actual CDF curve and *Simu2* with assumed linear CDF curve as shown earlier in Fig. 6.6. For most parts, the charts in Fig. 6.7–Fig. 6.8 show a close overlap between *Simu1* and *Simu2*. In all the charts of Fig. 6.7–Fig. 6.8, it is observed that the Nearest Neighbor curve gives the minimum disutility, which is obvious as best scheduling policy is followed for operating DRT with this design.

The column  $|\Delta U| \%$  among Tables 6.8 – 6.17 stands for the absolute percentage difference of simulation disutility matched at the optimal cycle lengths obtained from the respective analytical curve for a design method and the actual simulation optimal cycle length (see Fig. 6.7 as an example demonstration for *No-backtracking design*). The values of  $|\Delta U|$  percentages that are exceptionally high in magnitude are not reported in any of the Tables 6.8–6.17 as performance evaluation would be immaterial with the estimated optimal cycle lengths and hence, should not be preferred as better choice of cycle lengths are available with other design methods.

It is observed from the values of Tables 6.8 – 6.17, for extremely low-demand of 50, operating the DRT system with either of the design methods yields  $C_{opt}$  that is close to simulation results. The *No-backtracking design* curve quite closely follows the simulation curves, *Simu1* and *Simu2* for demands = 50, 80 and 100 but deviates

for demand = 250. For demands of 50, 80 and 100, the *Nearest Neighbor* and the *Approximate TSP* yield  $C_{opt}$  (as equal to  $C_m$ ) that deviate from simulation outputs. However, for a very high demand of 250, the *Nearest Neighbor* and *Approximate TSP* curves give optimal cycle lengths and minimum disutility that are very close to the simulation results and almost match  $C_{opt}$ .

The error term (expressed as  $ErrC_{opt}\%$ ) in the tables for the  $C_{opt}$  are with respect to the deviation from the nearest value of optimal cycle lengths of *Simu2*. Note *Simu2* results are more relevant for comparison than *Simu1* as all the analytical modeling has been performed using a constant demand assumption with time for the peak hours of commuting. Also note that the optimal cycle lengths obtained using Nearest Neighbor, Random and Approximate TSP are actually the minimum cycle length values that is mandatory to serve the farthest passenger within a rectangle area ( 14 mins for  $L = 2$ ,  $W = 0.5$  and 9 mins for  $L = 1$ ,  $W = 1$ , respectively). This is also mentioned in Table 6.7 for minimum headway/cycle length needed for simulation.

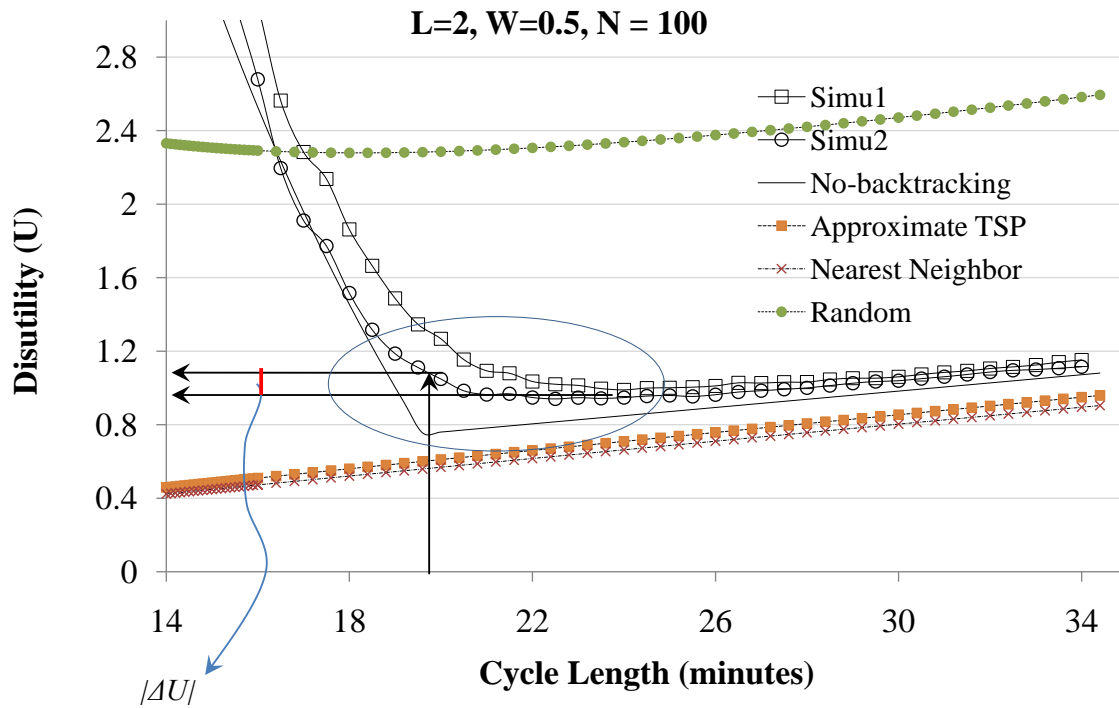


Figure 6.7 Case 1 disutility versus cycle length variation for passenger demand = 100

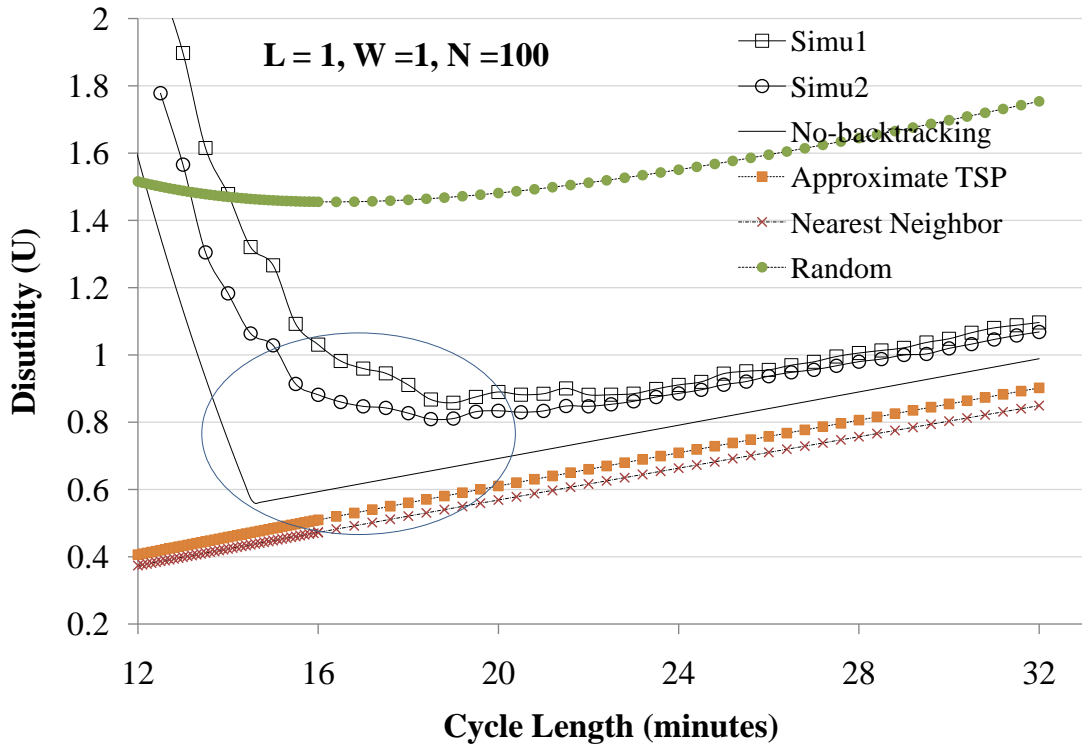


Figure 6.8 Case 2 disutility versus cycle length variation for passenger demand = 100

Table 6.8 Case 1: Simulation results

N	Simu1		Simu2	
	U	$C_{opt}$	U	$C_{opt}$
50	0.83	17-18	0.82	16-19
80	0.90	20-22	0.88	19-22
100	1.00	23-27	0.90	22-26
250	2.2	41-45	2.1	44-47

**Table 6.9 Case 1: Analytical results with Design Method I**

N	U	$C_{opt}$	$ \Delta U  \%$	Err $ C_{opt}  \%$
50	0.30	$C_m$	–	14
80	0.38	$C_m$	–	35
100	0.44	$C_m$	–	57
250	1.10	27	27	4

**Table 6.10 Case 1: Analytical results with Design Method II**

N	U	$C_{opt}$	$ \Delta U  \%$	Err $ C_{opt}  \%$
50	0.30	$C_m$	–	14
80	0.41	$C_m$	–	35
100	0.45	$C_m$	–	57
250	1.61	<b>35</b>	12	0

**Table 6.11 Case 1: Analytical results with Design Method III**

N	U	$C_{opt}$	$ \Delta U  \%$	Err $ C_{opt}  \%$
50	0.58	<b>16</b>	0	0
80	0.60	<b>18</b>	16	5
100	0.70	<b>19</b>	22	12
250	2.20	45	57	27

**Table 6.12 Case 1: Analytical results with Design Method IV**

N	U	$C_{opt}$	$ \Delta U  \%$	Err $ C_{opt}  \%$
50	0.50	$C_m$	–	14
80	1.70	18	–	6
100	2.30	18	–	18
250	1.60	$C_m$	–	14

**Table 6.13 Case 2: Simulation results**

		Simu1		Simu2	
N	U	$C_{opt}$	U	$C_{opt}$	
50	0.71	14-15	0.70	13-17	
80	0.81	16-18	0.80	15-19	
100	0.88	19-21	0.82	17-20	
250	2.20	42-44	1.83	36-40	

**Table 6.14 Case 2: Analytical results with Design Method I**

N	U	$C_{opt}$	$ \Delta U  \%$	Err $ C_{opt}  \%$
50	0.20	$C_m$	–	44
80	0.27	$C_m$	–	67
100	0.28	$C_m$	–	88
250	1.10	26	–	3



**Table 6.15 Case 2: Analytical results with Design Method II**

N	U	$C_{opt}$	$ \Delta U  \%$	Err $ C_{opt}  \%$
50	0.27	$C_m$	–	44
80	0.30	$C_m$	–	67
100	0.31	$C_m$	–	88
250	1.60	<b>35</b>	11	2

**Table 6.16 Case 2: Analytical results with Design Method III**

N	U	$C_{opt}$	$ \Delta U  \%$	Err $ C_{opt}  \%$
50	0.40	<b>10.7</b>	0	17
80	0.45	<b>12.7</b>	21	15
100	0.56	<b>14.5</b>	30	15
250	2.40	25.7	–	0

**Table 6.17 Case 2: Analytical results with Design Method IV**

N	U	$C_{opt}$	$ \Delta U  \%$	Err $ C_{opt}  \%$
50	0.30	$C_m$	–	44
80	0.70	$C_m$	43	51
100	1.50	15.3	–	18
250	1.52	$C_m$	125	42

With no-backtracking design method III, the results show a good match for optimal cycle lengths with the simulation plots of *Simu1* and *Simu2*, especially for lower demands. Thus, the *No-backtracking* policy is compared with some of the existing real case transit system examples that experience similar low demands. Comparisons

are made with RTD Call-n-Ride (CnR) that function similar to demand responsive transit with the data from the month of October 2008 (see Table 6.18) and the peak headway used by the operating transit agencies. An image in Fig. 6.9 shows a snapshot of the spread of RTD CnR services which are mostly concentrated towards suburban areas.

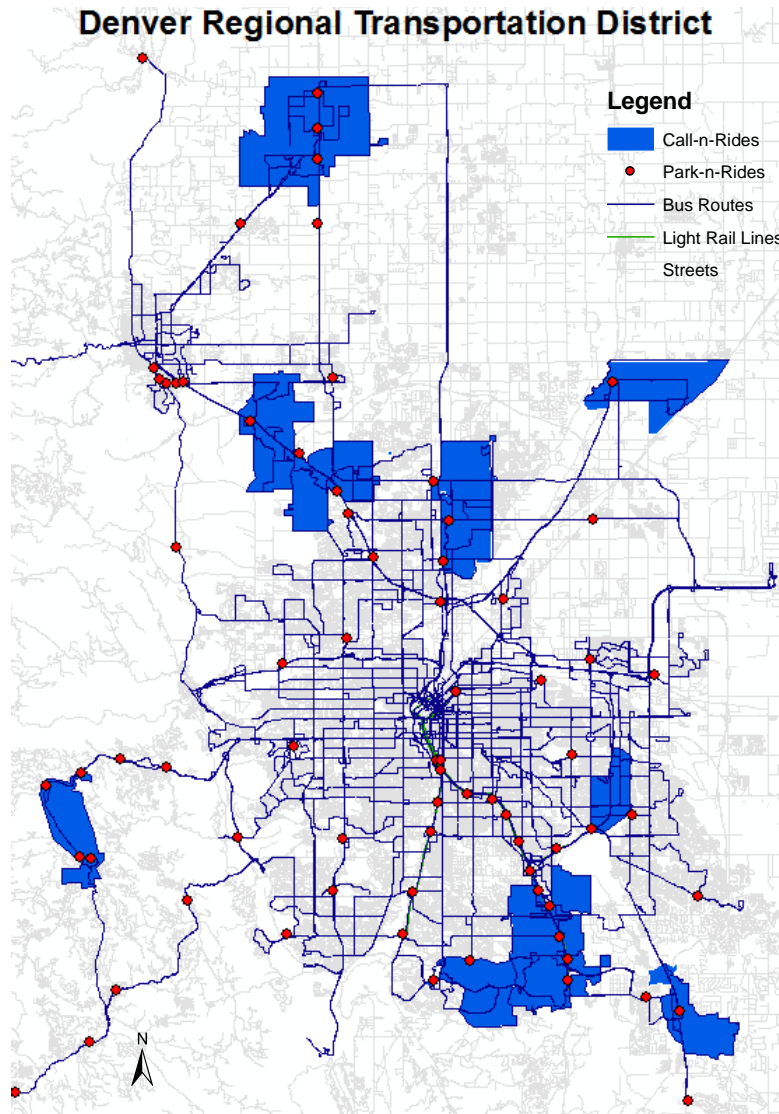


Figure 6.9 Denver RTD Call-n-Ride System Map

The spatial distribution of the passenger requests is assumed to be uniform over the rectangular service area for the real CnR services which is the same assumption as for deriving the analytical framework in (6.17). This is a very approximate assumption of demand distribution as for most of the CnR Routes (except for Lone Tree). The peak hours are assumed to be from 5 am to 9 am as assumed in the simulation.

Analytical peak headways/cycle lengths computed for these Routes show close similarities with the peak hour headways used in practice with no-backtracking design method. The sharp deviation in peak headway is observed for Lone Tree Route due to incorrect assumption of a uniform demand distribution over the area.

**Table 6.18 Performance and service information data for RTD Call-n-Ride**

Performance Data		Service Information				
Route	Boardings Per Service Hour	Area Coverage (sq. mile)	Approx. L (miles)	Approx. W (miles)	Peak Headway in Practice (min)	Peak Headway Analytical (min)
N Inverness	9.5	2.12	1.5	1.5	10	15.7
Meridian	8.7	1.07	1.6	0.9	15	13.8
Interlocken	7.7	5.39	3.0	1.7	30	26.7
S Inverness	7.4	1.11	1.5	0.7	10	12.1
Broomfield	4.5	7.13	3.2	2.2	30	27.4
Louisville	4.1	8.20	3.3	2.5	30	28.6
Dry Creek	3.8	4.74	2.5	2.0	30	21.6
Lone Tree	3.3	6.35	3.3	1.8	60	25.8

Call-n-ride services for which peak headway data were available (Potts et al. (2010)); approximate values of length and width are obtained using Google Earth; peak headways are calculated using equation (6.17) and design method (*III*).

#### 6.4 Summary and Research Contribution

This part of the dissertation develops an analytical model for estimating optimal service cycle length of a demand responsive feeder transit (DRT) service designed to serve passengers, especially during peak periods. Demand data from National Household Travel Survey 2009 are used for model development. The proposed model describes the relationship between the scheduled ‘time points’ for vehicle dispatch and service standards provided to customers, allowing for an easy computation of near optimal cycle length, which otherwise can only be estimated through exhaustive simulations. With an optimal cycle length, obtained for any given demand and service area, desired transit service standards can be achieved. In this study, we define the weighted sum of the passengers’ expected waiting time and expected riding time that represents transit service standards, as disutility. The objective function consists of minimization of this disutility function. The proposed model is validated through simulations in which a heuristic based scheduling strategy (popularly known as “insertion heuristic”) is used for efficient pick-up/drop-off of passengers.

The timely dispatch of DRT shuttles at optimal cycle lengths results in the best feeder system performance most crucial at peak periods of demand. To retain and increase existing ridership, deciding on the most preferred (or optimal) cycle length is crucial. It is observed that this optimal cycle length can be computed with ease using simple analytical model presented in this part of study, thus, cutting on time and energy in obtaining the same results by performing exhaustive simulations. The analytical model for obtaining an optimal cycle length proposed in this dissertation is sensitive to demand and feeder service area and can be readily used to decide best dispatch policies to operate demand responsive feeder transit system. For service

areas of length = 2 miles, width = 0.5 mile, and demands 50–100, the optimal cycle lengths vary between 17–27 minutes for the peak hours of commuting. For exactly same passenger demand values and for a length of 1 mile and width of 1 mile of the service area, the approximate optimal cycle lengths are found to be 13–20 minutes.

Further, increasing the passenger demand to 250, optimal cycle lengths for service area of length 2 miles and width 0.5 mile are found to vary between 30 to 34 minutes. The optimal values for service areas of length 1 mile and width 1 mile are in the range of 28–32 minutes. Comparisons with a real example from Denver's RTD of flexible Call-n-Ride service shows that model predicts a much accurate optimal cycle length that could be used to enhance passenger service standards of the transit.

This study showed that the disutility value corresponding to the cycle length recommended by the analytical model differed very modestly from the optimal value calculated by simulation for different sets of feeder service areas and demand densities. Hence, for any community having a travel demand behavior falling within the national household statistics, the proposed model can be used for designing and better operating DRT-based feeder systems. Researchers and planners concerned about transit scheduling can use the analytical model derived in this section to devise strategies to cause minimal loss to revenue by optimizing vehicle dispatch times. Any other model that specifies value of number of passengers served for a given value of cycle length, can be integrated to the proposed analytical model of this section to evaluate the efficiency of any under-performing demand-responsive, call-n-ride or dial-a-ride transit system.

## 7. POLICY OBJECTIVES AND ISSUES FROM SOME BEST PRACTICES

This section summarizes policy objectives and issues with currently existing flexible public transportation services operating throughout the United States. Analysis of five of the demand transit services, functioning as flexible public transportation service by different agencies, are presented from the Transit Cooperative Research Synthesis 2010 Report (Potts et al. (2010)). Policy objectives for best practices from these successful flexible public transportation services have been discussed along with recommendations to issues raised for their operations. These recommendations are based on the work performed in this dissertation and the author is confident of observing significant improvements in demand responsive services if the policy recommendations are appropriately implemented.

### 7.1 Mason County Transportation Authority (MCTA)

#### 7.1.1 Policy Objectives

The Mason County Transportation Authority (MCTA) operates demand-responsive transit service for the general public throughout the Mason County (WA) and some nearby connected counties. MCTA operates fixed route services to cater to an increasing ridership demand and favorable travel demand patterns. These fixed routes are also provided with deviations (up to 1 mile) in the form of a flexible demand-responsive features off the route. The purpose is to provide access to those who experience difficulty in getting to a bus stop. The image in Fig. 7.1 shows existing Route 5 which undergoes deviation from its fixed route.

The primary policy objective of providing a flexible transit by the MCTA is to cover a large area, which has an existing low-demand density, with transit. By operating flexible public transportation services, other similar services which might incur expenditure such as ADA-complementary transit services, are also eliminated.

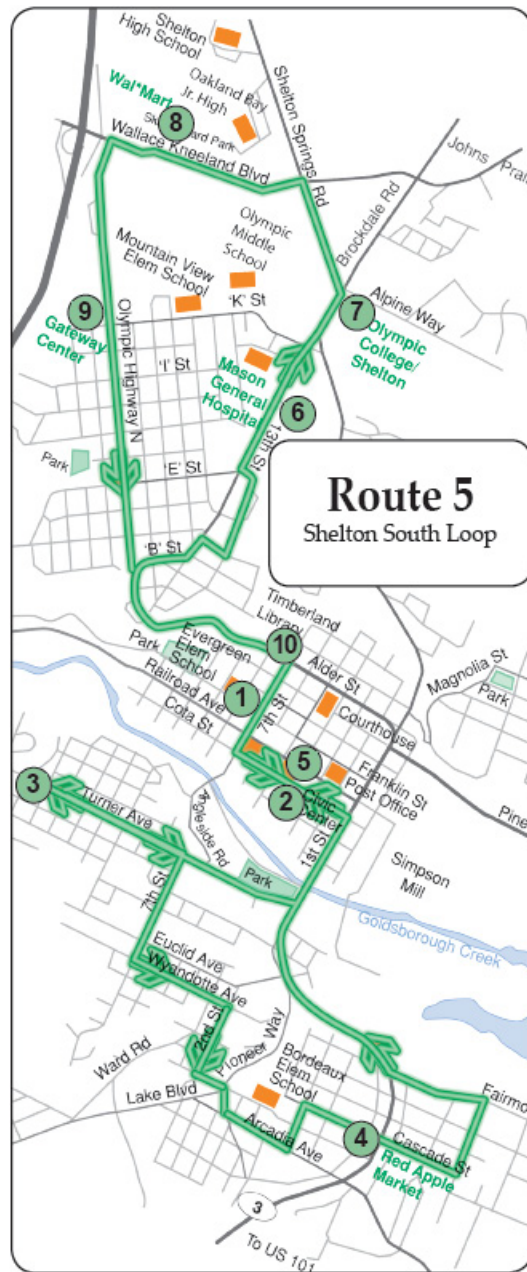


Figure 7.1 Route 5, Mason County Transportation Authority (Source: MCTA (2012))

## 7.1.2 Operational Issues and Recommendations

Mason County Transportation Authority is in need for better operating of flexible transit systems. One of the main concerns for the flexible transit operators of MCTA is the problem of scheduling. An improved technology is needed for solutions to problems of dispatching the shuttles in an optimal manner. However, with changes in geographic topography of the service areas, even advanced technologies such as Automated Vehicle Location (AVL) are rendered ineffective. Fortunately, the models presented in this dissertation can be easily used to address this problem and derive optimal dispatch policies for any topographic service area and demand density value. An improvement in built environment can also be carried out to meet the desired topographical requirement using a better street connectivity indicator concept proposed in this dissertation.

## 7.2 St. Joseph Transit

### 7.2.1 Policy Objectives

St. Joseph Transit operates flexible public transportation service within the City of St. Joseph, Missouri. The policy objective of flexible transit system is to provide coverage to large and low demand density areas. Flexible transit systems also reduce the expense of providing ADA-paratransit service and arise from the fixed-route system with possible route deviations whenever request for stops are made outside these regular fixed routes. The bus stops for route deviations are usually the pre-approved locations. The allowed deviations from fixed routes are not more than (3/4) mile from the designated fixed route. There is also restriction in the number of deviations that the buses can make with a maximum of 10 deviations per trip. As per the report documented by Potts et al. (2010), an estimated 25 percent of



approximately 1400 daily passengers form the deviation passengers. The image in Fig. 7.2 shows the transit route map of Route 11 of St. Joseph Transit.

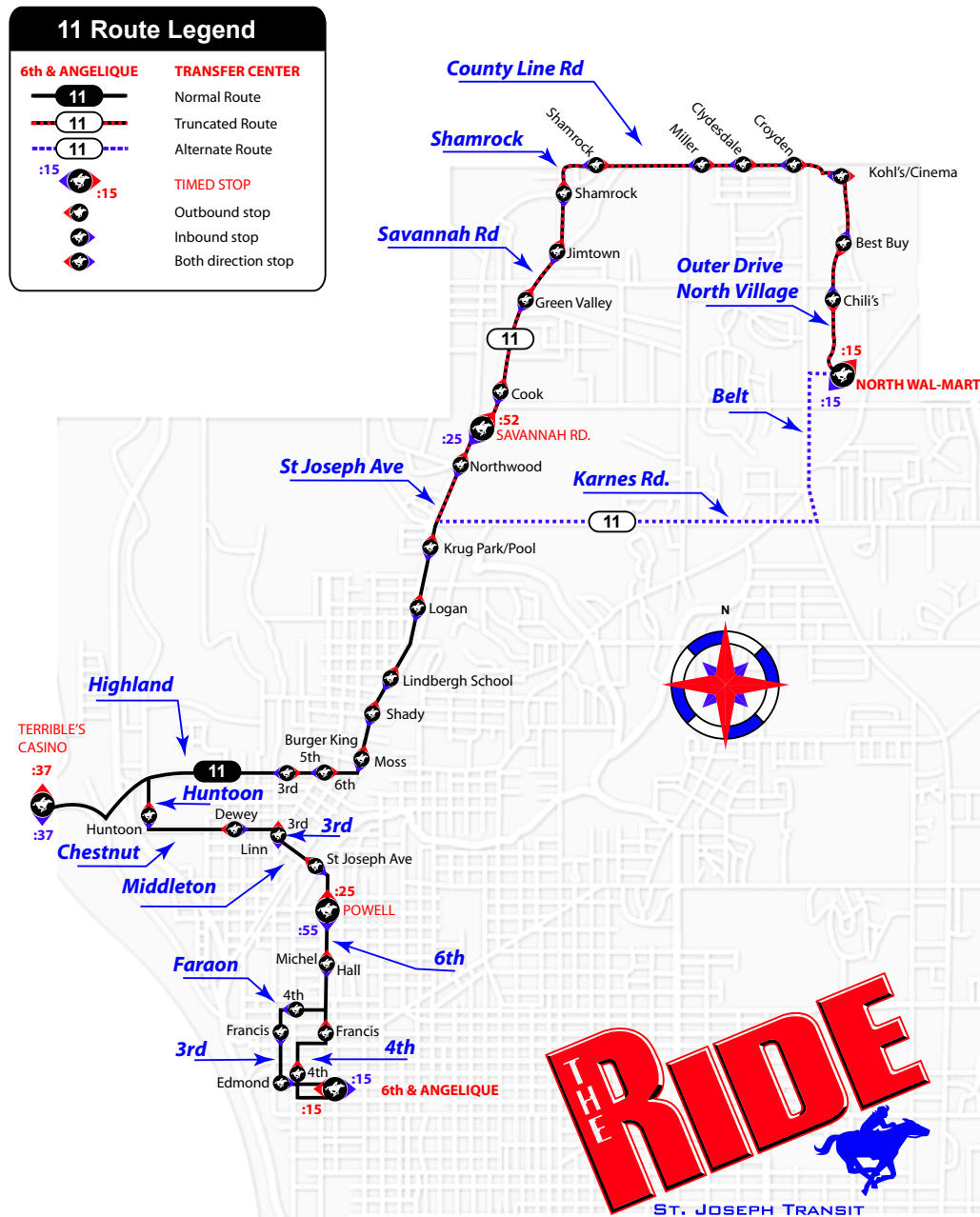


Figure 7.2 Route 11, St. Joseph Transit (Source: SJT (2012))

## 7.2.2 Operational Issues and Recommendations

Operational issues for operating a flexible transit system by St. Joseph Transit agency results from financial constraints, forcing the agency to use lesser number of shuttles for service with increased headways. This leads to too much of extra waiting and in-vehicle traveling by passengers – a practice which ultimately leads to low ridership and killing almost any possibility of having a fixed-route service from ridership increase. This problem can be partially solved by at least operating the transit services with optimal cycle length based on models suggested in this research. Further analysis of the street connectivity can lead to better policy and decision making by the St. Joseph Transit agency in operating a successful and profitable flexible transit system.

## 7.3 Potomac and Rappahannock Transportation Commission (PRTC)

### 7.3.1 Policy Objectives

The Potomac and Rappahannock Transportation Commission (PRTC) provides transit service along the busy I-95 and I-66 corridors in Northern Virginia and parts of the southwest of Washington, DC. The transit service provided by PRTC is known by different names such as Omnilink that operates as a local demand-responsive bus service. This demand-responsive bus service operates as a route-deviation system in conjunction with fixed-route characteristics. The transit service is provided for all area residents and no separate ADA paratransit service is operated.

The policy objective of the PRTC in providing a demand-responsive type of flexible transit service consists of providing coverage to large and low-demand density areas. The flexible transit service aims to balance customer access and routing efficiency with a more frequent service on routes for all riders. Buses operated by the PRTC follow a fixed route and schedule and deviate off route upon request by

passengers. The deviation service is provided for not more than (3/4) mile distance on either sides of each route. After every deviation, the buses always return to the regular route and are required to serve all stops. The image in Fig. 7.3 shows one of the examples of the PRTC route of Woodbridge/Lake Ridge Omnilink transit system.

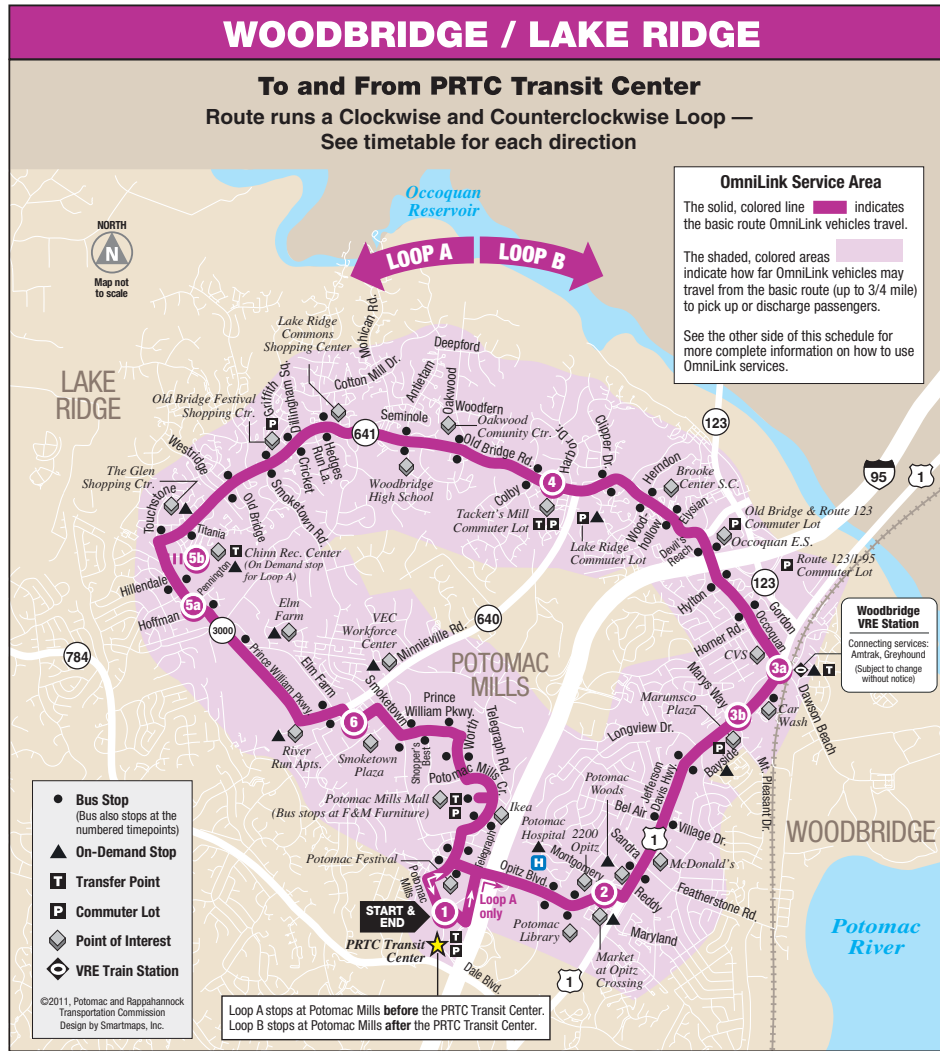


Figure 7.3 Woodbridge/Lake Ridge Omnilink transit system (Source: PRTC (2012))

### 7.3.2 Operational Issues and Recommendations

The operational issues are mainly the scheduling and dispatching related to transit buses. PRTC uses Intelligent Transportation Systems (ITS) technology and real-time information for overcoming difficulties faced in bus schedules and dispatch. In fact, PRTC is one of the first transit agency in the United States that automated flex-route project. Trip deviations by the flexible transit buses are such that there is no more than 5 minutes delay at each stop. The flexible transit services provided by PRTC can be further enhanced by improving shuttle operations using the strategies suggested in this dissertation, such as deciding on the critical link and re-routing in case of street link closures if a grid street system is involved. Further, investigating optimal block lengths where the flexible transit system can operate best within a grid street framework. The assessment of any street by a connectivity indicator can help further reduce delays in operating flexible transit service.

## 7.4 Charleston Area Regional Transportation Authority (CARTA)

### 7.4.1 Policy Objectives

Flexible transportation services are provided by The Charleston Area Regional Transportation Authority (CARTA) in four flexible zone routes serving areas of Charleston, South Carolina. The map in Fig. 7.4 shows the 402 Bus route for Isle of Palms and Sullivan's Island Zone that has flex-route service. Advance requests might be made to use the flexible bus services to board at a given stop along the route. Similar to most other flexible transportation services in the United States, CARTA aims to provide transportation coverage to large and low-demand density areas as part of its policy objective. The purpose of providing a flexible service is also to create potential for a future fixed-route service in the area that would result in increased revenues and profits.



Figure 7.4 Flex Bus Route 402 for Isle of Palms and Sullivan's Island Zone shown as dotted line (Source: CARTA (2012))

## 7.4.2 Operational Issues and Recommendations

Like most other transit agencies in the United States, operating flexible transit services requires funds which is a major concern for CARTA. Moreover, a distinct performance measure is still missing that could assess the level of service provided by the flexible transit. Hence, the methodologies used in this dissertation can be utilized to set level-of-service standards to assess performance of a demand responsive transit (which is a flexible transit system). Specifically, models such as that for the new street connectivity indicator, reflective of the built environment, can be used to precisely evaluate performance of the flexible transit.

## 7.5 Omnitrans

### 7.5.1 Policy Objectives

Omnitrans provides transit services to the County of San Bernardino and the cities of Chino, Colton, Fontana, Loma Linda, Montclair, Ontario, Redlands, Rialto, San Bernardino, and Upland in California. OmniLink operated by Omnitrans is a complete dial-a-ride service. Currently, two routes in the communities of Chino Hills and Yucaipa have the flexible public transportation service facility operated under OmniLink (see Fig. 7.5 and Fig. 7.6). The policy objective of Omnitrans in implementing flexible public transportation service is to provide transit service to low-demand density areas for which fixed-route transit is not feasible.

### Omnilink Chino Hills

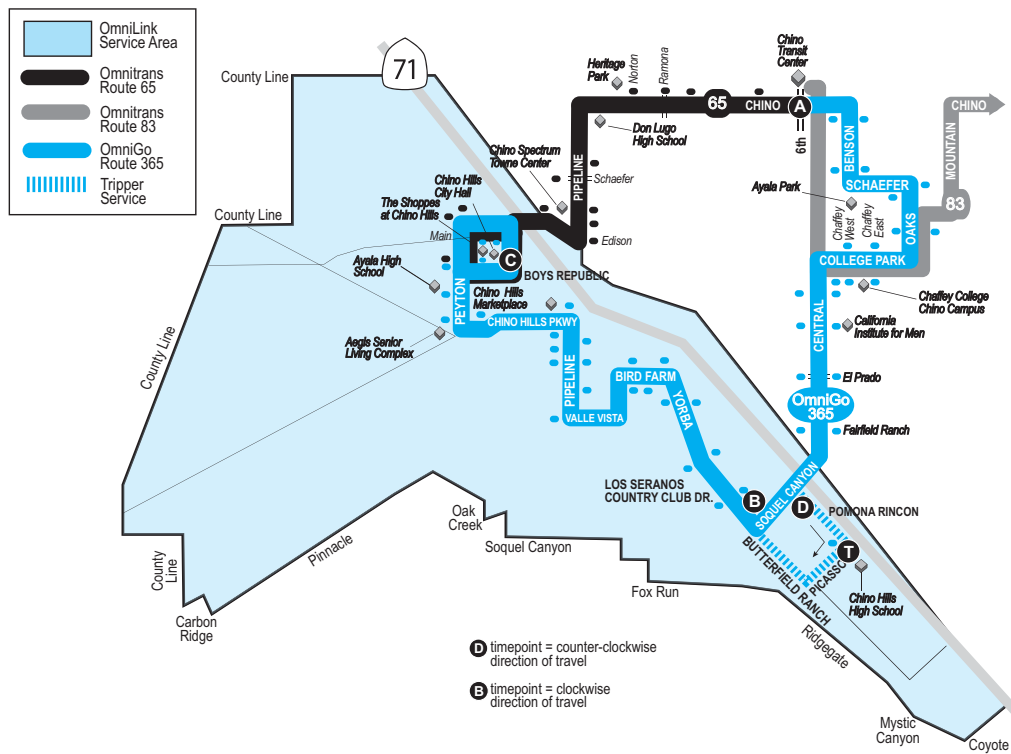


Figure 7.5 Flexible public transportation service in the Chino Hills (Source: Omnitrans (2012))

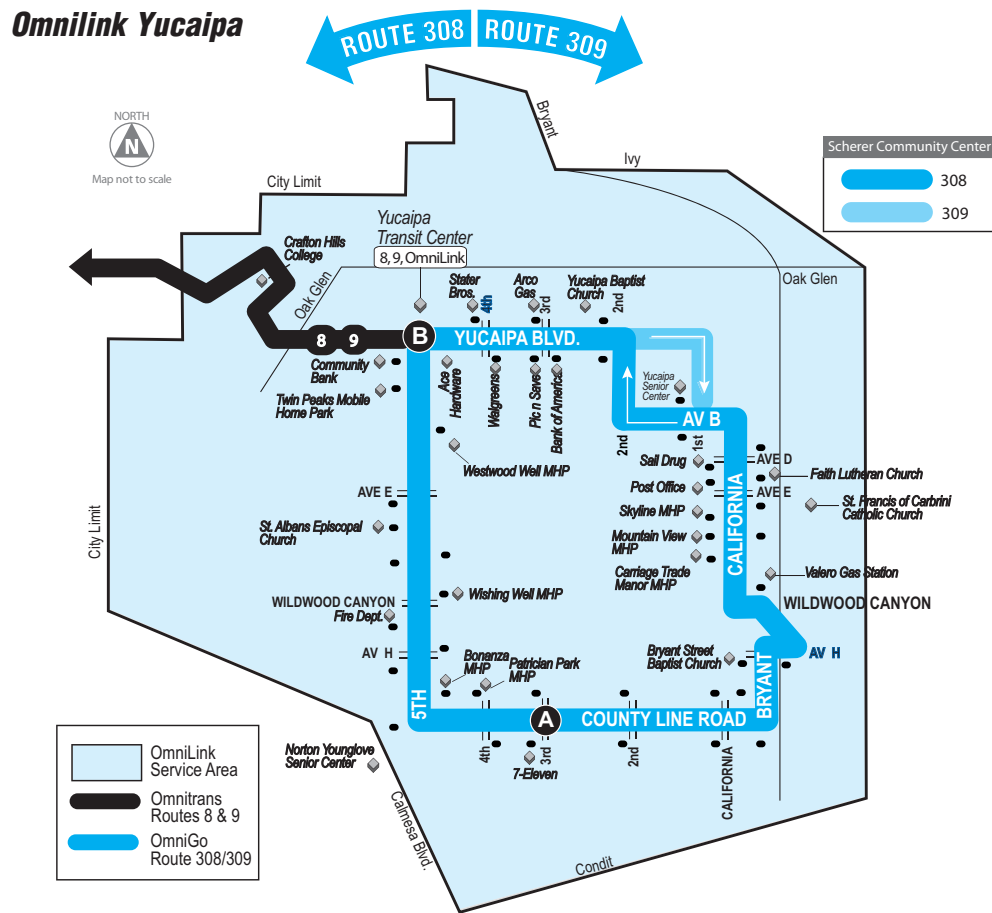


Figure 7.6 Flexible public transportation service in the Yucaipa area (Source: Omnitrans (2012))

### 7.5.2 Operational Issues and Recommendations

Omnitrans aims to enhance passengers per revenue hour by making scheduling improvements. In this perspective, models for optimal scheduling in this dissertation will be very handy for planners and transit operators of Omnitrans in improving strategies for shuttle dispatch. Further, the relationship between street system and shuttle performance through the new connectivity indicator can also be utilized to enhance ridership. This can be supplemented by analyzing critical street links along with optimal block lengths within a grid street network system for dial-a-ride transit.



## 8. CONCLUSIONS

The proposed research addresses four main issues related to predicting and improving first/last mile feeder demand responsive transit performance with regard to street network connectivity in a given community. Four motivating and interrelated tasks that drove this research consist of

(i) *quantification of existing travel demand and street network density into a single street connectivity indicator and using this connectivity indicator as a predictor of DRT performance*

(ii) *using the new street connectivity indicator to evaluate the criticality of street link(s) for a grid street network system,*

(iii) *further, using the indicator to derive optimal street block lengths for best DRT performance over a grid street framework, and finally,*

(iv) *developing an optimal scheduling model with rectilinear metric approximations to real street-based paths in order to predict the best DRT service standards.*

Feeder transit services provide the ultimate first/last mile access for passengers and their performance is intuitively dependent upon the street network design and its connectivity, as vehicles are potentially required to reach any point in the service area to serve the demand. The higher the network connectivity and lower demand, the faster and more efficiently vehicles are able to serve customers and the better the feeder transit service performance. A more informative and more detailed relationship between the road network design (and its connectivity) and the expected transit performance has been presented in this work that would be very desirable

information to have for properly planning the development of residential areas with the goal of enhancing their transportation mobility. Subsequently, this correlation has been scientifically investigated and presented in this dissertation. Thus, quantification of demand density and street density into a single street connectivity index is an important product of this work which would enable planners and policy makers predict DRT performance with ease.

The fact that all individual links in a street network play a role in impacting DRT performance, the information regarding the critical links would help in reconstructing shuttle routes during passenger pick-up/drop-off in case of a particular link's failure. Certainly connectivity would be impacted due to a link's removal or addition into a street network. This in turn should influence DRT performance. Shuttle dispatch cycle lengths can also be adjusted to counter-effect performance degradation of the DRT. Under such variable occurrences, this part of the research makes a vital contribution to describing interrelationships among the new derived connectivity index, street block lengths and shuttle cycle lengths to decide on the critical link(s) over a grid street network system.

Though literature reviews have shown that street connectivity is directly related to block lengths and efficient shuttle dispatch times are important for DRT performance, there is an absence of clear process that could show how street-based paths and shuttle dispatch cycle lengths might affect DRT performance. This research precisely fills this missing gap. On one hand, an optimal street block length would help planners decide on street spacing for efficient transit systems and the optimal cycle length, on the other hand, would allow operators to decide best dispatch policies for improving transit service quality.

The topics explored in this dissertation would be vital as connectivity studies are useful in implementation of traffic plans that reduce Vehicle Miles Traveled and policies existing at the present times do not precisely link performance measure of a transit with respect to street network design and shuttle dispatch cycle lengths.

## REFERENCES

- Ahouissoussi, N.B.C., M.E. Wetzstein. 1998. A comparative cost analysis of biodiesel, compressed natural gas, methanol and diesel for transit bus systems. *Resource and Energy Economics* **20** 1–15.
- Aldaihani, M., L. Quadrifoglio, M. Dessouky, R.W. Hall. 2004. Network design for a grid hybrid transit service. *Transportation Research, Part A: Policy and Practice* **38** 511–530.
- Allen, E. 1997. Measuring the new urbanism with community indicators. *In Contrasts and Transitions, American Planning Association National Conference American Planning Association, San Diego, CA.*
- Alp, O., N. K. Erkip, R. Gullu. 2003. Optimal lot–sizing/vehicle-dispatching policies under stochastic lead times and stepwise fixed costs. *Operations Research* **51** 160–166. URL <http://www.jstor.org/stable/3088558>.
- APTA. 2012. *American Public Transportation Association*. URL <http://www.apta.com/RESOURCES/STATISTICS/Pages/ridershipreport.aspx>. Accessed on 2nd February 2012.
- Aultman-Hall, L., M. Roorda, B. Baetz. 1997. Using gis for evaluation of neighborhood pedestrian accessibility. *Journal of Urban Planning and Development* **123** 10–17.
- Baaj, M. H., H.S. Mahmassani. 1995. Hybrid route generation heuristic algorithm for the design of transit networks. *Transportation Research C* **3** 31–50.
- Badami, M. G., M. Haider. 2007. An analysis of public bus transit performance in indian cities. *Transportation Research Part A: Policy and Practice* **41(10)** 961–981.

- Balakrishnan, A., T. L. Magnanti, P. Mirchandani. 1994. A dual-based algorithm for multi-level network design. *Management Science* **40** 567–581.
- Ball, M. O., B. L. Golden. 1989. Finding the most vital arcs in a network. *Operations Research Letters* **8** 73–76.
- Ballou, R. H., H. Rahardja, N. Sakai. 2002. Selected country circuitry factors for road travel distance estimation. *Transportation Research Part A : Policy and Practice* **36** 843–848.
- Barr, R. S., B.L. Golden, J.P. Kelly, M.G.C. Resende, W.R. Stewart. 1995. Designing and reporting on computational experiments with heuristic methods. *Journal of Heuristics* **1** 9–32.
- Beardwood, J., J. H. Halton, J. M. Hammersley. 1959. The shortest path through many points. *Proc. Cambridge Philos. Soc.* **55** 299–327.
- Bertini, R., A. El-Geneidy. 2004. Using archived data to generate transit performance measures. *Transportation Research Record* **1841** 109–119.
- Boarnet, M., R. Crane. 2001. The influence of land use on travel behavior: specification and estimation strategies. *Transportation Research Part A* **35** 823–845.
- Boarnet, M., S. Sarmiento. 1998. Can land-use policy really affect travel behavior? a study of the link between non-work travel and land-use characteristics. *Urban Studies* **35** 1155–1169.
- Calgary. 2010. *Plan it Calgary – Local Transportation Connectivity Study*. URL [www.calgary.ca/planit/](http://www.calgary.ca/planit/). Accessed on 22nd August 2010.
- Cambridge Systematics, Inc. 1999. Performance based planning manual: Multimodal transportation development of a performance based planning process. National Cooperative Highway Research Program Project 8-32(2). TRB, National Research Council, Washington, D.C.

- Campbell, A. M., M. Savelsbergh. 2004. Efficient insertion heuristics for vehicle routing and scheduling problems. *Transportation Science* **38(3)** 369–378.
- Cardillo, A., S. Scellato, V. Latora, S. Porta. 2006. Structural properties of planar graphs of urban street patterns. *Phys. Rev. E* **73** 66–107.
- CARTA. 2012. *Charleston Area Regional Transportation Authority (SC) – Transit System*. URL <http://www.ridecarta.com/>. Accessed on 12th January 2012.
- Ceder, A., Y. Israeli. 1998. User and operator perspective in transit network design. *The 77th Annual Meeting of TRB, Washington, DC*.
- Cervero, R., R. Gorham. 1995. Commuting in transit versus automobile neighborhoods. *Journal of the American Planning Association* **61(2)** 210–224.
- Cervero, R., K. Kockelman. 1997. Travel demand and the 3ds: Density, diversity, and design. *Transportation Research D* **2** 199–219.
- Cervero, R., C. Radisch. 1995. Travel choices in pedestrian versus automobile oriented neighborhoods. *Transport Policy* **3** 127–141.
- Chan, N., S. Shaheen. 2011. Ridesharing in north america: Past, present and future. *Transportation Research Board Annual Meeting*.
- Chandra, S., L. Quadrifoglio. 2012. A new connectivity indicator to predict performance for feeder transit services. *Transport Research Board 2012 Annual Meeting, Transportation Research Board, Washington DC, Paper no. 2160.*
- Chandra, S., C-W. Shen, L. Quadrifoglio. 2011. A simulation study to derive the optimal cycle length for feeder transit services. *International Journal of Information Systems in the Service Sector* **3(3)** 27–47.
- Chang, S.K.J., S.C. Hsu. 2004. Modeling of passenger waiting time in multimodal station with constrained capacity on intercity transit. *Journal of the Eastern Asia Society for Transportation Studies* **8(1)** 51–60.

- Chowdhury, M. S., S. I.-J. Chien. 2001. Dynamic vehicle dispatching at intermodal transfer station. *Transportation Research Record* **1753** 61–68.
- Chowdhury, M. S., S. I.-J. Chien. 2011. Joint optimization of bus size, headway and slack time for efficient timed transfer. *Transportation Research Record* **2218** 48–58.
- Cordeau, J. F. 2006. A branch-and-cut algorithm for the dial-a-ride problem. *Operations Research* **54** 573–586.
- Cordeau, J. F., G. Laporte. 2007. The dial-a-ride problem: Models and algorithms. *Ann Oper Res* **152** 29–46.
- Corley, H. W., D. Y. Sha. 1982. Most vital links and nodes in weighted networks. *Operations Research Letters* **1** 157–160.
- Cortes, C. E., L. Pages, R. Jayakrishnan. 2005. Microsimulation of flexible transit system designs in realistic urban networks. *In Transportation Research Record: Journal of the Transportation Research Board of the National Academies, Washington, D.C.* **1923** 153–163.
- Crane, R., R. Crepeau. 1998. Does neighborhood design influence travel?: A behavioral analysis of travel diary and gis data. *Transportation Research D* **3** 225–238.
- Current, J. R., C. S. Revelle, J. L. Cohon. 1986. The hierarchical network design problem. *European J. Opnl. Res.* **27** 57–66.
- Daganzo, C. F. 1990. Some properties of polling systems. *Queueing Syst.* **6(2)** 137–154.
- Daganzo, C. F. 2010. Structure of competitive transit networks. *Transportation Research Part B* **44 (4)** 434–446.

- Daganzo, C.F. 2004. *Logistics Systems Analysis*. Springer-Verlag, Heidelberg, Germany.
- DeMaio, P. 2009. Bike-sharing: history, impacts, models of provision, and future. *Journal of Public Transportation* **14** (4) 41–56.
- Derrible, S., C. Kennedy. 2010a. Characterizing metro networks: state, form, and structure. *Transportation* **37**(2) 275–297.
- Derrible, S., C. Kennedy. 2010b. Evaluating, comparing, and improving metro networks: an application to the toronto proposed plans. *Transportation Research Record* **2146** 43–51.
- Derrible, S., C. Kennedy. 2010c. The complexity and robustness of metro networks. *Physica A : Statistical Mechanics and Its Applications* **389**(17) 3678–3691.
- Dessouky, M. M., R. Hall, A. Nowroozi, K. Mourikas. 1999. Bus dispatching at timed transfer transit stations using bus tracking technology. *Transportation Research Part C* **7** (4) 187–209.
- Diana, M., M. Dessouky. 2004. A new regret insertion heuristic for solving large-scale dial-a-ride problems with time windows. *Transportation Research Part B: Methodological* **38**(6) 539–557.
- Diana, M., M. M. Dessouky, N. Xia. 2006. A model for the fleet sizing of demand responsive transportation services with time windows. *Transportation Research, Part B: Methodological* **40** 651–666.
- Dill, J. 2004. Measuring network connectivity for bicycling and walking. *Transport Research Board 2004 Annual Meeting, Transportation Research Board, Washington DC, (CD-ROM)*.

- Estrada, M., M. Roca-Riu, H. Badia, F. Robuste, C. F. Daganzo. 2011. Design and implementation of efficient transit networks: procedure, case study and validity test. *Transp Res, Part A, Policy Pract* **45** 935–950.
- Ewing, R. 1996. Best development practices: Doing the right thing and making money at the same time. Tech. rep., American Planning Association, and Chicago, IL. American Planning Association, and Chicago, IL.
- Fawaz, M. Y., G. F. Newell. 1976a. Optimal spacing for a rectangular grid transportation network–i. *Transportation Research* **10(2)** 111–29.
- Fawaz, M. Y., G. F. Newell. 1976b. Optimal spacings for a rectangular grid transportation network–ii: revised assignments. *Transportation Research* **10** 121–129.
- Fielding, G. H., T.T. Babitsky, M.E. Brenner. 1985. Performance evaluation for bus transit. *Transportation Research A* **19(1)** 73–82.
- Fitzpatrick, K., K. M. Hall, D. Perkinson, R. L. Nowlin, R. Koppa. 1996. *Guidelines for the location and design of bus stops*. Texas Transportation Institute at Texas A&M University. Transit Cooperative Research Program Project A – 19.
- Frank, L. D., B. Stone Jr., W. Bachman. 2000. Linking land use with household vehicle emissions in the central puget sound: methodological framework and findings. *Transportation Research Part D* **5** 173–196.
- Gaboune, B., G. Laporte, F. Soumis. 1993. Expected distances between two uniformly distributed random points in rectangles and rectangular parallelepipeds. *J. Oper. Res. Soc.* **44 (5)** 513–519.
- Gleason, J. M., D.T. Barnum. 1986. Toward valid measures of public sector productivity: Performance measures in urban transit. *Management Science* **28(4)** 379–386.



- Greenwald, M., M.G. Boarnet. 2001. The built environment as a determinant of walking behavior analyzing non-work pedestrian travel in portland, oregon. *Transp Res Record* **1780** 33–42.
- Haas, P. M., C. Makarewicz, A. Benedict, S. Bernstein. 2009. Estimating transportation costs by characteristics of neighborhood and household. *Transportation Research Record* **2077** 62–70.
- Hadas, Y., A. Ceder. 2010. Public transit network connectivity: Spatial-based performance indicators. *Transportation Research Record: Journal of the Transportation Research Board* **2143** 1–8.
- Handy, S., R.G. Paterson, K. Butler. 2003. Planning for street connectivity: Getting from here to there. Tech. rep., American Planning Association, PAS Report Number 515.
- Hess, P. M. 1997. Measures of connectivity. *Places* **11** 58–65.
- Hess, P. M., A. V. Moudon, M. C. Snyder, K. Stanilov. 1999. Site design and pedestrian travel. *Transportation Research Record* **1674** 9–19.
- Hongqi, H. 2009. Urban transit dispatch based on queuing theory. *In the proceedings of the Fifth International Conference on Natural Computation*. 468–472.
- Horn, M. E. T. 2002. Fleet scheduling and dispatching for demand-responsive passenger services. *Transportation Research C* **10(1)** 35–63.
- Ignall, E., P. Kolesar. 1974. Optimal dispatching of an n infinite-capacity shuttle: Control at a single terminal. *Operations Research* **22** 1008–1024.
- Jaillet, P. 1988. A priori solution of a traveling salesman problem in which a random subset of the customers are visited. *Oper. Res.* **36** 929–936.

- Jaw, J.-J., A. R. Odoni, H. N. Psaraftis, N. H.M. Wilson. 1986. A heuristic algorithm for the multi-vehicle advance request dial-a-ride problem with time windows. *Transportation Research Part-B* **20(3)** 243–257.
- Jenelius, E., T. Petersen, L.-G. Mattsson. 2006. Importance and exposure in road network vulnerability analysis. *Transportation Research Part A : Policy and Practice* **40** 537–560.
- Kansky, K. J. 1963. Structure of transportation networks: Relationships between network geometry and regional characteristics. Ph.D. thesis, University of Chicago, Chicago.
- Kearney, A. R., R. DeYoung. 1995. A knowledge-based intervention for promoting carpooling. *Environment and Behavior* **27(5)** 650–678.
- Knoop, V. V., H. Zuylen, S. Hoogendoorn. 2008. The need of spillback modelling when assessing consequences of blockings in a road network. *European Journal of Transport and Infrastructure Research* **8** 287–300.
- Koffman, D. 2004. Operational experiences with flexible transit services: a synthesis of transit practice. *TCRP Synthesis, vol. 53, Transportation Research Board, Washington, DC*.
- Kostof, S. 1991. The city shaped: Urban patterns and meanings through history. Boston, MA.
- Lam, T. M., H. J. Schuler. 1981. Public transit connectivity, vol 1 (report dmt-084). Tech. rep., Institute of Transport Studies, University of California, Irvine, CA.
- Lam, T. M., H. J. Schuler. 1982. Connectivity index for systemwide transit route and schedule performance. *Transportation Research Record* **854** 17–23.
- Lee, Y. J., V.R. Vuchic. 2005. Transit network design with variable demand. *Journal of Transportation Engineering* **131(1)** 1–10.

- Li, X., L. Quadrifoglio. 2010. Feeder transit services: Choosing between fixed or demand responsive policy. *Transportation Research, Part C: Emerging Technologies* **18** 770–780.
- Mately, M., L. M. Goldman, B. J. Fineman. 2001. Pedestrian travel potential in northern new jersey. *Transportation Research Record* **1705** 1–8.
- MATLAB. 2009. *Online Documentation MATLAB R2010b*. URL <http://www.mathworks.com/>. Accessed 6th January 2009.
- MCTA. 2012. *Mason County Transportation Authority (WA) – Transportation Services*. URL <http://www.masontransit.org/>. Accessed on 4th January 2012.
- Melachrinoudis, E., A. B. Ilhan, H. Min. 2007. A dial-a-ride problem for client transportation in a healthcare organization. *Computers & Operations Research* **34** 742–759.
- Messenger, T., R. Ewing. 1996. Transit-oriented development in the sunbelt. *Transportation Research Record* **1552** 145–152.
- Miyagawa, M. 2009. Optimal hierarchical system of a grid road network. *Annals of Operations Research* **172** 349–361.
- Moilanen, A., M. Nieminen. 2002. Simple connectivity measures in spatial ecology. *Ecology* **83** 1131–1145.
- Moudon, A. V., P. Hess, M. C. Snyder, K. Stanilov. 1997. Effects of site design on pedestrian travel in mixed-use, mediumdensity environments. *Transp Res Record* **1578** 48–55.
- MUTCD. 2009. *Manual on Uniform Traffic Control Devices*. Federal Highway Administration, U S Department of Transportation. URL <http://mutcd.fhwa.dot.gov/>. Accessed on 10th December 2011.

- NHTS. 2009. *National Household Travel Survey Data Center*. URL <http://nhts.ornl.gov/>. Accessed on 10th December 2009.
- Nourbakhsh, S. M., Y. Ouyang. 2012. A structured flexible transit system for low demand areas. *Transportation Research Part B: Methodological* **46(1)** 204–216.
- Omnitrans. 2012. *Omnitrans (CA) – Route Maps & Schedules*. URL <http://www.omnitrans.org/>. Accessed on 7th January 2012.
- O’Sullivan, S., J. Morrall. 1996. Walking distances to and from light-rail transit stations. *Transportation Res Record* **1538** 19–26.
- Ozekici, S. 1987. Average waiting time in queues with scheduled batch services. *Transportation Science* **21(1)** 55–61.
- Peponis, J., D. Allen, D. Haynie, M. Scoppa, Z. Zhang. 2007. Measuring the configuration of street networks. *The 6th International Space Syntax Symposium, Istanbul, Turkey*.
- Peponis, J., S. Bafna, Z. Zhang. 2008. The connectivity of streets: reach and directional distance. *Environment and Planning B: Planning and Design* **35(5)** 881–901.
- Potts, J. F., M. A. Marshall, E. C. Crockett, J. Washington. 2010. A guide for planning and operating flexible public transportation services. volume 140 of tcpr synthesis report. Tech. rep., Transportation Research Board.
- PRTC. 2012. *Potomac and Rappahannock Transportation Commission (VA) – System Map*. URL <http://www.prtctransit.org/>. Accessed on 11th January 2012.
- Psaraftis, H. N. 1980. A dynamic programming approach to the single-vehicle, many-to-many immediate request dial-a-ride problem. *Transportation Science* **14** 130–154.

- Quadrifoglio, L., S. Chandra, C-W. Shen. 2009. Transit services for sprawling areas with relatively low demand density: A pilot study in the Texas border's colonias. Tech. rep., The Southwest Region University Transportation Center, Texas Transportation Institute, Texas A&M University System.
- Quadrifoglio, L., M. Dessouky, K. Palmer. 2007. An insertion heuristic for scheduling mass services. *Journal of Scheduling* **10** 25–40.
- Quadrifoglio, L., R.W. Hall, M. Dessouky. 2006. Performance and design of mass services: Bounds on the maximum longitudinal velocity. *Transportation Science* **40** 351–363.
- Quadrifoglio, L., X. Li. 2009. A methodology to derive the critical demand density for designing and operating feeder transit services. *Transportation Research, Part B: Methodological* **43** 922–935.
- Randall, T. A., B. W. Baetz. 2001. Evaluating pedestrian connectivity for suburban sustainability. *Journal of Urban Planning and Development* **127** 1–15.
- Reilly, M. K. 2002. The influence of urban form and land use on mode choice - evidence from the 1996 bay area travel survey. *In the Annual Meeting of the Transportation Research Board, Washington, DC*.
- Ropke, S., J. F. Cordeau, G. Laporte. 2007. Models and branch-and-cut algorithms for pickup and delivery problems with time windows. *Networks* **49** 258–272.
- Siksna, A. 1997. The effects of block size and form in north american and Australian city centres. *Urban Morphology* **1** 19–33.
- Silva, R. T. 2000. The connectivity of infrastructure networks and the urban space of Sao Paulo in the 1990s. *International Journal of Urban and Regional Research* **24** 139–164.

- SJT. 2012. *City of St. Joseph Transit (MO) – Individual Routes and Schedules*. URL <http://www.stjoemo.info/transit/>. Accessed on 10th January 2012.
- Song, Y. 2003. Impacts of urban growth management on urban form: A comparative study of portland, oregon, orange county, florida and montgomery county, maryland. Tech. rep., National Center for Smart Growth Research and Education, University of Maryland.
- Song, Y., G. J. Knaap. 2004. Measuring urban form: is portland winning the war on sprawl? *Journal of the American Planning Association* **70(2)** 210–225.
- Southworth, M., P.M. Owens. 1993. The evolving metropolis: studies of community, neighborhood, and street form at the urban edge. *J Am Plann Assoc* **59** 271–287.
- Steiner, F., K. Butler. 2007. *Planning and Urban Design Standards*. John Wiley & Sons, Inc.
- StreetMap. 2011. *StreetMap Premium for ArcGIS*. URL <http://www.esri.com/data/streetmap/index.html>. Accessed on 10th November 2011.
- Szablowski, P. J. 2001. Discrete normal distribution and its relationship with jacobi theta functions. *Statistics and Probability Letters* **52** 289–299.
- Taylor, M. A. P., S. V. C. Sehkar, G. M. D’Este. 2006. Application of accessibility based methods for vulnerability analysis of strategic road networks. *Networks and Spatial Economics* **6** 267–291.
- TCRP. 1999. Transit capacity and quality of service manual. Tech. Rep. 6, Transportation Research Board, National Research Council, Washington, D.C.
- Tischendorf, L., L. Fahrig. 2000. How should we measure landscape connectivity? *Landscape Ecology* **15** 633–641.

- TNRIS. 2011. *Texas Natural Resources Information Systems Maps & Data*. URL <http://www.tnris.org/>. Accessed on 4th February 2012.
- TriMet. 2012. *TriMet Paratransit Program*. URL <http://trimet.org/lift/index.htm>. Accessed on 5th January 2012.
- VDOT. 2010. *Virginia Department of Transportation (VDOT) Projects*. URL <http://www.vdot.virginia.gov/>. Accessed 12th December 2010.
- Wardman, M. 2004. Public transport values of time. *Transport Policy* **11(4)** 363–377.
- Wibowo, S. S., P. Olszewski. 2005. Modeling walking accessibility to public transport terminals: Case study of singapore mass rapid transit. *Journal of the Eastern Asia Society for Transportation Studies* **6** 147–156.
- Wilson, N. H. M., D. Roos. 1971. Dial-a-ride: an overview of a new demand-responsive transportation system. Tech. rep., Urban Systems Laboratory Report USL TR-71-03, MIT, Cambridge, MA.
- Wiransinghe, S. C., G. Liu. 1995. Optimal schedule design for a transit route with one intermediate time point. *Transportation Planning and Technology* **19** 121–145.
- Xie, C., H. L. Gong, F. H. Wang. 2010. A solution for the last mile problem of the beijing rapid transit network: Local shuttle bus system. *18th International Conference on Geoinformatics*, pp.1-6.
- Zhao, F., X. Zeng. 2008. Optimization of transit route network, vehicle headways and timetables for large-scale transit network. *European Journal of Operational Research* **186(2)** 841–855.

## VITA

Shailesh Chandra received his Bachelor of Technology degree in civil engineering from the Indian Institute of Technology Delhi in 2006 and his Master of Science in civil engineering from Texas A&M University in 2009. He continued to pursue his doctoral studies in the civil engineering Department at Texas A&M University and graduated with his Ph.D in August 2012. His research interests include scheduling, algorithms, heuristics and optimization of transit systems. He is also actively involved in research related to economic impacts of transportation accessibility and connectivity.

Dr. Chandra may be reached at 401A, CE/TTI Building, Texas Transportation Institute, TAMU, College Station, TX 77843-3136.

His email is: [chandrashailesh@gmail.com](mailto:chandrashailesh@gmail.com)