MOVING FROM CONVENTIONAL BUS SERVICE TOWARDS BUS RAPID TRANSIT: ESTABLISHING PRIORITIES

by

María del Pilar Rodríguez

Civil Engineer, Universidad de los Andes (1998)

Submitted to the Department of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN TRANSPORTATION

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2003

Copyright © Massachusetts Institute of Technology 2003. All rights reserved.

Signature of Author ____________________________ Department of Civil and Environmental Engineering

November 5, 2002

Certified by ____________________________

Professor Nigel H.M. Wilson
Thesis Supervisor

Accepted by ____________________________

Oral Buyukozturk
Chairman, Departmental Committee on Graduate Students
Moving from conventional bus service towards bus rapid transit: establishing priorities

by

María del Pilar Rodríguez

Submitted to the Department of Civil and Environmental Engineering on February 2003 in partial fulfillment of the requirements for the degree of Master of Science in Transportation

Abstract

This thesis structures a process to support transit agencies in their decision-making when improving their current conventional bus service (CBS) towards a higher quality system such as Bus Rapid Transit (BRT). Four major tasks were conducted as follows.

First a literature review was performed to study relevant prior research and BRT cases in operation in Pittsburgh, Los Angeles, Bogotá, Curitiba, and Ottawa.

Second, and based on the case studies and literature review, eight key attributes and components of BRT systems were identified. The key attributes defined were: 1) right of way priority; 2) expedited boarding and alighting; 3) knowledge-based planning and operations; 4) high frequency; 5) high reliability; 6) distinct image; 7) connectivity; 8) land use integration. The physical bus components that could be changed in order to achieve these attributes were identified as the right-of-way, stops, vehicles, fare collection system, signal priority system, and automated vehicle location (AVL) system.

The third task focused on developing a prioritization process to understand the variables that would lead to achieve the first two key attributes. All components but AVL systems were identified to impact these key attributes. The evaluation process to prioritize the critical variables of each component was based on the time savings and cost associated with their implementation. Time savings were evaluated from a user standpoint as the total travel time, including access time, waiting time, and in-vehicle time. Time savings for the agency were evaluated through running time reductions.

Finally, the process was applied to Chicago transit Authority Express service 49 on Western Avenue in Chicago, IL. As a result, the implementation of the prioritized variables was recommended on two phases. The first phase (1 – 3 years) includes reducing the stop spacing on the X49 route to increase coverage and demand, upgrade all buses used in the route to low-floor buses, expedite fare collection process through wider use of transit cards, implement active signal priority, implement preferential treatment for buses, and finally upgrade to contact-less smart cards. The second phase (3 – 5) years, includes implementing off-vehicle fare payment and conducting further analysis to determine the cost-effectiveness and feasibility of an exclusive lane operation.

Thesis Supervisor: Nigel H. M. Wilson
Title: Professor of Civil and Environmental Engineering
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABLE OF CONTENTS</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>LIST OF ACRONYMS</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>1.1 OBJECTIVES</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>1.2 BACKGROUND</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>1.3 METHODOLOGY / APPROACH</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>1.4 THESIS CONTENT</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>2 LITERATURE REVIEW</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>2.1 GENERAL BRT</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>2.2 BRT COMPONENTS</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>2.2.1 Right-of-way</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>2.2.2 Stops</td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>2.2.3 Vehicles</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>2.2.4 Fare Collection</td>
<td></td>
<td>34</td>
</tr>
<tr>
<td>2.2.5 Signal Priority</td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>2.3 EVALUATION MEASURES</td>
<td></td>
<td>37</td>
</tr>
<tr>
<td>2.3.1 Access time</td>
<td></td>
<td>37</td>
</tr>
<tr>
<td>2.3.2 Waiting time, headway variation, and dwell time</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>3 CASE STUDIES</td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>3.1 CURITIBA: INTEGRATED BUS NETWORK</td>
<td></td>
<td>44</td>
</tr>
<tr>
<td>3.2 BOGOTÁ: TRANSMILENIO</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>3.3 OTTAWA: TRANSITWAY</td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>3.4 PITTSBURGH: SOUTH, EAST, AND WEST BUSWAY</td>
<td></td>
<td>62</td>
</tr>
</tbody>
</table>
## Table of contents

3.5 **LOS ANGELES: METRO RAPID** .................................................. 66

3.6 **FINDINGS** ............................................................................. 71
  3.6.1 *Key BRT attributes* ......................................................... 71
  3.6.2 *Other findings* ................................................................. 76

4 **BUS RAPID TRANSIT** .............................................................. 79

  4.1 *What is BRT?* ...................................................................... 79
  
  4.2 **KEY BRT ATTRIBUTES** ................................................... 82
    4.2.1 *Right-of-way priority* ................................................... 82
    4.2.2 *Expediting boarding and alighting* ................................. 83
    4.2.3 *Knowledge-based planning and operations* .................... 84
    4.2.4 *High frequency* ............................................................. 85
    4.2.5 *High reliability* ............................................................ 85
    4.2.6 *Connectivity* ................................................................. 86
    4.2.7 *Land use integration* .................................................... 87
    4.2.8 *Distinct image* ............................................................. 87

  4.3 **BRT COMPONENTS** ........................................................... 88
    4.3.1 *Right-of-way* ............................................................... 91
    4.3.2 *Stops* ........................................................................... 98
    4.3.3 *Vehicles* .................................................................... 100
    4.3.4 *Fare Collection* ........................................................... 105
    4.3.5 *Signal System* ............................................................. 107

  4.4 **SUMMARY** ........................................................................ 108

5 **ANALYZING THE IMPLEMENTATION PROCESS** ....................... 110

  5.1 **IMPLEMENTATION PROCESS OVERVIEW** ......................... 110
  
  5.2 **STEP 1: UNDERSTAND TRANSIT SYSTEM** ....................... 114
  
  5.3 **STEP 2: SELECT BRT CORRIDOR** .................................... 114
  
  5.4 **STEP 3: ASSESS CURRENT CORRIDOR PERFORMANCE** .... 117

  5.5 **STEP 4: DEFINE IMPLEMENTATION STRATEGY** .................. 119
    5.5.1 *All-at-once* ............................................................... 119
    5.5.2 *Incremental* ............................................................... 120

  5.6 **STEP 5: EVALUATE BRT COMPONENTS** ............................ 123
    5.6.1 *Access time* ............................................................. 125
    5.6.2 *Waiting time* ............................................................ 133
5.6.3 In-vehicle time ................................................................. 146
5.6.4 Running time ................................................................. 155

5.7 Step 6: Prioritize BRT Components ........................................... 158

6 Application: Western Corridor in Chicago .................. 160
6.1 Applying the Process: Establishing Priorities ................. 160
   6.1.1 Step 1: Understand current transit system ................. 160
   6.1.2 Step 2: Select BRT corridor ............................................ 163
   6.1.3 Step 3: Assess corridor current performance ............... 165
   6.1.4 Step 4: Define implementation strategies .................. 180
   6.1.5 Step 5: Evaluate BRT components ............................... 183
   6.1.6 Step 6: Prioritize BRT components ............................... 205

6.2 Recommendations .............................................................. 214

7 Conclusions ........................................................................... 217

References ................................................................................. 221

Appendix A: Configuration of Example Route .............. 227

Appendix B: Finding Average Walking Distances .......... 228
LIST OF FIGURES

Figure 2-1 CIVIS bus exterior ................................................................. 32
Figure 2-2 CIVIS bus interior ................................................................. 33
Figure 2-3 Impacts of boarding rates changes (Vandebona and Richardson, 1985)........ 35
Figure 3-1 Curitiba’s system map................................................................. 45
Figure 3-2 Curitiba’s express vehicles in exclusive lanes ................................ 46
Figure 3-3 Direct bus in Curitiba at a “tube station”.................................. 47
Figure 3-4 Interior of Curitiba “tube station”............................................ 47
Figure 3-5 Transmilenio’s exclusive lanes in Avenida Caracas ....................... 52
Figure 3-6 Transmilenio station in Avenida Caracas .................................... 53
Figure 3-7 Identifying totem at Calle 80 terminal ...................................... 53
Figure 3-8 Trunk bus docking at station ................................................... 54
Figure 3-9 AVL control software screen.................................................. 56
Figure 3-10 Ottawa’s Transitway............................................................... 61
Figure 3-11 MetroRapid system map....................................................... 67
Figure 3-12 LA Metro Rapid station and real-time information display........... 68
Figure 3-13 Metro Rapid bus ................................................................. 69
Figure 4-1 Physical components and their critical decision variables............... 91
Figure 4-2 Degree of right-of-way exclusivity.......................................... 92
Figure 4-3 Sample of exclusive lanes at grade (with intersections) ............... 93
Figure 4-4 Sample of grade separated exclusive lanes (without intersections) .... 93
| Figure 4-5 | Degree of right-of-way guidance | 94 |
| Figure 4-6 | Lateral mechanical guidance | 95 |
| Figure 4-7 | Central rail mechanical guidance | 96 |
| Figure 4-8 | Optical guidance | 96 |
| Figure 4-9 | Magnetic guidance | 96 |
| Figure 4-10 | Inductive cable guidance | 97 |
| Figure 4-11 | Proposed guided bus in Eugene, OR | 98 |
| Figure 4-12 | Stop spacing alternatives | 99 |
| Figure 4-13 | Boarding level alternatives | 101 |
| Figure 4-14 | Curitiba high-floor bus lowering ramp | 102 |
| Figure 4-15 | Low-floor bus with ramp | 102 |
| Figure 4-16 | Low-floor bus with gap | 103 |
| Figure 4-17 | Free level boarding | 103 |
| Figure 4-18 | Vehicle capacity alternatives | 104 |
| Figure 4-19 | Number of doors | 105 |
| Figure 4-20 | Fare payment location alternatives | 106 |
| Figure 4-21 | Payment media alternatives | 107 |
| Figure 4-22 | Signal priority methods | 108 |
| Figure 5-1 | Implementation process | 111 |
| Figure 5-2 | Simultaneous and iterative design process of a BRT system | 113 |
| Figure 5-3 | Bus travel time components | 118 |
Figure 5-4 Scheme of bus route, stations, and catchment areas ........................................ 128
Figure 5-5 Station Catchment Area configurations ................................................................ 128
Figure 5-6 Impact of Stop Spacing on Access Time .............................................................. 130
Figure 5-7 Access Time and Coverage .................................................................................. 132
Figure 5-8 Passenger waiting time along the route ................................................................. 139
Figure 5-9 Lane exclusivity impact on passenger waiting time ............................................. 141
Figure 5-10 Range of alternatives for some critical variables ................................................ 143
Figure 5-11 Impact of boarding / alighting times on passenger waiting time .................... 144
Figure 5-12 Signal priority method impact on waiting time .................................................. 146
Figure 5-13 In-vehicle speed profile ..................................................................................... 148
Figure 5-14 Impact of lane exclusivity on In-Vehicle time .................................................... 151
Figure 5-15 Impact of Stop Spacing in In-vehicle time ......................................................... 153
Figure 5-16 In-Vehicle time impact from boarding/alighting times and doors time .......... 154
Figure 5-17 Impacts on running time ..................................................................................... 157
Figure 6-1 Map of North, Central, and South CTA transit network ..................................... 162
Figure 6-2 Routes serving Western Avenue .......................................................................... 165
Figure 6-3 Schematic of the X49 route and stops ................................................................. 169
Figure 6-4 Daily transfers between 49 and X49 and all other CTA routes ......................... 173
Figure 6-5 Daily transfers to/from X49 from/to all CTA routes ........................................... 174
Figure 6-6 Travel time components in route X49 from data collected ............................... 175
Figure 6-7 Speed profile in Western Avenue ....................................................................... 176
Figure 6-8 Relationship between stop spacing and operational speed ..................... 177

Figure 6-9 signal system ................................................................................................. 179

Figure 6-10 Current waiting times along service X49 ...................................................... 185

Figure 6-11 Waiting Time impact from Degree of lane exclusivity ................................ 188

Figure 6-12 Impact of lane exclusivity on in-vehicle time ............................................. 189

Figure 6-13 Impact of lane exclusivity on running time .................................................... 189

Figure 6-14 Impact of stop spacing on access time ......................................................... 192

Figure 6-15 Impact of Stop Spacing in In-vehicle Time .................................................... 193

Figure 6-16 Stop spacing impact on running time ......................................................... 194

Figure 6-17 Summary of travel and running time impact from feasible variables .......... 206

Figure 6-18 Cost of reducing running and travel time by 1% for each alternative ............ 211

Figure 6-19 Cost of reducing running and travel time by 1% (alternative 2) ................. 212
LIST OF TABLES

Table 1-1 Case studies .................................................................................................................. 18
Table 3-1 Total Annual Cost Comparison Based on 625,000 Population Level ...................... 59
Table 4-1 Sample of BRT literature definitions ........................................................................ 81
Table 4-2 BRT key attributes ..................................................................................................... 82
Table 4-3 Relationships between physical components and key BRT attributes .................... 90
Table 5-1 Selected evaluation measures ...................................................................................... 124
Table 5-2 Relationship between evaluation measures and critical variables ............................... 125
Table 5-3 Relationship between waiting time and critical variables ........................................ 133
Table 5-4 Variables affected by degree of lane exclusivity ........................................................ 141
Table 5-5 Variables affected by signal priority method ............................................................... 145
Table 5-6 Relationship between in-vehicle time and critical variables ...................................... 147
Table 6-1 Bus and Rail figures in Chicago ("CTA website," 2002) ............................................. 160
Table 6-2 Intersection inventory ................................................................................................. 171
Table 6-3 Expected reductions from lane exclusivity improvements ......................................... 190
Table 6-4 Expected time reductions from changes on stop spacing ......................................... 195
Table 6-5 Service times assumed for X49 boarding level improvements ................................ 197
Table 6-6 Expected impact from boarding level improvements ............................................... 197
Table 6-7 Assumed passenger service times for payment location improvements .................... 198
Table 6-8 Expected impact from fare payment location improvements .................................... 199
Table 6-9 CTA boarding rates (transactions per minute) by fare media ...................... 200
Table 6-10 Assumed passenger service times for payment media improvements......... 200
Table 6-11 Expected time reductions from payment media improvements ............... 201
Table 6-12 Assumed passenger service times for No. of doors improvements .......... 202
Table 6-13 Expected time reductions from changes to the number of doors ............. 203
Table 6-14 Values assumed for signal priority variables ..................................... 203
Table 6-15 Expected impact from improvements to signal priority method .......... 204
Table 6-16 Costs to implement feasible variable alternatives in Western corridor ......... 208
Table 6-17 Cost of reducing travel and running time by each alternative .............. 210
# LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVL</td>
<td>Automatic Vehicle Location system</td>
</tr>
<tr>
<td>APTA</td>
<td>American Public Transportation Association</td>
</tr>
<tr>
<td>BRT</td>
<td>Bus Rapid Transit</td>
</tr>
<tr>
<td>CBS</td>
<td>Conventional Bus Service</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
</tr>
<tr>
<td>CTA</td>
<td>Chicago Transit Authority</td>
</tr>
<tr>
<td>DOT</td>
<td>Department of Transportation</td>
</tr>
<tr>
<td>FS</td>
<td>Far-side</td>
</tr>
<tr>
<td>FTA</td>
<td>Federal Transit Administration</td>
</tr>
<tr>
<td>LA</td>
<td>Los Angeles</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied Natural Gas</td>
</tr>
<tr>
<td>MBTA</td>
<td>Massachusetts Bay Transportation Authority</td>
</tr>
<tr>
<td>MRT</td>
<td>Mass Rapid Transit</td>
</tr>
<tr>
<td>NB</td>
<td>Northbound</td>
</tr>
<tr>
<td>NE</td>
<td>Northeast</td>
</tr>
<tr>
<td>NS</td>
<td>Near-side</td>
</tr>
<tr>
<td>NW</td>
<td>Northwest</td>
</tr>
<tr>
<td>PRHTA</td>
<td>Puerto Rico Highway and Transportation Authority</td>
</tr>
<tr>
<td>ROW</td>
<td>Right-of-way</td>
</tr>
<tr>
<td>SB</td>
<td>Southbound</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>SE</td>
<td>Southeast</td>
</tr>
<tr>
<td>SW</td>
<td>Southwest</td>
</tr>
<tr>
<td>TCRP</td>
<td>Transportation Cooperative Research Program</td>
</tr>
<tr>
<td>TOD</td>
<td>Transit Oriented Development</td>
</tr>
<tr>
<td>TU</td>
<td>Tren Urbano</td>
</tr>
<tr>
<td>UIC</td>
<td>University of Illinois Chicago</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

1.1 Objectives

The main objective of this thesis is to structure a process to support transit agencies in their decision-making when improving their current Conventional Bus Service (CBS) towards a higher quality system such as Bus Rapid Transit (BRT). The main questions to be answered are:

1. What are the determinant characteristics of successful BRT and what is their relative importance?
2. How can an agency prioritize BRT elements when moving from CBS towards BRT?
3. How can this prioritization process be applied to the specific case of Chicago, IL?

1.2 Background

Buses are the most extensively used transit mode in the United States (US) (APTA, 2000), they provide transit coverage and sometimes connectivity but usually do not include many features often associated with rail, such as exclusive right-of-way, stations, level boarding, high operating speed, short headways, expedited fare collection, and real-time passenger information. Thus, users perceive buses as offering lower quality service. However, bus systems can in fact be implemented with such features delivering "rail quality" to users, this concept is today known as BRT, which stands for Bus Rapid Transit. BRT is usually implemented in areas where ridership is not sufficient to justify

---

1 Conventional Bus Service (CBS) refers to bus service as it currently exists generally in the United States. The term implies a service that has little or no special infrastructure, no distinct image, and performance usually inferior to that of both private automobile and rail transit. Its operational characteristics generally include low frequency, low reliability, low quality waiting areas, and slow operational speed.
the capacity provided by rail solutions or where the cost of rail infrastructure is too high, and users are seeking a better quality in transit than conventional bus service.

During the last decade, the United States (US) transportation community has increasingly turned its eyes to Bus Rapid Transit (BRT) as a mass transportation alternative to rail. Mainly, three interest groups have promoted this special attention: the federal government, urban planners, and transit agencies. Given the Federal Government’s major role in funding capital investment, its interest in promoting BRT is at least partially financial (Sislak, 2000). BRT systems have been deployed in other countries including Brazil (Curitiba and Porto Alegre), Ecuador (Quito), and Colombia (Bogotá) at a cost, on average, one tenth that of rail (HalcrowFox, 2000), yet providing high quality service to riders. In these cities, high quality bus systems were implemented as an alternative to expensive rail systems and have proved successful in terms of mobility, accessibility, environment and land use impacts. Urban planners see that BRT provides an opportunity to revitalize cities in the short to medium term. These opportunities include reinforcing downtown, developing more transit-oriented communities, and improving the environment. Transit agencies, many of which have been in a period of bus ridership stagnation or slow growth during the last two decades, consider BRT as a path to increased competitiveness, and as a strategy to retain and attract new customers. Despite this joint support for BRT the extent of actual implementation in the US to date is quite limited.

Although some medium-size cities in the US have been successful in their attempts to provide better service moving towards BRT (i.e. Pittsburgh), many others have not yet been able to introduce full BRT into their transit systems. The limited extent of implementation in the US appears not to be caused primarily by lack of support from the government or low benefits from the projects; rather it stems from the fact that implementing system-wide changes in old and established transit agencies is a complex task. It requires many changes in infrastructure, operations, management, and the
organization itself, all of which are difficult to implement in this type of agency. Thus, although the benefits of BRT seem to be accepted wisdom within the public transportation field, and the technology has been broadly studied and practically proven, transit agencies are struggling with the implementation of such projects. This thesis aims to provide insight to transit agencies that are in the decision-making and design processes of BRT systems. It includes an analysis of the key features of BRT technology and the issues of deploying those features in the field. This includes the critical question of whether discrete and incremental implementation of these features is more or less appropriate than an all-at-once approach.

The amount of previous research in this subject is substantial yet limited. On the one hand, we find a large number of research projects that have dealt with the design and implementation of CBS improvements. These improvements are all components of what we know today as BRT. These studies range from the scheduling of more reliable bus services, to the use of AVL data to provide real time passenger information, to station aesthetics. On the other hand, few formal research projects have analyzed BRT in depth as an integrated public transport mode. At the same time, given the popularity of BRT during the past few years, one can find many documents in the internet referring to BRT, or articles in non-peer reviewed publications such as transit magazines, and newspapers.

During the 1970s and 1980s most of the relevant research in this area focused on the usage of highway lanes as bus priority lanes. This trend in research was largely a response to actual practice at that point, when the belief that measures to improve bus service had to include separation from general traffic led practitioners to provide that separation in highway lanes. Rapidly, most of the few implemented “highway bus priority lanes” downgraded into High Occupancy Vehicles (HOV) (Vuchic, Bruun et al., 1994) and research in this area moved into the operational issues of the coexistence of private and public vehicles. During the 1990s, the scope of this research went beyond operational issues; customer satisfaction concerns led to studies on comfort, vehicle and
Moving from Conventional Bus Service towards Bus Rapid Transit  

Ch. 1. Introduction

station design, real-time information for passengers, aesthetics, signage, emissions, noise, etc. As a result, today there exist a broad set of studies that address both the status of CBS and paradigms for bus service. However, the question of how best to make the transition between those two states remains unanswered.

At this point, the most valuable resource on BRT seems to be the documented cases where it has been implemented. The Federal Transit Administration’s BRT initiative website (http://www.fta.dot.gov/brtl) has become a well-known base resource; the website links to different projects, contains a reference guide, and provides some content on BRT. The most important documents on BRT will be described and assessed in the Literature Review chapter.

Undoubtedly, the most important long established BRT system in the world is in Curitiba, Brazil. In fact, Brazil can be nominated the father country of BRT since many of the most successful BRT systems are among its cities, such as the above mentioned system in Curitiba as well as those in Porto Alegre, Goiania, Sao Paulo, and Belo Horizonte. The greatest knowledge on design and operation of BRT systems certainly resides with Brazil’s transportation engineers and urban planners who designed and operate these systems. A detailed description of the Curitiba system and the reasons for it becoming the BRT paradigm, will be given in the Case Studies chapter. In North America, the outstanding cases certainly are Pittsburgh and lately Los Angeles in the US, and Ottawa in Canada. These will also be analyzed as case studies in this thesis.

1.3 Methodology / approach

To accomplish the objectives of this thesis, four major tasks are conducted as follows:

---

¹ The system in Pittsburgh is almost as old as the one in Curitiba, however, its impacts on the city have been limited compared to the one in Curitiba.
1. Study relevant prior research and actual cases
2. Identify components and key attributes of BRT
3. Develop a prioritization and implementation process
4. Apply the process to a specific case

The first task aims to create a solid understanding of the standpoints of CBS and BRT in both academia and practice. This task includes a literature review and a set of case studies. The literature review mainly relies on documents produced in the past two decades about potential CBS improvements. Few theoretical documents exist on integrated BRT systems, most of the literature describes particular systems or is informally published in websites. Thus, in addition to formal journal papers and books, several content websites are used as references. The analysis of actual BRT cases leads to a definition of the critical issues in BRT implementation and operation. The chosen case studies are listed in Table 1-1.

<table>
<thead>
<tr>
<th>International Cases</th>
<th>Domestic Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curitiba, Brazil</td>
<td>Pittsburgh, PA</td>
</tr>
<tr>
<td>Ottawa, Canada</td>
<td>Los Angeles, CA</td>
</tr>
<tr>
<td>Bogotá, Colombia</td>
<td></td>
</tr>
</tbody>
</table>

The second task seeks to determine the set of BRT elements that compose the system and the attributes that are considered the main drivers for success. The basis for this task is the understanding gained from the previous one, the literature review and the case studies. The list of components is short considering all the elements that must be accounted for in public transit systems, however it contains the determinant components of BRT. To establish the key attributes, a comprehensive list of elements is developed that includes physical, service, and system elements. From this comprehensive list, the key ones for successful BRT are chosen. Choosing the key ones is based on the literature,
case studies, judgment, and analysis. The basic criteria to determine which elements are important are a) the ones that have been implemented in successful BRT cases, b) the ones that have a direct and positive impact on travel time, and c) the ones that bring the bus service closer to rail operational standards.

The third task constitutes finding the relative importance of the key components and prioritizing them to create an implementation process. Their relative importance is addressed through a benefit/cost analysis. This analysis is limited to the components that are measurable, have solid background literature, and are of most importance to the agency, due to their costs or controversy. Benefits and costs are calculated for both agency and customers. By determining the relative importance of these elements, implementation priorities can be assigned to help agencies decide which element to implement under a fixed budget or time constraint. All the information obtained during the prioritization supports the agency’s implementation process when seeking to improve their system using BRT features. At the end of the day, the objective of this task is to ensure that the agency asks itself all the relevant questions when developing this transition strategy. This thesis will provide some insight into the issues, giving the agency some alternative solutions, and if no particular answer applies, some insight into how to approach the issue. Therefore, the process and its content, in a structured manner, enlighten the user on the alternative approaches to every issue. The main steps within this process are

1. understand the current transit system,
2. select the potential BRT corridor,
3. assess the corridor’s current performance,
4. define the implementation strategy,
5. evaluate BRT components,
6. prioritize BRT components,
7. design,
8. build, and
9. operate the system.

The last task in this methodology is to apply the process developed, to the extent possible with the information available to the specific case of Chicago, IL.

1.4 Thesis content

The remainder of this thesis is divided into six chapters. Chapter 2 contains the literature review of published documents and content websites. The case studies constitute Chapter 3, in which two cases from the US will be examined (Pittsburgh and Los Angeles) along with three international cases (Curitiba, Bogotá, and Ottawa). These case studies, rather than a simple description of the systems, focus on evaluating what are the main components of each system, the key factors for their success and the lessons that can be learned. Chapter 4 builds on the lessons learned from the case studies to propose a set of key components and attributes for general BRT and present alternative solutions for each component. Chapter 5 studies the relative importance of these components in terms of their impact on users and the agency and proposes a process to prioritize and implement these components into an agency’s current system. The application of this process to Chicago is presented in Chapter 6. Finally, Chapter 7 summarizes the work, its value, the conclusions that can be reached from it, the strengths and weaknesses of the process and analyses performed, and recommends topics for further research.
2 LITERATURE REVIEW

The literature reviewed in this chapter can be classified into the following three areas:

5. General BRT
6. BRT components
7. Evaluation measures

The first area, general BRT includes publications that approach BRT as a transportation mode or in an integrated manner. Often, this includes its definition, operational characteristics, costs, design, and implementation issues.

The second area includes literature on the components of BRT. Generally, this literature is not specific to BRT, but it is considered here because it addresses improvements of CBS components that are the key BRT features, for example right-of-way exclusivity, stations, fare collection systems, passenger information systems, and Automatic Vehicle Location (AVL) systems.

The third area, evaluation measures, covers literature required to evaluate the impacts; hence it is composed of publications on travel time (e.g. waiting time, dwell time), on agencies costs (e.g. operational costs, capital costs), and transit evaluation methodologies.

2.1 General BRT

Literature that addresses Bus Rapid Transit as a public transport mode is very recent in the US; mostly from the 1990s. Predecessors of BRT literature were the 1970s discussions on operational issues of HOV lanes and bus lanes on highways. In the 1980s some papers were published describing the public transport systems in Curitiba, Pittsburgh, and Ottawa. European literature started addressing Transports collectifs en site propre earlier, but the focus was primarily on rail solutions.
(Vuchic, Bruun et al., 1994) described a potentially higher quality bus mode called Bus Transit System (BTS). The report defines the two “extremes” of bus services as Basic Bus System (BBS) on the lower end and Bus Transit Systems (BTS) on the higher end. The first one consists of buses running on streets without any special treatment. The latter, is defined as buses operating in separated right-of-ways, with extensive priority, special stations, modern control systems, offering fast and reliable service, and with a strong public image. BTS is parallel to the concept known today as BRT. Vuchic finds that the best BTS system in North America is Ottawa, and the most successful within the US is Pittsburgh, PA.

The report also emphasizes the importance of right-of-way priority to achieve a high quality bus service that is able to attract new riders. One of his conclusions reads:

“Physical compatibility of buses with other highway vehicles should not represent an obstacle to their physical separation from other traffic. Exclusive bus facilities and maximum separation of buses through regulatory measures are a sine qua non for creation of high quality Bus Transit Systems which can successfully compete with the automobile, and thus play a major role in a multi-modal urban transportation system.”

Vuchic also examines the major reasons for failure to maintain bus preferential treatment studying the downgrading of bus priority lanes into HOV lanes. The main reasons cited are:

- Lack of clear policy favoring transit over other modes;
- Inadequate support and sometimes even opposition by city and, particularly, state transportation/highway departments;
- Federal policy (supported even by the FTA) endorsing HOV facilities, even where they replace busways and bus lanes, thus degrading transit services;
- Pressures by auto/highway interest lobbies;
Moving from Conventional Bus Service towards Bus Rapid Transit

Ch. 2. Literature review

- The false belief that “gaps between buses on highways can be utilized by other vehicles” without realizing the negative impacts such mixed traffic has on transit services and image;
- Regulation enforcement problems;
- Inadequate expertise and lack of initiative by transit agencies and traffic engineers.

Between 1994 and 2000 very few papers were published in journals addressing BRT issues, rather many newspaper and transit magazines started publishing articles about BRT experiences such as Curitiba, Pittsburgh, and Ottawa.

BRT was boosted in the US with the launch of FTA’s BRT Demonstration project. As part of the project, the FTA published a document called “Issues in Bus Rapid Transit”. This document (Goodman, Laube et al., 1999) defines BRT “as an integrated, well-defined system that would provide for significantly faster operating speeds, greater service reliability, and increased convenience, matching the quality of rail transit when implemented in appropriate settings”. The document reviews the most well known BRT experience in the world: Curitiba, and studies the US experience to date and potential US applications and concerns.

(FTA, 2000) launched the BRT demonstration project website. The site is an introduction to BRT features and illustrates its main points with case studies from:
- the Orlando Lymmo,
- the South Dade Busway in Miami,
- the Vancouver Rapid Bus Line,
- the Curitiba system, and
- the Ottawa Transitway.

Schimek, the author of the website’s content, lists and discusses what are considered the main BRT features as follows:
• **Right-of-way.** The right-of-way can be designated as busways, expressway lanes, or arterial bus lanes. A premise in the discussion is that priority or exclusivity is given to the buses. The main advantages of these facilities are the speed provided to the buses, and the flexibility of the infrastructure. The flexibility allows for the service to start operations as soon as parts of the line are finished; the system also allows for buses to leave the exclusive lanes and operate in mixed traffic as needed. Expressway lanes are most suitable for long-distance commuter service. Arterial exclusive lanes suffer from the paradox that they are most needed where they are most difficult to implement. Usually the most congested areas, such as CBDs, are where exclusive lanes can provide the most benefits to both users and the agency, but at the same time, these are the areas where private auto owners will be most opposed to yielding a lane to buses.

• **Stops: spacing and design.** In the stations section it claimed that although many studies have been done to optimize stop spacing, stops must ultimately be placed at major trip generators and attractors. Two related topics are given special emphasis, 1) the longitudinal placement, far-side or near-side; and 2) the bus stop zone type including the merging delays and operational consequences of each type.

• **Signal priority.** Illustrates the difference between passive priority and active priority. The first one seeks to favor roads with significant transit use. The second one involves detecting a transit vehicle, and depending on the traffic congestion and the vehicle situation, giving priority to the transit vehicle.

• **Vehicle design.** Low-floor vehicles are emphasized as the appropriate vehicles for BRT. In addition, aspects other than the height of the floor are also discussed such as the internal circulation, the number and width of doors, emissions, and propulsion.

• **Fare collection.** This section discusses several techniques to reduce on-board fare collection time, but mainly stresses that off-vehicle fare collection must be
Moving from Conventional Bus Service towards Bus Rapid Transit

- **Marketing, information, and AVL.** In this section, the need for marketing and information to customers is stressed. These two activities depend on AVL systems. Providing information to customers is an often neglected but crucial aspect of high-quality transit service.

- **Land use policy.** Finally, transit oriented development is considered a key companion, although not a consequence, to BRT projects.

(Kang and Diaz, 2000) affirm that the definition of BRT goes beyond any particular application of technology, facility improvement or service configuration. They argue that what differentiates BRT from other forms of bus service is the way in which it combines technology improvements with a comprehensive operation plan and a thoughtful customer interface. The authors consider that these three are the essential elements of BRT, which in turn have key sub-elements to consider as follows:

<table>
<thead>
<tr>
<th>Element</th>
<th>Technology</th>
<th>Operating Plan</th>
<th>Customer interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-elements</td>
<td>Vehicles</td>
<td>Route structure</td>
<td>Marketing strategy</td>
</tr>
<tr>
<td></td>
<td>Guideway</td>
<td>Service frequency</td>
<td>Fare structure</td>
</tr>
<tr>
<td></td>
<td>Control systems</td>
<td>Stop/station spacing</td>
<td>Security</td>
</tr>
<tr>
<td></td>
<td>Fare collection</td>
<td>Service span</td>
<td>Passenger information</td>
</tr>
<tr>
<td></td>
<td>Passenger information</td>
<td>Network structure</td>
<td>Architecture and design</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Degree of integration with other services</td>
<td></td>
</tr>
</tbody>
</table>

The most important arguments in the paper are the following:

- Vehicles are the central element of BRT technology.
- An advantage of BRT is its flexibility in terms of implementation, from which several cities have benefited (i.e. Porto Alegre and Curitiba)
• BRT is a flexible mode that can provide the solution to those cities caught in the chicken and egg situation with land use and mass rapid transit: it is difficult to support a high-capacity transit system (without significant subsidies) without associated transit-supportive development patterns, but it is also difficult to support transit-oriented development patterns without a high-quality transit system.

This paper is valuable since it is the first formal attempt to define and characterize the wide-spread usage of the term BRT; however, it lacks a methodology and structure to support the conclusion about the essential elements of BRT.

(Diaz and Schneck, 2000) looked more closely at one of the elements addressed in the previous reference: the operating plan. The paper explains in more detailed the meaning of each sub-element. In addition it illustrates the flexible range of solutions to each sub-element with examples from case studies. Their most important conclusion is that each element of a BRT operating plan should be designed to meet the specific market demands, physical constraints, and accessibility goals for particular corridors and metropolitan areas.

(GAO, 2001) The General Accounting Office submitted a report to Congress comparing BRT and LRT. The cases and numbers used by the research team have been hotly debated within the transportation community with concerns raised about a bias towards BRT benefits. However, despite this argument about the figures, this report is relevant to the transportation community and not because of its content, but because it is probably the only formal report about BRT and LRT in the hands of the decision-makers. The report supports FTA’s project to encourage transit agencies to start thinking about this alternative to rail systems, emphasizing the lower cost of BRT technology, but achieving a similar quality if implemented appropriately.

(Mulhern, 2001) During a presentation given at MIT CTS Speaker Series, Mulhern presents the SilverLine as the new BRT system for the city of Boston. In the year 2010,
the SilverLine is expected to carry 8,500 pass/peak hour/dir, the same expected ridership as for the Green Line (Light Rail) and 2,000 more passengers than the Blue Line (Heavy Rail). According to the presentation the main reasons to implement BRT systems are its flexibility, capacity, convenience, capability of incremental implementation, and cost-effectiveness. The main BRT components are:

- Right-of-way: exclusive lanes.
- Stations: conveniently located, integrated with communities.
- New vehicles: environmentally friendly, low floor, wide doors.
- Service frequency: high, eliminate reliance on the schedule in dense urban areas.
- Route structure: simple, color coded, understandable maps.
- Fare collection system: fast media payment, easily understandable structure.

Intelligent Transportation System (ITS): to improve operations safety, speed, reliability, customer convenience, and maintenance.

### 2.2 BRT components

#### 2.2.1 Right-of-way

(Salter and Memon, 1977) simulated a bus priority lane implemented in the city of Bradford, England during peak hours, to study the characteristics that would optimize passenger throughput. The bus priority lane was to be converted from a mixed-traffic lane. Assuming an average load of 50 pass/bus and auto occupancy of 1.5 pass/veh, the authors found that the reduction in travel time due to the priority scheme depends heavily on the percentage of buses in the corridor and overall traffic. For example, when only 5% of the vehicular flow is buses, a priority scheme results in increases in passengers’ journey time at most of the traffic flow levels studied. This indicates that corridors with higher traffic flows will be better off by converting a lane to bus priority to increase
passenger throughput. However, that conclusion assumes a significant mode shift from cars to buses to fill up the buses with an average load of 50 pass/peak hour.

(Vuchic, Kikuchi et al., 1995) states that the flexibility of buses, which has always been considered one of the mode’s advantages, has instead become a major liability. Buses allow for a flexible operation, which might be a plus for services with low and moderate ridership; however, bus flexibility also implies lack of permanence, lack of distinction from other traffic, and great difficulty in achieving separation from other traffic.

Based on his 1994 report, Vuchic continues the study of HOV facilities and busways. He studies the modal split and long-term effect of four alternative policies to cope with congestion in a corridor, the alternatives are:

8. C/B – convert a freeway lane to Bus lane
9. C/H – convert a freeway lane to HOV lane
10. A/B – add bus lane
11. A/H – add an HOV lane

Considering that the major goals of the policies are to promote transit and change modal split in its favor, the C/B approach appears to be the best and the A/H the worst. Despite this most cities are adding HOV lanes, usually arguing that converting a mixed traffic lane to a bus lane is “politically unacceptable”. This paper indicates that alternative ways of highway upgrading differ so substantially in terms of impacts that they should each be systematically analyzed.

2.2.2 Stops


This report comprehensively addresses the issue of bus stop locations. The report is divided into three parts. The first part tackles the “big picture” issues; in this part special emphasis is given to the need for coordination and cooperation between public and
private interests to improve bus stops' performance, including bus operation, accessibility, comfort, and convenience.

The second part addresses all the issues related to the street-side of the bus stop, which includes placement considerations, types of stop zone, vehicle characteristics, and roadway and intersection design. Under the placement considerations, the trade-off between close stops and farther apart stops is raised. On the one hand, close stops have short walk distances, but more frequent stops, and therefore a longer in-vehicle time. On the other hand, far apart stops induce longer walk distances, but more infrequent stops, thus shorter in-vehicle time. Typical bus stop spacing distances are given for different environments, such as Central Business Districts (CBD), urban areas, suburban areas, and rural areas. This part also includes comparative analyses of the longitudinal placement (far-side, near-side, or mid-block) and zone types (curb-side, bus bay, open bus bay, queue jumper bus bay, or nub). The analysis of vehicle characteristics and roadway and intersection design sections are not as thorough as the previous ones, however they constitute a general useful guideline when no other specific information on these topics is known.

The third part of the report addresses the curb-side factors, which include discussions on pedestrian access, ADA guidelines, waiting or accessory pads, shelters, and amenities. Similar to sections of the first chapter, this one does not answer all the questions, although it addresses all the correct issues and poses all the questions to be resolved.

The report is well organized, concise, and definitely a useful guide to start thinking about all the issues to be resolved in placing a bus stop correctly. The main contribution of the report is two checklists given with each main chapter. The checklists are a short discussion of every issue to be considered from the curb-side and the street side.
2.2.3 Vehicles

(Dejeammes, Coffin et al., 1999) studied the relationship that exists between bus stops and low-floor vehicles to achieve vertical and horizontal gaps that can comfortably accommodate people with disabilities. The results suggest that the improved bus stops and guidance systems tested increase the probability of appropriate docking at stops. The target gaps in the tests were drawn from the European Transport Research action COST 322, which establishes a horizontal gap of 10 cm (4 in approx.) and vertical gap of 5 cm (2 in approx.) for wheelchairs or 30 cm (12 in approx.) and 15 – 20 cm (5 – 8 in approx.) respectively, for people with reduced mobility.

The primary feature recommended for bus stop design is an extended bay (bus bulb) or on-line configuration. The two guidance systems developed are called GIBUS and VISEE. The first is a docking aid device, which displays the distance to curb in the final approach. The second is a guiding system with automated steering for docking, which resulted in narrower gaps and lower workload for drivers, but greater cost. GIBUS, together with the new bus stop design achieved the target gap of 10 cm.

(Dauby, 2000) stresses the small contribution of public transport to pollution as a whole compared to private cars and to other pollutant sources in the world. Nonetheless, transit operators are trying to identify the most suitable, environmentally friendly solution for their fleet. A review of most of the available technologies is made, and finally the most feasible ones today are chosen for deeper review: diesel, Compressed Natural Gas (CNG), and Liquefied Natural Gas (LPG).

The advantages and disadvantages of each one do not vary significantly from previous literature. Diesel is a high-efficiency, proven, reliable, compact and economic converter of mechanical energy, and it achieves pollution levels compliant with EURO III norms. CNG achieves lower levels of pollution, is already compliant with EURO V norms, but has low energy density (25% of diesel) and higher capital and maintenance
costs. LPG offers environmental performances that are slightly below those of CNG, but has three times the energy density, and the cost is 10% higher than diesel vehicles.

The study finally emphasizes the complexity of the decision when choosing a fuel, particularly because of the difficulty in drawing financial conclusions. Fuel selection should be made considering local characteristics and needs of the city. In general, diesel appears to offer the best compromise between cost, eco-balance, longevity of infrastructure, and the density of energy yields. Decision-makers often encourage CNG investment based on the pollution levels achieved by the fuel. However, gas’s quality advantages over diesel are becoming smaller to levels such that it is becoming increasingly difficult to justify CNG’s additional financial costs. Furthermore, recent scientific findings appear to show that the toxicity of particles is linked more to their size than to their number or their mass; the smaller they are, the greater their carcinogenic effect. And gas particles are extremely small, usually beyond detection threshold, in which case, the argument that emissions from gas engines are not harmful could be refuted.

(Dauby, 2001) states that public transport investment in recent decades has been focused on rail solutions while buses handle nearly 80% of the entire workload of public transportation worldwide. Governments are reluctant to invest in buses, due in part to their bad image in the eyes of the public, authorities, and operators. Hence bus service with an improved image is needed, which will be achieved by thinking in terms of a bus system that integrates the vehicles, the infrastructure, and the operating policies. This approach is needed because the infrastructure independence of the bus, which was before considered an advantage, has turned against it, confining it to increasingly overcrowded roadways.

Proposed improvements to vehicles are an enhanced, more stylish look, comfort features like air conditioning, low floor, and environmental-friendly fuel. However, it is
stated that no efforts to improve the service quality will succeed if they are restricted to the vehicle alone; the infrastructure must also receive attention. The infrastructure enhancements are focused on reserved lanes and priority, but also address guidance systems and stop design. Operational enhancements should focus on the primary problem of reliability, which can be partially addressed with AVL systems and their applications to improve operation, however, the real solution with today's level of congestion is once again, exclusive infrastructure.

(Jack, 2001) reviews the buses presented in the Exhibition of the 2001 UITP Congress Mobility and City Transport. The author highlights the attention given to the new CIVIS bus by Irisbus, which has the style and passenger appeal of a tram, but without the high infrastructure costs and the noise of steel wheels on steel rails. Figure 2-1 shows the exterior look of the CIVIS bus at a bus manufacturers fair. Figure 2-2 shows the interior of the CIVIS bus.

Figure 2-1 CIVIS bus exterior
Some of the features of this vehicle are:

- Central driving position for better visibility
- Color monitor below the console that allows the driver to see the curb while docking at stops
- All-electric or diesel-electric engine, with the electrical equipment on the roof to maximize low floor space for passengers
- Guidance system in front of the vehicle
- Tram-like interior design

In terms of fuel systems, it seems like diesel has regained its leading position compared to CNG, and the most promising contender among other technologies is fuel cells. Only two CNG buses were shown at the exhibition and some important manufacturers made no reference at all to this technology.

Another highlighted innovation was bus bodies made with composite materials, which weigh 1 ton less than conventional metal structures and are equally strong.
2.2.4 Fare Collection

(Vandebona and Richardson, 1985) reviewed empirical values of boarding and alighting rates found in several previous studies. Findings in those studies indicate that the alighting rate (if no on-board ticket validation is needed at the end of the trip) is found to be consistently between 1 and 1.5 seconds per passenger. Most of these studies considered a regular bus door width and some steps to get on and off the bus. Under this same configuration, boarding rates depend on the payment media and the interaction needed between the driver and the passenger. Some boarding rates found are shown in the following table.

<table>
<thead>
<tr>
<th>Type of fare collection system</th>
<th>Boarding [sec/pass]</th>
<th>Study</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-man operation</td>
<td>1.0 – 2.0</td>
<td>Cundill and Watts, 1974</td>
<td>Exact fare systems at the upper end, and change provided by the driver at the lower end</td>
</tr>
<tr>
<td>One-man operation</td>
<td>2.3 – 5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roving conductors and proof-of-payment</td>
<td>1.5 – 2.5</td>
<td>Grigg, 1982</td>
<td></td>
</tr>
<tr>
<td>Flat-fare one-man</td>
<td>3.0 – 5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone fares one-man</td>
<td>3.5 – 8.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The authors state that different fare collection systems (from driver payment to proof-of-payment) and vehicle design, influence the boarding and alighting rates, which in turn affect the service productivity and level of service. Their findings indicate that slower boarding rates produce a slower and less reliable service, while the variability of boarding rates has little effect on route travel time, but does contribute to greater unreliability. The study used a simulation model of a tram route that has similar characteristics to a heavy urban bus route in an exclusive lane (i.e. 5-minute headway, 18 km long, 32 signalized intersections, 75-passengers vehicles, and cruise speed of 50 km/h). Route productivity is measured in terms of route travel time and level of service in terms of different user related characteristics of the route. Some of these characteristics and their changes when moving from an 8 sec/pass-boarding rate (driver operation...
providing change) to a 1 sec/pass one (proof-of payment) are shown in Figure 2-3. The figure indicates that this change in fare collection system can provide:

- 20% reduction in route travel time,
- 22% reduction in average passenger waiting time,
- 25% reduction in average waiting time,
- 80% reduction on the probability of having buses bunched on the route

Although these figures need to be carefully analyzed before applying them in a different context, they do show the general sensitivity and impact on route performance of different fare collection systems.

![Figure 2-3 Impacts of boarding rates changes (Vande bona and Richardson, 1985)](image)

(Kraft and Bergen, 1974) reached the interesting overall conclusion that off-peak boarding and alighting rates are lower than peak rates. This might be explained by the type of passengers that use peak hour services: mostly regular commuters that are familiar with the service, and often use the most expedited payment media available.
Although most of the work done during the 1980s and early 1990s, considered the possibility of having off-vehicle fare collection, the boarding rate never was considered to be lower than 1 sec/pass because of the station and vehicle designs, which included sequential boarding by the passengers and a vertical movement to get off or on the bus. Steer Davies Gleave ("Transmilenio Volumen V: Plan de Operación," 1999) indicates that systems with off-vehicle fare collection, level boarding, and wide doors, can achieve boarding rates as low as 0.33 sec/pass. This rate is actually achieved in Transmilenio in Bogotá, Colombia.

2.2.5 Signal Priority

(Hunter-Zaworski, Kloos et al., 1995) studied two techniques of traffic signal priority in Portland: green extension – early green and queue jump. Also, two bus detection technologies were used, System A and System B. System A used radio frequency activated tags on the bus with special radio frequency readers installed along roadside. System B used a special transmitter on the bus that was read through standard vehicle loop detectors imbedded in the pavement. The before and after traffic surveys provided inconclusive data about the impact of bus signal priority on traffic, although it was concluded that both bus travel time and bus passenger delay for the route studied (Powell Number 9) was reduced slightly with the bus signal priority systems.

(Furth and Muller, 2000) studied the conditional priority system implemented in Eindhoven, Netherlands. Traffic impacts were analyzed for three scenarios: no priority, unconditional or absolute priority and conditional priority. The authors found that unconditional priority increased total vehicular delays significantly, even compared to no-priority schemes. Conditional priority generated similar levels of delay to the no-priority case but significantly improved schedule adherence.

(Chada and Newland, 2002) examined how different bus signal priority schemes impact traffic operations. It was concluded that bus signal priority offers fewer benefits in
areas with extremely high bus volumes or very light traffic. It was also determined that real time control strategies offer the greatest overall benefits. The study produced a framework and spreadsheet that helps agencies understand their needs for signal priority and guides them on the appropriate technology given their local conditions.

2.3 Evaluation measures

While literature on the specific topic of evaluating BRT components is sparse, literature on closely related issues, including passenger travel time, bus running time, reliability, and cost of time abound. Literature can be found based on analytical, empirical, and simulation research. This section presents literature in all three of these forms and is discussed by specific components used for evaluation.

2.3.1 Access time

Passengers travel time is comprised by access time, waiting time, and in-vehicle time. Access is the time passengers spend getting from the starting point of their trip (e.g. home, office) to the transit stop. Usually, this access portion of the journey is made walking; however other transport means could be used such as bike or even car in the case of a park-and-ride service.

The extent of research conducted on access time is rather brief compared to that on waiting time and in-vehicle time. Access time references are usually found in the context of optimizing stop spacing or stop location.

(Vuchic and Newell, 1968) presented one of the first approaches to evaluate stop spacing using continuous functions to describe boarding and alighting demand. The paper focuses on rail station spacing using bus as the access mode.

(Lesley, 1976) also applied the continuum approach to bus lines. He assumed circular catchment areas around bus stops, with the radius equal to one-half the stop
Moving from Conventional Bus Service towards Bus Rapid Transit

Ch. 2. Literature review

spacing. This assumption led to a counterintuitive result that as stop spacing increases demand increases as well, without bound.

(Vaughn and Cousins, 1977) extended Vuchic and Newell’s work including walking access and many-to-many travel demand. The authors assumed a Poisson distribution for stop location, which doubles average walking distance. It was also found that due to practical constraints stops are not always spaced at regular intervals. As a result, expected average walking distances are 25% greater than the stop spacing.

(Wirasinghe and Ghoneim, 1981) presented a bus route also modeled with the continuum approach. Passenger access (walking) time was formulated as a function of demand density, cruising speed, and the decision variable: stop spacing. Optimal stop spacing was found minimizing the sum of societal costs in the area adjacent to the corridor.

(Furth and Rahbee, 2000) used a discrete approach to model the impacts of bus stop spacing including shorter walking time parallel to the bus route. The authors used net walking time instead of absolute walking time to evaluate the impacts on access time. Net walking time is the walking time parallel to the bus route minus the change in in-vehicle time resulting from that walk. In this case the in-vehicle time was weighted to reflect the relative disutility of walking and riding time.

2.3.2 Waiting time, headway variation, and dwell time

The resulting passenger waiting time at a bus stop depends on two aspects: bus arrival time distribution and passenger arrival time patterns. Bus arrival distribution is defined by its headway and headway variability. The headway represents the predictable portion of the waiting time for passengers and contributes to determining the passenger arrival pattern; while its variability represents the unpredictable portion of the waiting time for passengers. Passenger arrival pattern can be of two forms, random or timed. Random passenger arrival times are often assumed for high frequency routes. As
headway increases passengers tend to time their arrival to the stop, and during the minutes prior to the bus arrival, passenger arrival rate increases; as a result the expected waiting time is reduced. Furthermore, bus and passenger arrivals appear to be correlated since reducing headway variability induces more timed passenger arrivals and constant number of waiting passengers, which in turn, induces further reliability.

Passenger waiting time modeling was pioneered by (Welding, 1957), who derived the following equation to model passenger waiting time.

\[
E(W) = E(H) \left[ 1 + \frac{V(H)}{E(H)^2} \right] = E(H) \left[ 1 + \text{Cov}(H)^2 \right]
\]  

(2.1)

where,

\[
E(W) = \text{Expected Passenger Waiting Time},
\]

\[
E(H) = \text{Expected Headway},
\]

\[
V(H) = \text{Variance of Headway}, \text{ and}
\]

\[
\text{Cov}(H) = \text{Coefficient of Variation of Headway}.
\]

Equation 2-1 has been used in a number of studies including (Holroyd and Scraggs, 1966; Osuna and Newell, 1972; Barnett, 1974; Seddon and Day, 1974; Hendrickson, 1981) and it relies on two important assumptions:

12. Passenger arrivals are random, instead of timed
13. There are no capacity constraints, thus all passengers are able to board the first vehicle to arrive

Eq. 2-1 implies that if bus headways are constant, the average wait time would be half the expected headway; thus, under a third assumption

14. There is no headway variation \((V(H) = 0)\)

Equation 2-1 reduces to
Due to the resulting simplicity and the accuracy level desired, some studies (Newell, 1979; Wirasinghe, 1980) have used Equation 2-2 to model passenger waiting time. Then, under the assumption of random passenger arrival Equation 2-2 can be seen as a lower bound for passenger waiting time. The upper bound is provided by the Equation 2-1 under the consideration of random vehicle arrivals, \( \text{Cov}(H) = 1 \) and the expected waiting time would be equal to the expected headway.

Although, the random passenger arrival assumption leads to a simple equation it does not accurately reflect reality. Passengers are sometimes aware of the schedule and time their arrival to the station, making waiting times lower than those projected by the previous equations. The difference between the theoretical value given by Equation 2-1 and actual times increases as headways are longer and especially if buses are on time.

Many studies have tried to capture the effect of timed passenger arrivals on waiting times. Empirical studies have tried to formulate equations of expected waiting times based on real operations data.

(Seddon and Day, 1974) modeled off-peak waiting time in Manchester as

\[
E(W) = 1.79 + 0.14 \times E(H)
\]

An interesting observation in this study is that passengers were found to wait longer for low frequency buses than for high frequency ones. This points to the intuitive observation that the cost of missing a low frequency bus is higher than that of missing a high frequency bus. Thus, passenger waiting times on different routes and time periods might need to be weighted in order to be compared.

(Day, 1976) modeled waiting time in England based on a sample of over 10,000 passengers in bus routes with headways between 4 min and 30 min and found:
Moving from Conventional Bus Service towards Bus Rapid Transit

Ch. 2. Literature review

\[
E(W) = \frac{E(H)}{0.05*E(H) + 2.08} + \frac{0.56*V(H)}{E(H)}
\]

(Abkowitz and Engelstein, 1984) modeled southern California Rapid Transit District passenger waiting time

\[
E(W) = -0.784 + 0.497* E(H) + 0.0726 * V(H)
\]

Replacing \(E(H)\) and \(V(H)\) in these models with theoretical values, it is observed for the first model that \(E(W)\) with \(E(H)\) equal to or higher than 10 min are lower than the theoretical value, indicating that passengers start timing their arrival for headways above 10 min. The second and third models indicate that people start timing their arrival for headways as low as 5 min.

(Okrent, 1974) estimated beta and gamma distributions to fit data observed at bus stops in Chicago and Evanston, Illinois. His conclusion was that passengers start timing their arrival after 12 min or 13 min headways.

(Jolliffe and Hutchinson, 1975) suggested a model that accounts for different types of passenger arrival distributions by classifying passengers into three categories:

- passengers that wait zero minutes because they arrive at the bus stop at the same time of the bus
- passengers that time their arrival to minimize their waiting time at the stop
- passengers that arrive randomly

(Bowman and Turnquist, 1981) proposed a model with only two types of passengers, those that arrive at random and those that time their arrivals. Bus arrival times were modeled with a lognormal distribution. The contribution of this work was the relation between the parameters of the non-random arrivals distribution with the service quality (i.e. frequency and reliability). The model suggests that an improvement in reliability results in lower waiting times due to a stronger coordination between passenger
and bus arrivals. Furthermore, the results indicate that average passenger waiting time is more sensitive to reliability improvements and less sensitive to frequency than previously assumed.

As indicated by the waiting time references, headway variation is crucial to model bus operations, and therefore accurately determine passenger waiting time. Headway variation is a result of travel time variations of successive buses. The process is triggered by an unexpected event that delays the bus, resulting in a late arrival at its next stop, thus experiencing a greater dwelling time due to extra passengers that have arrived at the stop. The process repeats at subsequent stops with delay increasing as the bus moves along the route until unavoidably the trailing bus catches up with the front one. This phenomenon is recognized as bus bunching and has been widely studied.

Many studies have also been devoted to modeling headway variation, with significant progress made by (Adebisi, 1986) in terms of mathematical modeling of headway variation. The real innovation in this model was the inclusion of a stop skipping probability and correlation factors between successive bus running times $\rho_t$ and bus loads $\rho_q$. The first correlation factor allowed the model to represent a wide range of traffic conditions and driver behavior. The second correlation factor allowed the model to represent varying conditions of passenger crowding in successive buses.
3 CASE STUDIES

This chapter studies five cases of BRT systems, two in the US, one in Canada, and two in Latin America. The main objective in this chapter is to identify the key attributes and elements that led to higher service quality in these BRT systems.

To achieve this objective three steps were followed. First, information on each case was collected through published literature, interviews, and direct experience. Second, elements of these systems that differentiate them from CBS were identified. To accomplish this a comprehensive matrix of CBS elements was created and compared with information in each case study. Thus, elements that were found different on BRT systems resulting in higher quality were recognized. The matrix classified elements into three categories:

- Physical (i.e. stops, right-of-way, vehicles, public space)
- Service (i.e. headway, service hours, schedule)
- System (i.e. land-use integration, connectivity with other modes, customer information)

Third, an analysis was done to understand the attributes that resulted from these different elements. For example elements such as exclusive lanes and signal priority result in the attribute of right-of-way priority. Finally, the key BRT attributes are presented in the last section of this chapter as the findings of the case studies.

The following sections present the case studies; they all consist of two parts. First, a brief introduction to the system is given, which includes basic operational information for the system. The cases were chosen due to their high operational quality, but also to include a good mix of infrastructure, operations, and implementation strategies. Second,

3 The reader should not expect a detailed description of each system; to obtain that information the reader should refer to the bibliography cited for each system.
the physical, service, and system elements that differentiate the case from CBS are outlined and briefly explained.

3.1 Curitiba: Integrated bus network

The integrated bus network at Curitiba is widely considered the most successful BRT system in the world. While Curitiba’s population is around 2.2 million inhabitants, the integrated bus network carries 1.3 million passengers per day. Despite the high motorization rate in Curitiba by Latin America standards (1 car for every 3 people), and high income per capita, transit trips account for 55% of all daily trips, and 70% of daily work trips. The system also provides high levels of customer satisfaction with about 89% of customers satisfied or very satisfied with the service. In addition to the ridership levels

---

4 References used for information on Curitiba’s integrated transportation network:


and high quality and capacity achieved, a tight correlation between land use and public transportation has been a key factor for success in Curitiba. Zoning and land use regulation has resulted in transit-oriented development around high capacity transit corridors.

The integrated system consists of different services. The backbone of the system consists of five exclusive right-of-way corridors served by bi-articulated buses that run from downtown to the East, West, North, South, and Southeast of the city. Routes on these corridors are known as Express. Figure 3-1 shows a map of the integrated system, with exclusive lane corridors highlighted. Other services include feeder routes to the Express services, Direct services that run on streets parallel to the Express routes but make fewer stops, Inter-district services, and Circular routes that connect all Express corridors.

Figure 3-1 Curitiba’s system map
The responsible public agency, URBS, plans and controls operations, but private operators provide the service. The ten private operators make a profit out of their public transportation business and the system does not receive operational subsidies from the government.

**Physical elements**

- **Right-of-way.** The system has 58 km of exclusive lanes that constitute the main transit axes of the city; Figure 3-2 shows one of them.

![Figure 3-2 Curitiba’s express vehicles in exclusive lanes](image)

- **Stops.**
  - As opposed to CBS stops, Curitiba implemented small stations on the sidewalks, known as “tube-stations”. Architects and planners have debated the design of the stations for years. However, it is undeniable that they are very functional and have become a landmark of the city, making bus stops distinctive places.
  - The design is modular allowing stations to grow if necessary. Figure 3-3 and Figure 3-4 show a tube station in use from the outside and inside.
• Vehicles.
  - Express and Direct buses are traditional *high-floor* design; 90 cm (approx. 35 inches) from the pavement. This high platform combined with the station’s high floor provides *level boarding*.
  - The fleet has vehicles of *varying capacity* to match different demand levels. The highest capacity vehicles are *bi-articulated* (270 passengers) that operate in the exclusive lanes.
- A different color-code is used for each type of service (i.e. Express, Direct, Inter-district), which makes it easier for users to understand the system and provides the system with an image of its own.
- The vehicles have multiple wide doors that expedite the boarding and alighting process.

**Terminals.** The system has multiple terminals at the end of and along the exclusive lanes corridors that ease barrier-free, no cost transfers in the system. Both the feeder and trunk buses enter the terminals and the transfer are produced in their platforms. There are some in-route terminals, which are often within the right-of-way of the trunk buses to minimize waiting time for through passengers.

**Service elements**

- **Network structure.** 58 km of exclusive lanes are supported by 270 km of feeder routes and 185 km of inter-district routes.
- **Services.** The system provides different kinds of service. Express routes run along the exclusive corridors and stop at all stations, usually every 500 m. Direct routes run on streets parallel to the exclusive lane corridors and stop less frequently, usually every 800 m. Feeder routes operate in the neighborhoods, and begin and end at express route terminals, and usually stop at designated places about 200 meters apart. Circular routes connect all Express routes.
- **Speed.** Operational speed is between 20 – 25 km/hr (12.5 – 15.5 mph) on the Express and Direct services.
- **Headway.** Headways on the Express routes during peak hours could be as low as 1.5 min and usually are between 2 min and 5 min.
- **Boarding/alighting process.**
  - Pre-boarding fare payment at stations
- **Level-boarding** achieved with high platform stations and matching high floor vehicles
- **No boarding gap** achieved with ramps lowered by the buses

- **Dwell time.** Dwell times are short, usually 15 to 19 seconds for a bi-articulated bus in the peak hour. Not only are dwell times short but they are also consistent. Due to level boarding, wide and multiple door entry, and fare pre-payment, dwell times are less dependent on the demand at each station, and thus less variable.

- **Schedule.** The system relies on *headway-based operations* instead of schedule based-operations.

**System elements**

- **Land use correlation.** Exclusive lane corridors serve the highest density areas of the city. Additionally, the zoning rules of the city encourage mixed use on the corridors.

- **Integration and connectivity.** The system offers good integration to its customers, both in terms of fare and infrastructure. Transfers are made in barrier-free terminals and at no extra cost for the users.

- **Service provider.** Ten private companies operate the buses under the planning and control of a public agency.

- **Financial performance.** All private service providers earn an *operating profit.* Neither the national nor the state government subsidize daily operations, they only support capital investment.

- **Implementation.** The system has grown over 30 years matching the population growth and development in Curitiba.

- **Cost.** Both *capital and operational cost are low.* The most recent exclusive lane corridor was completed at a cost of US$1.5 millions per kilometer in 1994.
3.2 Bogotá: Transmilenio

Bogotá, Colombia, recently implemented a BRT system called Transmilenio, which started operations in December 2000. Transmilenio, as the integrated system in Curitiba, operates as a trunk-feeder system. Exclusive lanes are used only by trunk routes, which meet feeder routes in Terminals at the end of the exclusive lane corridors. The portion implemented represents phase I of the complete system. The infrastructure in this first phase consists of 38 km of exclusive lanes, 100 km of feeder routes, 57 stations, and 4 transfer terminals. Today, the 470 articulated buses are carrying 690,000 passengers per day. The trunk operation is backed by 303 feeder buses.

Transmilenio is notable for its high capacity; in peak hours, the downtown portion of the exclusive lane corridors carry around 42,000 pass/hour/dir. This figure is higher than most heavy rail systems in the US. Ridership forecasts have been exceeded; technical studies predicted a weekday demand of 550,000 passengers for the first phase,

5 References used for information on Bogotá’s Transmilenio system:


which is yet to be completed (one terminal will start operation in December 2002) and the demand is already 25% above the predicted values.

Two other aspects are worth noting in the case of Bogotá. First, Transmilenio is not an isolated transportation project, although it is the most important element, it is only one of the elements of the transportation policy adopted by the city four years ago. The city has rejected car-based development and instead is encouraging the development of a high quality public transportation network. The network includes hundreds of kilometers of high-quality bike paths throughout the city, and the rehabilitation of sidewalks. Other related projects discourage automobile use such as private cars restriction during peak hours, and tighter parking policies.

The second aspect relates to the public space accompanying every Transmilenio trunk corridor. The stations are located in the median of the street, which in some cases have a highway configuration and not a downtown arterial. Thus, relating the station to the side of the street was carefully done by building into every station, to the extent possible, a public space or plaza that relates the transit system with the urban grid. Landscaping and sidewalk rehabilitation (most of them had been used for parking) was done all along the corridors to provide pedestrians a high quality environment and encourage walking.

Physical elements

- **Right-of-way.** Transmilenio has 38 km of exclusive lanes that are the main operational axes. All the corridors have over-taking capabilities: 28 km have two lanes in each direction along the entire corridor and 10 km have one lane between stations and two lanes in front of stations that allow express buses to overtake local buses. Figure 3-5 shows the main corridor Avenida Caracas. Average passenger travel time has been reduced by 32% with the implementation of Transmilenio.
Figure 3-5 Transmilenio’s exclusive lanes in Avenida Caracas

• **Stops.**
  - Transmilenio has *stations* instead of stops, located in the street median.
  - The materials and design of the stations are coordinated with the public space surrounding the stations; all together they provide the system with its own *stylish image*.
  - The stations are *modular* to match infrastructure with demand as needed.
  - Average *station spacing* is around 500 m. Figure 3-6 shows the entrance of a Transmilenio station in Avenida Caracas.

• **Public space.** Transmilenio invested a significant amount of money in public spaces and urban streetscaping around the stations. These public spaces are treated as extensions of the stations into the sidewalks and neighborhoods. All streetscaping amenities (i.e. trashcan, benches, lighting, totems) were designed as part of the system and help provide the system with a distinct image. In most cases, neighborhoods surrounding the corridors are low income, and the public space around
Transmilenio stations is recognized as the highest quality space in the neighborhood. Figure 3-7 shows a large totem identifying one of the Terminal stations. Each of the 57 stations has one or more identical totems with the name of the station so that users can identify the station from several blocks away.

Figure 3-6 Transmilenio station in Avenida Caracas

Figure 3-7 Identifying totem at Calle 80 terminal
• Vehicles.
  - All vehicles operating in the exclusive lanes are high-floor; 90 cm (35 in approx.) above the pavement. This high platform combined with the station’s high platform provides level boarding for the system.
  - All trunk vehicles are articulated with capacity for 160 passengers.
  - Trunk and feeder services are easily distinguishable by their color-coded buses. Trunk buses are red and feeder buses are green.
  - The vehicles have multiple wide doors that expedite the boarding and alighting process. Figure 3-8 shows a trunk bus docking at a station; the doors are located in the left side of the bus due to the median location of the stations.

Figure 3-8 Trunk bus docking at station

• Terminals. The system has 4 end-route terminals and 4 intermediate transfer terminals along the exclusive lanes corridors. At these facilities, passengers have free transfers between trunk and feeder buses.

• Fare collection. Fare vending and payment occurs at the entrance of the stations. The medium is contact-less SmartCards. Passengers can buy 1 trip, 2 trip, or 10 trip cards, and they must validate their cards when entering and leaving the station. Although
double validation is somewhat burdensome for passengers, it provides the agency with a great amount of information to plan and operate the system according to demand patterns.

**Service elements**

- **Network structure.** The 38 km of exclusive lanes are supported by 100 km of feeder routes.

- **Services.** The system has two main types of services, trunk routes that operate in the exclusive lanes and feeder routes. The trunk routes can be divided into two types, express and local routes. Express routes stop only at certain locations serving a reduced number of origins and destinations. Local routes stop at all stations on the exclusive corridors.

- **Speed.** Operational speed for local services is around 22km/hr (13.8 mph) and for express services is 25 - 30 km/hr (17.5 – 19 mph).

- **Headway.** Headways in the trunk corridors during peak hours are 2 – 3 min, and during off-peak headways usually are 5 min.

- **Boarding/alighting process.**
  - Pre-boarding fare payment at stations
  - Level-boarding achieved with high platform stations and matching high floor vehicles
  - Very small boarding gap of about 10 – 15 cm (4 – 6 in) achieved without ramps, only by precise docking of buses at stations

- **Dwelling.** Dwell times are short, usually 15 to 20 seconds. The operational standards state that the maximum dwell time at stations must be 25 seconds. As in the Curitiba case, dwell times are consistent, eliminating one of the main sources of unreliability in operation.
Moving from Conventional Bus Service towards Bus Rapid Transit

Ch. 3. Case studies

- **Schedule.** The system relies on *headway-based operations* instead of schedule based-operations, which means that rather to control and adhere to a schedule, the control center is trying to maintain a regular headway at all times.

- **Control system.** Vehicles are monitored in *real time* through an *AVL system* and control is centralized at a control center. Voice and data communications is available at all times between the vehicles and the control center. Figure 3-9 shows a screen of the AVL system available for the controllers at the control center.

![Figure 3-9 AVL control software screen](image)

**System elements**

- **Cost.** The *low capital cost* of the system compared with rail alternatives has ensured the *continuity* of the system (the next three corridors are under design and their operation is being procured). The infrastructure costs (without vehicles) were US$5.3 million per kilometer or US$198 millions. The cost of the vehicles, which were assumed by the private operators was US$87.5 millions.

- **Integration and connectivity.** The system offers good integration to its customers, both in terms of *fare and infrastructure*. Free transfers can be made in terminals. In
addition to the local feeder routes, passengers can also transfer to suburban bus routes for a slightly higher fare.

- **Service provider.** Four *private companies* provide service, while planning and control remains with the public agency.

- **Financial performance.** Revenue from fare collection covers operation, maintenance, vehicle depreciation, *operating profit* for all private operators, the fare collection system provider, and the public agency operations. Neither the national government nor the city subsidizes daily operations. The infrastructure, however, is paid by the federal government (70%) and city (30%).

- **Implementation.** Although the master plan considers a staged implementation over the next 15 years, the first phase was planned, procured, and built in *three years*.

- **Public agency.** The public transit agency that controls the system was created along the way with the infrastructure. An efficient *organizational structure* was created resulting in an agency with only 88 employees.
3.3 Ottawa: Transitway

Ottawa has two transit agencies operating in its region: the Ottawa-Carleton Regional Transit Commission (OC Transpo) and la Societe de transport de L'Outaouais (STO). OC Transpo is the larger of the two with 826 buses and moves more passengers to their destinations than any other comparably sized bus system in North America. The system serves a metropolitan region with a population of 650,000 inhabitants and in 1994 ridership was 74 million.

Ottawa disproves some of the common transit industry assumptions. The first is that large population, high densities, and captive riders are needed to generate significant transit ridership. Metropolitan Ottawa has only 900,000 inhabitants, not particularly high densities, and a large portion of choice riders. The second assumption is that severe auto congestion, high parking rates, and high transit subsidies are needed to influence mode choice, however Ottawa’s traffic congestion is not high, parking rates downtown are about $7 per day, the bus one-way fare is $1.85 and annual ridership is 74 million. Finally, there is the premise that passengers will choose rail but avoid buses at all cost.

---

6 For information on Ottawa’s Transitway refer to:


"The way ahead: becoming the best of the best". KPMG Consultants (1999). Ottawa,


Research Results Digest 22.

OC Transpo shows that regardless of the technology it is the convenience and quality of the service that attracts riders.

OC Transpo system is best known for its Transitway, a busway that provides rapid and frequent bus service. In the 1960s and 1970s Ottawa and its suburbs created a metropolitan development plan that rejected a freeway pattern instead relying more heavily on public transportation. Four different at-grade transit alternatives were considered; two were based on light rail and two on bus. The four alternatives were evaluated in terms of costs (capital and operating), level of service, staging flexibility, and environmental impact. The heaviest weight within the criteria was given to costs. The calculated costs are shown in Table 3-1.

**Table 3-1 Total Annual Cost Comparison Based on 625,000 Population Level**

<table>
<thead>
<tr>
<th></th>
<th>Busway</th>
<th>Light Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Operating</td>
<td>Capital</td>
</tr>
<tr>
<td>Standard Busway</td>
<td>$93.93</td>
<td>$32.11</td>
</tr>
<tr>
<td>Articulated Busway</td>
<td>$83.67</td>
<td>$32.95</td>
</tr>
<tr>
<td>Standard Feeder Bus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Articulated Feeder Bus</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Finally the busway using articulated vehicles was chosen and the first portion of the system started operations in 1983. The Transitway has become the backbone of Ottawa’s transportation system with 32.6 km (of which 19.6 are exclusive lanes) and 23 stations. Weekday ridership is 200,000 passengers and the peak hour ridership is 10,000 passengers/hour/direction, which is a considerably larger number of commuters than those who use the Queensway, the region’s major freeway. Figure 3-10 shows three pictures of the Transitway’s right-of-way and stations.
In contrast with the previous two cases, this system does not operate only with a trunk-feeder configuration. The Transitway is also used by routes that start operating in mixed traffic and later join the exclusive lanes. This way, more riders are provided with one-seat rides to downtown.

**Physical elements**

- **Right-of-way.** The Transitway system operates in 19.6 km of exclusive lanes, 9.7 km of priority lanes on arterials, and 3.3 km of mixed traffic.

- **Stops.** As in the two previous cases Ottawa’s Transitway has *stations* instead of stops. The stations in the busway can accommodate all types of buses operated by OC Transpo, and up to three buses simultaneously. Stations have secure *bike racks* to encourage intermodal bike-bus trips.

- **Vehicles.**
  - *Articulated buses* comprise the fleet of the two routes that use the Transitway.
  - Most vehicles have *high-platform with steps*, but *some are low-floor* to provide accessibility for disabled customers.
  - The vehicles allow *bikes to be taken on-board*.

- **Park-and-ride.** The system has five integrated *park-and-ride lots* that provide over 1500 free parking spaces to customers.

- **Fare collection.** Customers can pay their fare with *exact cash, tickets, or monthly passes*. Cash fares are collected on board the buses. However, 75% of the passengers use monthly passes, those customers, as well as transfer users, are allowed to board through the rear door of articulated buses. A free transfer ticket can be requested when boarding the bus. Fare payment control is through random inspections.

**Service elements**
• **Network structure.** Routes other than the Transitway ones serve as feeders to the system, most of them either start and/or finish at a busway station. Transfers also occur from the park-and-ride facilities.

• **Services.** The system has three different types of services: express routes, local routes, and Transitway routes. Transitway routes operate only in the busway, express routes use the busway and mixed traffic streets, local routes operate only in mixed traffic streets but connect to busway stations.

• **Speed.** Operational speed in the two main Transitway routes (95 and 97) is around 35 km/hr (21.8 mph).

• **Headway.** During peak periods, headways in Transitway routes vary from 3 min to 5 min. During off-peak hours, headways go up to maximum of 10 min but are usually 8 min.

Figure 3-10 Ottawa’s Transitway
System elements

- **Cost.** The system has low operating costs due to the flexibility of the buses that allow a close relationship between demand and capacity.

- **Implementation.** The system was designed and in fact has been built in stages as funds have become available. The system is designed so that it will be able to accommodate a large increase in passenger demand in the future. In addition, planners designed the busways so that they could be converted to light rail if future levels of ridership make such conversion desirable.

- **Land use integration.** Land zoning rules are related to transit development in the city. Also the agency has been successful in achieving good station area development jointly with private companies.

- **Customer information.** The Transitway has different user information signs than other routes in Ottawa so that users can distinguish busway routes from conventional bus routes. In addition, the Transitway map is designed in a schematic way resembling a rail map.

3.4 Pittsburgh: South, East, and West Busway

The central city of Pittsburgh has relatively high population and employment densities, and low levels of auto ownership, which all translate into good potential for high levels of transit use. The city today has a light rail system and a network of busways that provide the main modes of public transportation.

---

7 For information on Pittsburgh’s busway system refer to:


Pittsburgh was the first city in the US to build and operate exclusive busways. The system started 24 years ago as a simple bypass for the buses to avoid traffic and has become the most touted BRT system in the US. The system consists of three busways as follows:

- **South Busway**: 4.3 miles; opened in December 1977; 17 routes
- **East Busway**: 6.8 miles; opened in February 1983; 31 routes
- **West Busway**: 5 miles; opened in September 2000; 14 routes

It is difficult to describe the Pittsburgh system in its entirety because as busways have been implemented over the years, new features have been added to each one. Thus, operational characteristics are not consistent across all three busways.

Ridership in all three busways is approximately 47,000 passengers per day. The East busway carries approximately 30,000 riders on an average weekday, making it the Port Authority's most used, the South busway transports 10,000 riders per day, and the West busway carries approximately 7,000 customers per day, with ridership expected to grow upon completion of all proposed park and ride lots.

**Physical elements**

- **Right-of-way.** The complete busway system in Pittsburgh consists of 26 km (16.1 mi) of exclusive lanes. In the West busway, the number of lanes varies from two to four, allowing express buses to overtake local buses. Significant reductions in travel time have been achieved due to the exclusive treatment for buses:
  - With the construction of the East busway, a trip from Wilkinsburg to downtown that took 20 to 60 min, depending on traffic and weather conditions, was reduced to 9 to 13 min, depending on passenger stops.
  - The West busway reduced travel time by up to 26 min for the morning peak direction and slightly less in the afternoon peak.
- The South busway saved 6 to 11 min in running time for the buses, which allowed eliminating 160 bus trips.

- **Stops.** The new West busway, has *stations* which are completely *ADA compliant* and with other *amenities* such as public phones, customer service and security phone systems, landscaping, and scheduling information. The stations are also notable for their *stylish curvilinear shelters*.

- **Vehicles.** Different types of buses operate in the system, however, as new busways are built vehicles have been bought with more comfort amenities for the users. Most buses are conventional, high-platform, step access buses, but lately some low-floor vehicles have been introduced.

- **Fare collection.** The fare collection process is conventionally done on-board, with fare collection boxes.

- **Park-and-ride.** In the design of the West busway (the last one to be opened) the importance of linking transit and private cars was recognized. Hence, a series of *park-and-ride facilities* were included in the busway, which will provide more than 2,800 parking spaces.

- **Signal priority.** The West busway routes that use mixed traffic facilities at the end of the route are provided with *synchronized traffic signals* at West Carson Street.

- **Public space.** The most recent and planned busways include public space as an important feature of the transit system. The East Busway extension was designed with a linear park with pedestrian paths for walking, biking, and skating, landscaping amenities such as trees, benches, lighting, and improved pedestrian access to stations.

**Service elements**

- **Services.** As in Ottawa, the exclusive infrastructure serves *two types of routes*: In the East busway, two routes use only the busway infrastructure (locals), and 29 suburban
routes travel partially in mixed traffic and partially in the busways (express or flyer). Flyer routes usually only stop at two of the six East Busway stations.

- **Speed.** Average operational speed in the busways is 22 km/hr (13.8 mph).
- **Headway.** Peak period headways in the busways vary between 5 and 10 min.

**System elements**

- **Ridership.** Routes using the South busway increased ridership by 16% after its introduction.

- **Cost.** Capital costs are not as low as in other BRT projects. Due to Pittsburgh’s topography, the West busway project included rehabilitating 11 existing bridges and an old railroad tunnel. As a result total costs were US$326.8 million, or US$65.4 million per mile (US$40.8 million per kilometer). The 2.3-mile extension for the East busway is projected to cost US$62.8 million, or US$27.3 million per mile (US$17.1 million per kilometer). This extension includes significant investment in public space along the busway.

- **Integration and connectivity.** A reduced fare (US$0.25 extra) allows customers to transfer between bus routes.

- **Implementation.** Stageability and operational flexibility of the system have been key factors in Pittsburgh’s busway network. The system has been built over the years as funds have become available, however every piece built always provided positive impacts that helped in gaining buy-in to continue onto the following phases.

- **Economic development.** The East busway, during its first 15 years attracted more than US$300 million of new private development along its 6.8 mile route, of which 76% is new construction. Development clustered at stations accounts for 58% of the total investment. The most common uses for the developments along the East Busway are retail, office, residential, and medical.
• **Lane enforcement.** Pittsburgh’s strategy to enforce the lanes has been to use exclusive lanes as much as possible, to the extent that it does not diminish operations. Thus, express and local PAT routes, Beaver County Transit Authority buses, and express airport bus service, all use the busways to show higher frequency to auto drivers.

3.5 **Los Angeles: Metro Rapid**

The Los Angeles Metro Rapid project started operations in June 2000. The project includes two routes, one on Whittier/Wilshire Boulevard (route 720) with 32 stops, and one on Ventura Boulevard (line 750) with 15 stops. Figure 3-11 shows a map of the Metro Rapid system.

The project introduced enhancements to elements of the previous local routes, such as signal system, stops, streetscape, and vehicles. These improvements have successfully reduced travel time, increased ridership, and built customer confidence. Total (Local + MetroRapid routes) daily ridership in the Whittier/Wilshire corridor increased 32.6% (20,666 extra unlinked trips) after the introduction of MetroRapid. However, ridership increased proportionally more in the local service than in the MetroRapid service (compared with the previous limited stop service). At the same time, daily ridership in the Ventura corridor increased by 26.4% (2,850 extra unlinked trips). In this case, the local

---

8 For information on Los Angeles’ Metro Rapid refer to:


"MTA.NET". Los Angeles County Metropolitan Transportation Authority (2002). (www.mta.net)

Moving from Conventional Bus Service towards Bus Rapid Transit

Ch. 3. Case studies

Service saw a significant ridership reduction from 10,800 daily trips to 4,650 after the introduction of the Metro Rapid service. Savings in running time in both corridors are 25% from previous local services. 30% to 40% of the savings are credited to the system's signal priority technology.

Figure 3-11 MetroRapid system map

The operational success of the phase I project has created political and community buy in to move onto the second phase of the project, which includes implementing BRT elements not introduced in the first phase (i.e. exclusive lanes, off-vehicle fare payment, multiple door boarding and alighting, and coordinated land use) and extending the system to other corridors.

---

9 No previous limited stop service was available in the Ventura corridor for comparison purposes.

10 This figure represents time savings for half a cycle, that is from one end of the corridor to the other. Time savings for users are certainly less, as trip lengths are usually shorter than the complete route.
Physical elements

- **Right-of-way.** The buses run in a *preferential lane* on the right lane of the corridors.
- **Stops.**
  - In contrast with the first three cases, infrastructure at the Metro Rapid stops resembles more those of CBS systems; there are no closed stations, only *shelters*, but provided with *technological features and comfort amenities* for the users.
  - Stops have been designated *stop stations* by the MTA to distinguish from regular CBS stops
  - Stop stations feature *real-time passenger information*; an electronic display shows waiting passengers when the next bus is arriving. Figure 3-12 shows a double-canopy stop and a detail on the real-time information display.
  - *Average stop spacing* is approximately 1360 mts (0.85 miles).
  - Metro Rapid stop stations are *far side* (far corners of intersections, after traffic lights), while local stops are on the near corner.
  - The *simple design* of the shelters allows for *local customization*.

![Figure 3-12 LA Metro Rapid station and real-time information display](image)
• **Public space.** Urban streetscaping was introduced in both corridors including aesthetically improved shelters, benches, landscaping, trash receptacles, security lighting and surveillance, increased sidewalk width, and enhanced crosswalks.

• **Vehicles.** Vehicles in both corridors are *low-floor* buses fueled with *Compressed Natural Gas*. Metro Rapid buses are differentiated from the rest of the fleet; they have a *special exterior paint scheme* and visual cues that coordinate with the station design. Figure 3-13 shows a Metro Rapid bus operating the ramp that allows reduced mobility passengers into the vehicle.

![Figure 3-13 Metro Rapid bus](image)

• **Fare collection.** As of today the system has conventional on-board fare collection system. Off-vehicle fare payment has been tested and will be implemented in Phase II.

**Service elements**

• **Services.** The Metro Rapid system consists only of the two routes running along the preferential lanes on Ventura and Whittier/Wilshire corridors. These services replaced
existing limited-stop service (where present), but existing local bus service remains on the same corridors. There is no formal feeder system in place.

- **Headway.** During weekday peak periods and directions headways are:
  - Ventura: 3 min to 7 min
  - Wilshire: 2 min to 4 min

- **Schedule.** Between approximately, 6 am and 6 pm, both services operate under a *headway-based* configuration.

- **Control system.** A new *Control Center* was built to manage Metro rapid operations. Controllers manage bus operations in real-time with a *graphical aid display*.

- **Signal priority.** The portion of the Wilshire corridor that lies within the City of Los Angeles has a *signal priority system*. The system allows a bus approaching an intersection automatically to trigger the signal to remain green for 10 extra seconds. However, at important intersections, the green phase can only be extended every other cycle. The system operates under *conditional priority*, thus buses arriving at the intersection within the scheduled headway are not given priority, to prevent “bus bunching”.

**System elements**

- **Cost.** The system was implemented at a *low capital cost*. The stops and their urban enhancement was implement at a cost of US$100,000 per mile. The bus signal priority system cost approximately US$20,000 per intersection. Total stops and signal priority costs were US$5,010,000 for the Wilshire corridor and US$3,264,300 for the Ventura corridor.

- **Integration and connectivity.** The Ventura corridor, at its eastern end, connects with the Red Line at the Universal City station. Wilshire/Whittier corridor has four connecting points with the Red Line, at Western, Normandie, Vermont, and
Alvarado. However, no special transfer fare is provided between the two modes, as in any other transfer in the system, passengers must pay US$0.25 to transfer.

- **Efficiency and effectiveness.** The system has experienced different results in terms of passengers per revenue hour and net subsidy per passenger in each corridor. On Wilshire, the increase in the demand has been so significant that it outweighs the cost of the extra service, increasing the number of passengers per revenue hour by 8.3% from 51.0 to 55.3, and reducing the net subsidy per passenger by 6.9% from US$0.79 to US$0.74. On the other hand, Ventura has experienced the opposite, passengers per revenue hour decreased by 36.2% from 47.4 to 30.2 and net subsidy increased by 91.2% from US$1.16 to US$2.22. This result in Ventura is due to the initial oversupply in the corridor.

- **Implementation.** The staged implementation strategy has been very successful in Los Angeles. A cautious approach in the first phase resulted in positive results, significant enough to build consensus around the system to move on to the second phase.

- **User-friendliness.** Metro Rapid was not an aggressive project in terms of infrastructure but it was in terms of customer information, comfort, and amenities. The system provides riders a more comfortable ride by enhancing public space, giving real-time information at stops, using new low-floor vehicles, and “branding” the system.

### 3.6 Findings

#### 3.6.1 Key BRT attributes

Based on evidence from the case studies, key BRT attributes resulting from elements in each category were identified as follows:

---

11 Figures are for all service in the corridor: Metro Rapid and local routes.
• Physical attributes
  - Right-of-way priority
  - Expedited boarding and alighting
• Service attributes
  - Knowledge-based operations
  - High frequency
  - High reliability
• System attributes
  - Distinct image
  - Connectivity
  - Land use coordination

Each one of these attributes will be analyzed in detail in the following chapter. However, a brief explanation of each follows.

**Right-of-way priority** mainly results from two elements, right-of-way and signal priority. In terms of right-of-way, the cases present two treatments: Curitiba, Bogotá, Ottawa, and Pittsburgh run in exclusive lanes, while the Los Angeles Metro Rapid runs in preferential lanes. In terms of signal priority, a wider range was found. Bogotá and Curitiba have no signal priority, Ottawa and Pittsburgh have signal synchronization in certain portions of the alignment, and Los Angeles’ operations rely heavily on an advanced conditional signal priority system. Right-of-way priority impacts users travel time and bus running time, as well as reliability, image, and the perception of permanence.

**Expedited boarding and alighting** results from three elements, the design of the stop, the design of the bus, and the fare collection system. Stops and vehicles must have matching boarding levels to reduce the time to access the vehicle. Ottawa, and to some extent Pittsburgh do not have matching stop-vehicle levels. Los Angeles provides curb
boarding to low-floor vehicles, however a gap still remains so that riders need to be careful in accessing the bus. Curitiba and Bogotá have free boarding level, providing either no gap or a horizontal gap of less than 15 cm (6 in). Boarding level, however, is of limited value in expediting the boarding process if not accompanied by an expedited fare collection system. Curitiba and Bogotá have off-vehicle fare payment and the other three cases have on-board payment, with resulting boarding rates depending on the payment medium (i.e. cash, magnetic tickets, contact less cards). Off-vehicle fare payment reduces dwell time variance, which is one of the most significant sources of variability, and thus unreliability on a bus route. Another element contributing to this attribute is the ability to board through multiple wide doors increasing passenger boarding rates. In the cases studied, Curitiba and Bogotá provide multiple door boarding, Ottawa has managed to provide a virtual multiple door boarding with its high share of monthly pass users and allowing them to board through the rear door, while the other two have front door only boarding, related to fare payment.

Knowledge-based planning and operations is an attribute resulting from the various systems that provide information to the planning and control agency, and its ability to make efficient use of it\textsuperscript{12}. These systems are normally the fare collection and AVL systems. The fare collection system and the control system in Bogotá provide the agency with the information needed (i.e. real origin/destination matrices, real-time station loads, load profiles, maximum load points) to plan and run the system based on actual users' travel patterns. In other cases, fare collection systems provide information that supports the planning process, however without the ability to provide real time information. Control systems provide location information for the vehicles. This can vary from supervisors on the route with as little information about the operations as the time

\textsuperscript{12} This attribute results from elements across all three categories, however it has been placed under service attributes since its impacts are strongly related to the operation itself.
the buses pass, to sophisticated control centers that display in real time operation information and loads for all vehicles. This attribute impacts accessibility, passenger waiting times, in-vehicle time (although to a lesser extent), and agency efficiency and effectiveness.

High frequency is an attribute embedded in a “virtuous” cycle since at first it usually results from high levels of demand, but often potential passengers will not use transit unless it has high frequency. In Latin America this is less the case given the low levels of motorization, and thus high levels of captive riders. However, in North America, the case studies show evidence that high frequency was a main factor in ridership increases. Very high frequencies (2 min and below) only operate reliably under priority rights-of-way.

High reliability results from different elements and it is achieved by diminishing sources of variability and by having the ability to control operations effectively in real time. Hence, elements that contribute to high reliability include the right-of-way, the signal priority system, the control system, the design of stops and vehicles, and the schedule. In Curitiba, high reliability is mostly achieved through headway-based operations, exclusive lanes, and expedited boarding. In Bogotá, in addition to the elements used in Curitiba, operations reliability heavily relies on the real-time control system.

Distinct image results from a series of infrastructure and management initiatives across the system. It could result from efforts in different elements, most notably fleet design, station design, user information design, exclusive lanes, graphic schemes, and public space design. Each case achieves this attribute through different strategies, and to different extents. Los Angeles has been very successful in creating a graphic scheme across the fleet and stops that distinguish Metro Rapid from other bus routes. In Bogotá, materials, colors, and style are consistent on all infrastructure elements including stations,
fleet, signs, trashcans, lighting, sidewalks, benches, and information kiosks. In addition, the style is innovative, and the materials are of high quality, which gives users a perception of a higher quality service and makes it easier for them to recognize it. In Ottawa, although the architectural design of the stations is often considered unattractive and obtrusive, the system is distinguishable due to the different signs, massive design of stations in the busway, and the busway itself.

**Connectivity** results from coordinated network operations, physical integration, fare integration, and schedule design. Network operations are observed in Curitiba, Ottawa, and Bogotá. The role of feeder routes is often underestimated and overlooked; however, the cases show their importance in supporting the spine of the system. In Curitiba, almost 80% of the trips in the system make at least one transfer. In Bogotá, nearly 40% of the demand in the trunk corridors comes from feeder routes. In Ottawa, the Transitway relies on other routes and other transport modes to collect its riders, as all non-busway routes, either start and/or finish at a busway station. Physical integration is crucial in trunk-feeder systems like the ones in Curitiba and Bogotá. In terms of fare integration, different configurations are observed. The most common one is the reduced fare for transferring, as in Los Angeles and Pittsburgh. On the other hand, Curitiba, Bogotá, and Ottawa offer free transfers between routes.

**Land use coordination** results from government regulations on transit supportive land use around the stations, parking restrictions, zoning rules, public space development, and public-private partnerships. Very good land use coordination in terms of government regulations and zoning is seen in Curitiba; where high densities and mixed use development along the express corridors has resulted in such travel patterns that during rush hours, commuters travel almost equally in both directions, and during non-peak hours buses are still heavily used. The transit-oriented development that Curitiba has had in the last 30 years has been a key factor for the success of its public transportation system. Ottawa, has also been successful in placing stations close to high density
residential and commercial areas, and tying future development along the corridors to densities supportive of mass transit. In Bogotá and Los Angeles, the system has been implemented for too short a period to assess its impact on land use development. However, both systems integrated public space as a key element, which is also part of coordinating land uses along the corridors.

3.6.2 Other findings

In addition to the key BRT attributes, several other findings emerge from these case studies. The cases of Curitiba, Bogotá, and Los Angeles show evidence that political will played a very important role in implementing the system. Finding support among local politicians and community consensus is a hard but crucial task to prioritize collective over individual transport, and a lot of political will from policy-makers is needed to achieve it.

There are two important differences between US and Latin American cities that make the focus on BRT different in each case: density and motorization. Densities in Latin America are typically much higher than those in North America. For example, Bogotá, has a density comparable only to that of Manhattan in the US. At the same time motorization rates are much lower in Latin America. As a result in Latin American demand blossoms everywhere while in North America, transit agencies have fierce competition with automobiles to attract choice riders. Thus,

- In North America, comfort, and "technological gadget" attributes seem to be more important than in Latin America, because of the need for transit to offer car users close to the same comfort that auto offers. In Latin America, the already high ridership gears the focus towards operational attributes. As a result BRT in the US is more concerned with issues such as vehicle interior design, station amenities, vehicle fuel, user information, and transit image.
- In North America, achieving operational speeds as high as the automobile is more crucial to be able to attract choice riders. It is worth noting that Curitiba’s operational speed in (the exclusive lanes) is the lowest of all systems studied.

- In the rush to speed up the routes, North American BRT initiatives or limited-stop services are being designed with very long stop spacing. For example, Los Angeles Metro Rapid has an average stop spacing of 1,360 mts (0.85 mi) and Pittsburgh’s East busway stop spacing is 1,813 mts (1.1 mi). This becomes an issue because usually bus systems are not able to attract passengers farther than 800 mts away, thus the corridor is not being covered by a buffer along its entire length, but rather by circles around each stop. A less radical approach can be made having a mid range stop spacing that is neither as long as rail’s (approx. 1600 mts or more), nor as short as CBS’ (approx. 200 mts or less).

- In Latin America, trunk-feeder systems work well because demand levels require a high-capacity operation in downtown corridors. In North America through-systems (feeders using exclusive lanes) are preferred both to provide customers with car-competitive one-seat rides and to show the exclusive infrastructure being well used to ease enforcement and public concerns.

- In America it is important to provide the car-transit interface in the form of convenient park-and ride facilities to capture suburban commuters.

- Low-floor vehicles certainly are an improvement for CBS, but without real level boarding and faster boarding/alighting the impact will not be very high.

- Fuel is much more of a concern in North America than it is in Latin America.

- In Latin America the systems can be profitable for the operators, which gives the system some healthy independence from the government since it does not rely on obtaining subsidies to cover its costs. Instead, the system uses its profit to renew its
fleets and undertake improvement projects. The profitability of the system is of course a result of the high efficiency of the system, which in turn is a result of the high turnover (or short trips) due to high densities and mixed land uses.
4 BUS RAPID TRANSIT

The objective of this chapter is to

- study the current interpretation of the term BRT, and
- determine how the key BRT attributes can be achieved.

First, a clear understanding of BRT is sought through previous definitions of BRT in the literature and from the case studies. Second, we analyze in more detail the key attributes of BRT found in the previous chapter and look for the components that will achieve such attributes understanding the relationships among them.

4.1 What is BRT?

We rely on the literature review to obtain the most generally accepted definition of BRT. The case studies provide us with a practical understanding of it. In both cases (theory and practice) definitions of BRT range widely. The objective of this section is to define BRT in the context of this thesis, clarifying the difference between an improved Conventional Bus Service (CBS) and a BRT service.

In terms of their infrastructure and operational capabilities, BRT systems can be placed between conventional bus and rail services. Whether they operate and deliver quality closer to one or the other is still unanswered. Specific definitions of Bus Rapid Transit are seldom found in the literature, and in practice different BRT systems incorporate widely varying applications of its components, resulting in quite different system configurations.

Generally, US literature attempts to define BRT13 in terms of:

- BRT features (e.g. exclusive lanes, off-vehicle fare payment),

---

13 The concept known today as BRT has been studied under different names, for example Vuchic, V. R., E. Brunn, et al., University of Pennsylvania and University of Delaware (1994). "The Bus Transit System: Its underutilized potential". Washington, D.C., named it Bus Transit System (BTS)
• BRT performance (e.g. higher frequency, higher reliability), or
• both features and performance.

The first option was mostly the case during the 1970s, when what is now called Bus Rapid Transit was usually synonymous with exclusive lanes on freeways mostly serving commuters. Today, most definitions include a set of key infrastructure features plus a list of typical operational characteristics. Table 4-1 presents definitions or statements on BRT from the literature.

As observed from the table no standard definition of BRT exists, but recurring characteristics are identified, such as its higher quality than CBS in terms of operations and comfort, and improved infrastructure.

A clear difference appears in the meaning of BRT in the US and the rest of the world (mostly Europe, Asia, and South America) with respect to the degree of exclusivity of the right-of-way. Although this seems to be a pure infrastructure characteristic, its final configuration might be the determinant of the service quality and the ideological motives behind a BRT project. In Europe, Asia, and South America, BRT or busways are often regarded as one of the Mass Rapid Transport (MRT) modes, which by definition “comprises those modes based on specific fixed track, or exclusive and separated usage of a potentially common user road track” excluding bus lanes, and other forms of priority for buses in mixed traffic (HalcrowFox, 2000). In this case a fundamental characteristic of BRT would be its exclusive right-of-way.

In the US, largely due to its high political cost, the issue of right-of-way exclusivity is being addressed through modest alternative plans such as signal priority and queue jumping. In this case, the understanding is that BRT could occur without dedicated right-of-way, but with other improvements to CBS.
BRT, however, is very flexible in its infrastructure and operations. Few BRT systems look and operate alike; no thresholds usually exist, such as stops must be at least \( x \) mts apart or headway must be at least \( y \) min.

**Table 4-1 Sample of BRT literature definitions**

<table>
<thead>
<tr>
<th>Type</th>
<th>Reference</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Features</td>
<td>Crain, 1975</td>
<td>The busway lanes are physically separated by concrete and flexible barriers from those serving the automobile traffic, and this makes it a bus rapid transit system.</td>
</tr>
<tr>
<td></td>
<td>Vuchic, 1994</td>
<td>In this system, buses operate on exclusive busways or separate lanes and they enjoy priority treatment at signals and intersections. They may have elaborate stations with convenient transfers among bus lines and between buses and other modes, fare collection, waiting rooms, information, and other facilities.</td>
</tr>
<tr>
<td>Performance</td>
<td>FTA, 1998</td>
<td>Conceived as an integrated, well-defined system, that would provide for significantly faster operating speeds, greater service reliability, and increased convenience, often matching the quality of rail transit when implemented in appropriate settings.</td>
</tr>
<tr>
<td></td>
<td>Kang and Diaz, 2000</td>
<td>The definition of BRT goes beyond any particular application of technology, facility improvement or service configuration. What differentiates BRT systems is the way in which they combine improvements in the technology with a comprehensive revision of the operating plan and thoughtful improvements to the interface of the system with the customer.</td>
</tr>
<tr>
<td></td>
<td>Sislak, 2000</td>
<td>...the underlying concept of BRT is simple: duplicate the reliability, level of service, comfort, and appeal of a modern LRT line while achieving the flexibility and cost-effectiveness inherent in bus systems.</td>
</tr>
<tr>
<td>Both</td>
<td>DMJM+Harris, 2001</td>
<td>BRT is more than just special buses or improved bus stops. It is a complete rapid transit system that combines flexible service and new technologies to improve customer convenience and reduce delays.</td>
</tr>
<tr>
<td></td>
<td>GAO, 2001</td>
<td>Bus Rapid Transit is not a single type of transit system; rather it encompasses a variety of approaches, including buses using exclusive busways or HOV lanes with other vehicles, and improving bus service on city arterial streets.</td>
</tr>
</tbody>
</table>

Although BRT usually achieves higher quality than CBS, due to their close nature BRT can be achieved by improving the physical components and operating plan of CBS. This thesis focuses on how transit agencies should go about improving those physical
components of bus service based on the impact that each one of the components’ enhancement will have on the system. The higher quality of BRT can be expressed in terms of its key attributes (i.e. high reliability, right-of-way priority), which are in turn achieved through the appropriate design and combination of components (i.e. stops, vehicles, right-of-way, fare collection). The following sections present both key attributes and components, and their relationship.

4.2 Key BRT attributes

The key BRT attributes that express this mode’s higher quality can be classified under Physical, Service, and System attributes as shown in Table 4-2. In order to implement successful BRT systems, transit agencies need to enhance their current bus systems to have these key BRT attributes. This list of key attributes results from the literature review and the case studies conducted in this thesis.

<table>
<thead>
<tr>
<th>Category</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>Right-of-way priority</td>
</tr>
<tr>
<td></td>
<td>Expedited boarding and alighting</td>
</tr>
<tr>
<td>Service</td>
<td>Knowledge-based operations</td>
</tr>
<tr>
<td></td>
<td>High frequency</td>
</tr>
<tr>
<td></td>
<td>High reliability</td>
</tr>
<tr>
<td>System</td>
<td>Land use correlation</td>
</tr>
<tr>
<td></td>
<td>Integration and connectivity</td>
</tr>
<tr>
<td></td>
<td>Distinct image</td>
</tr>
</tbody>
</table>

4.2.1 Right-of-way priority

This attribute relates to the ability of buses to have right-of-way priority over private cars, which in the case of BRT is its exclusive right-of-way. However, it could
be argued that there is no priority for buses on exclusive lanes when cars by their side are also running in their own exclusive, expedited right-of-way, called a highway. What matters when people are choosing transportation modes is the difference between the alternatives. Hence, the important characteristic at this point is to have buses able to move faster than or at least competitively with private automobiles. This ability is achieved by providing buses with exclusive lanes where congestion is reduced, and enhanced by implementing signal priority and/or queue jumping techniques for buses at intersections. This attribute is extremely important as with its implementation travel time for users is noticeably reduced, and vehicles operating costs for the agency decrease, as running times are reduced and buses are more productive.

Right-of-way priority seems to be the most crucial BRT attribute; yet, it is always the most difficult to achieve because where it can be easily implemented is where it is less needed (i.e. abandoned rail rights-of-way, with very few if any, trip generators or attractors). On the other hand, where right-of-way priority is needed the most (which is also where it will have the largest impact) is where it is most difficult to implement, where the congestion is heaviest, thus private auto drivers opposition will be strongest.

BRT is being marketed as a solution to increase CBS competitiveness, to attract choice riders and reduce the growing impact of congestion. However, if congestion is growing, how can the buses be more appealing to current car drivers if they are caught in the same traffic jams as well as having to stop many times along a customer’s trip?

It is not within the scope of this research to discuss the rationale for preferential treatment of buses, but for more information, you can refer to (Vuchic, Brunn et al., 1994; Litman, 2002).

4.2.2 Expedited boarding and alighting

Fast boarding and alighting can be achieved through a wide variety of mechanisms, but most of them concentrate on:
• getting, the processes of paying and validating the fare off the vehicle, and especially away from the driver, and
• providing the stop and vehicle with an integrated design that reduces the time required for all passengers to board and alight.

The importance of this attribute also stems from its potential to reduce dwell time, and dwell time variability, hence increasing overall route reliability. These reductions have important impacts on both users and the agency. The immediate ones would be shorter total travel time and higher reliability, which in turn could lead to lower mean passenger waiting times. The agency would observe shorter running time, thus more productive buses, and a potential reduction in fleet requirements.

4.2.3 Knowledge-based planning and operations

This attribute means that the transit agency designs the services, operates its vehicles, and controls its operations based on a large and reliable source of information about its system, including the demand. The source of information is usually achieved by implementing technological systems, such as:

• Fare Collection system, which would provide the agency with demand characteristics including origins, destinations, and transfer locations, and would allow the agency to plan accordingly optimizing its resources while providing a service that responds to users needs.
• Automatic Vehicle Locator (AVL) system, which would allow the agency to track buses in real time to control its operations to obtain for example, better regularity, and to identify potential and recurring problems.
• Passenger Information system, which would provide users with both, dynamic and static information on operations.
4.2.4 High frequency

High frequency is often regarded in the US as a bus no more than every 10 -12 minutes, although most of the successful BRT cases have headway around 5 min. If demand is on the lower end, higher frequencies can be achieved by using smaller buses. This attribute has two very important impacts; the first is simple and can be measured quantitatively, while the second one is more qualitative but presumably of greater importance:

- Waiting time reduction for passengers, assuming that below that threshold of 10-12 minutes passengers no longer time their arrivals, thus the waiting time decreases proportionally to the headway.
- Convenience and permanence; the more frequent a service the more convenient and appealing it is to users since they do not need to worry about the schedule. Permanence is a characteristic that helps to build demand because it provides a sense of reliability to customers. Permanence is usually achieved by distinct infrastructure or high frequency; while rail services usually have both, bus services often lack both.

4.2.5 High reliability

High reliability means that passengers can rely on the schedule of the bus. As the service has a higher frequency, this attributes tends to shift towards regularity instead of schedule adherence. Basically, it is achieved through strict control over the operations, both at the terminals and on route. Similar to the previous attribute, the importance of this one stems from the waiting time reductions and the convenience delivered to users.

Reliability is definitely a key issue for successful transit operations, to obtain reliability, we need to tackle the sources of variability on the route. Those sources, assuming that a timely departure from the terminal occurs include the number of stops and the boarding and alighting rates. The density of stops on a BRT route must be consistent; BRT vehicles must stop at every scheduled stop, not depending on whether
there are passengers or not to give consistency to the system. This policy might be unacceptable for the users on a CBS, but it is a common practice as well as an important element of the control system for rail services.

Another important source of variability in the route is boarding rates. Vandebona and Richardson (1985) showed that lower boarding and alighting rates led to lower service reliability.

4.2.6 Connectivity

Integration and connectivity refers not only to a system that is well integrated and connected within itself, but also to the rest of the transport network in the city. This attribute can be achieved through:

- operational enhancements such as coordinated schedules to ease transfers between routes
- technological enhancements including intelligent fare media that allow free or reduced-fare transfers
- infrastructure enhancements as providing special infrastructure at transfer points, or barrier free transfers.

Integration and connectivity are of great importance in BRT because these systems are rigid by nature and highly dependent, just like rail, on feeder routes. Providing good integration and connection in the system could make the difference between a system being feasible or not. For example, in Bogota, nearly 40% of the passengers on the trunk corridors arrive at the system through feeder routes (Transmilenio, 2002). It is well known that transfers impose a significant penalty on the bus utility, thus efforts to reduce transfer inconvenience will certainly be reflected in ridership levels.
4.2.7 Land use integration

This attribute refers to the types of land use and public spaces that the alignment serves. This attribute must be of extreme importance to the agency because it determines the relationship that the system has with the urban grid, landscape, and the citizens. It is in the best interest of the agency to design a BRT system through a high population density corridor, with origins as well as destination zones, and with high quality public spaces that connect the system with private spaces, to ensure high ridership. Often rapid transit systems are built where they are less controversial or less costly, but soon the consequences are seen on the ridership levels. Although MRT systems have the ability to shape their surroundings at least to some extent, if TOD is to result, most of the effort must be carried by the transit agency from the beginning of the project. Although most transit agencies do not have direct powers to alter land use, several efforts can be initiated at the transit agency to encourage appropriate development around the station. For example, selecting an appropriate corridor, lead initiatives within government agencies to encourage land uses supportive of transit, and dedicating monetary and human resources to the public space that connects the city and the transportation system.

4.2.8 Distinct image

Distinct image refers to the ability of the bus service to appeal to riders due to its image, which includes architectural and aesthetic design of the stops, vehicles, signs, urban landscape features, and the public space that connects the stops with the rest of the city. A distinct image is usually achieved through a modern and stylish design of the stations and vehicles creating a brand out of the transit system. It is difficult to establish the impact of this attribute quantitatively, but there is certainly a relationship between the image of any product and its consumption. A stylish system could potentially attract more riders and create a culture of a respected public space.
4.3 BRT components

Usually, to attain each of the key BRT attributes, several solutions with different levels of impact are available to the transit agency. For example, to obtain off-vehicle fare payment, one can opt for building closed stations with payment barriers such as the ones implemented in Curitiba or Bogotá. In this case, some curb or median space is needed to build the stations, infrastructure costs increase, landscape impacts must be considered, and level-boarding might result. However, off-vehicle fare payment can also be obtained with a proof-of-payment strategy. In this case, the user purchases the ticket before boarding the vehicle, but no stations or barriers are used for control, rather, random on-board checks are conducted. Choosing the appropriate alternative for each attribute, based on the goals, constraints, and impact level needed, is crucial to successful BRT implementation.

Although all key attributes are important to achieve high quality service, some of them deserve deeper analysis because of the magnitude and type of impacts. For example, right-of-way priority is often considered the most important attribute and at the same time the most difficult to implement due both to its costs and to strong opposition from car users. On the other hand, distinct image is a key attribute that lies completely within the transit agency control, little or no opposition is likely, and the costs associated with it are proportionally low. Key operations attributes are also obvious or desirable characteristics of all rapid transit systems. Little controversy is inherent in these attributes. In addition, although not always with a BRT focus, the design and implementation issues of most of them are being covered by other ongoing or recently completed MIT research.¹⁴

¹⁴ Knowledge-based operations: Erik Wile, David Barker; Frequency and connectivity: Yoosun Hong, Cordy Crockett; Reliability: Angela Moore; Distinct image and Land Use integration: Frances Switkes, Lilley Shuey, George Proakis
Thus, the remainder of this thesis focuses on studying the attributes that are most difficult to achieve, could produce stronger opposition, and are more expensive, which are considered to be the physical attributes.

To achieve a bus system with the key physical BRT attributes mentioned previously, transit agencies must make decisions on physical components including right-of-way, stops, vehicles, etc. The relationships between physical components and all key BRT attributes are shown in Table 4-3. This table shows physical components that must be considered when deciding how to achieve one key BRT attribute. And similarly, when making decisions on each physical component, which key BRT attributes are likely to be affected.

All key attributes, not only the physical ones, are shown in Table 4-3 because it is important to note that although only physical attribute components will be addressed in detail in the following sections, decisions made on each of them are likely to affect other attributes. For example, decisions on the type of vehicles will not only impact the boarding and alighting process but also the image, frequency, and reliability of the system.
Table 4-3 Relationships between physical components and key BRT attributes

<table>
<thead>
<tr>
<th>PHYSICAL COMPONENTS</th>
<th>Infrastructure</th>
<th>Vehicles</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right-of-way</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stops</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fare Collection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle Location</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>User Info. System</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From here on, this thesis will focus on the relative importance of the physical components that deal with achieving right-of-way priority and expedited boarding and alighting:

- Right of way
- Stops
- Vehicles
- Fare Collection system
- Signal System
To study the relative importance of these components, we first need to take a closer look at each to establish what the critical variables or decisions are. Each component involves a large number of questions or decisions. Some of those decisions are more important than others because they will largely determine the service quality and the degree to which the key attributes are achieved. For example, in the vehicle component, an agency will need to decide on the size, fuel, body’s material, color, seating arrangement, capacity, number of doors, door width, weight distribution, advertising policy, floor level, etc. However, in terms of providing BRT quality, some of these variables are critical, including boarding level, capacity, and number of doors. Figure 4-1 shows the critical variables identified for each component.

![Critical variables diagram](image)

Figure 4-1 Physical components and their critical decision variables

The following section will focus on the critical decisions, presenting the spectrum of alternative solutions for each and the impacts the agency should expect when moving along the spectrum.

4.3.1 Right-of-way

4.3.1.1 Degree of exclusivity

The degree of exclusivity spectrum is shown in Figure 4-2, ranging from mixed traffic, which is the common CBS situation to grade separated exclusive lanes. As discussed earlier, this thesis assumes that an extensive degree of exclusivity is required to
have a real BRT system with significant impact on service quality. The main key attribute achieved by a high degree of exclusivity is the right-of-way priority, which will substantially increase speed and therefore increase competitiveness with the automobile.

![Figure 4-2 Degree of right-of-way exclusivity](image)

Moving to the right, or increasing the degree of exclusivity, we can expect:

(+)  
- Higher speed  
- Shorter travel times  
- Shorter running times  
- Reduced headway variability  
- Reduced waiting time  
- Reduced waiting time variability  
- Higher vehicle productivity  
- Lower maintenance costs  
- Less peak vehicles required

(-)  
- Higher capital costs  
- More agency coordination efforts  
- Stronger private car owners opposition

Full “grade separation” refers to a situation where no intersections are encountered along the route, this might be achieved with over or under passes, or a completely elevated or underground alignment. The third and fourth stages of the spectrum are shown in Figure 4-3 and Figure 4-4, respectively.
The fact that the roadway needed for exclusive lanes is almost never owned or controlled by the transit agency but by "competing" agencies like the state highway department or the local city/municipality is a major impediment to achieving exclusive rights-of-way.
4.3.1.2 Degree of guidance

Degree of guidance is the extent to which the vehicles are guided along their right-of-way by any means, other than the driver. Although guidance might not by itself lead to achieving one of the key attributes and is often overlooked, it is considered here because it might make the difference in the project being built or not. Guidance systems allow reducing corridor width by 44%, from 5 m (including small shoulder) to 2.8 m, thus increasing the possibilities of fitting the exclusive lanes within current street cross-sections.

In this case the spectrum of choices varies from no guidance, to guidance along the complete alignment. Guidance at some portions of the alignment might be an intermediate alternative. Those portions will probably be the stations instead of inter-station sections, because at stations is where space is most critical –since we might want to allow overtaking. Additionally, by having guidance at the stations, the approach time per stop might also be reduced.

Figure 4-5 Degree of right-of-way guidance
Moving to the right, or increasing the degree of guidance, we can expect:

\[(+\)\]
- Reduced cross-section requirements
- Reduced approach and clearance time per stop
- Potential running speed increase\(^{15}\)
- Right-of-way self-enforcement
- Rail-like image
- Less stress for driver

\[(-\)\]
- Higher technology capital costs
- Higher technology maintenance costs
- Potential running speed decrease

It is beyond the scope of this research to discuss each of the technologies available in the market to provide guidance but some of them are shown in Figure 4-6 to 4-10. Often the cost of the guidance system is seen as an important obstacle to implementation; however, depending on the guidance mechanism selected, costs can vary widely. The lower end technologies are mechanical systems that can be implemented very easily on existing fleet. This type of mechanism is illustrated in Figure 4-6 a) and b).

\[\text{Figure 4-6 Lateral mechanical guidance}\]

\[\text{a)} \quad \text{b)}\]

\(^{15}\) Depending on the technology and previous conditions, running speed could either increase or decrease
Figure 4-7 presents another type of mechanical guidance but this time the guiding system is below the vehicle. A rail placed in the pavement guides the bus.

![Central rail mechanical guidance](image)

Figure 4-7 Central rail mechanical guidance

More technological advanced systems based on optical, magnetic, or inductive cable mechanisms are also available. These systems involve embedding in the pavement different parts of the system, and therefore are more expensive and require more maintenance.

![Optical guidance](image)

Figure 4-8 Optical guidance

![Magnetic guidance](image)

Figure 4-9 Magnetic guidance
Figure 4-10 Inductive cable guidance

Figure 4-11 shows a portion of the guideway of the BRT system planned for Eugene, Oregon, in its current status and with the future system. As shown, guidance also allows having a greener environment, as only two narrow strips of pavement are required.
4.3.2 Stops

4.3.2.1 Stop spacing

Stop spacing is the average spacing between stations. The spectrum varies from 50 meters (164 ft), which is extremely frequent stations, but is still seen in some CBS, to 1500 meters (4921 ft), which is a very high spacing but some BRT systems are being
planned with such stop spacing or even higher. For example, average stop spacing in Los Angeles Metro Rapid is 1360 mts (0.85 miles) and the Dulles corridor near Washington DC, was designed with stop spacing of 4,720 meters (2.9 miles).

Figure 4-12 Stop spacing alternatives

Moving to the right, or increasing the stop spacing, we can expect:

(+) • Reduced travel time • Reduced dwell time variability • Increased ridership due to lower in-vehicle time savings • Reduced running time

(-) • Higher mean passenger access time • Lower route coverage • Reduced ridership due to lower coverage • Reduced ridership due to higher access time

The main impact of increasing stop spacing is the reduction of dwell time, however very long spacing could cause a reduction in coverage and thus in ridership. While a catchment area of 500-meters radius is usually assumed for bus systems, BRT systems with high image and permanence might be able to attract customers from greater distances. As a general rule of thumb, stop spacing should not be higher than the catchment area radius, which covers approximately 95% of the corridor\(^{16}\), assuming even stop spacing. When the stop spacing is twice the radius, the coverage drops to

\(^{16}\) The corridor is a buffer around the route of\(R\) distance to each side of the street.
approximately 78% of the corridor area. Actual coverage may be lower than this because even stop spacing is almost impossible to achieve.

4.3.3 Vehicles

Three critical variables have been identified for this component: boarding level, vehicle capacity, and number of doors in the vehicle. The boarding level is in fact a variable that results from the decisions made on two components: vehicles and stops. The vehicle capacity relates to the number of people the vehicle is able to carry, and thus it is directly reflected in the size of the vehicle. The number of doors relates more to the number of doors that can effectively be used for boarding and alighting instead of the gross number of doors in the vehicle.

There is one variable of this component, vehicle fuel, which is usually very controversial and complex, but has been left aside in this thesis. We do recognize the importance of this decision in any transportation system, however it is not considered a determinant characteristic of BRT. A BRT system may be successful with any of the fuels available in the market. However, we consider it important to review briefly the standpoint on this matter. There are three main fuel alternatives: diesel, compressed natural gas (CNG), and electric. Electric buses are still uncommon, mostly due to battery limitations. Some advances have been made towards high-density batteries; however, their extremely high cost, and their complex disposable problem still make them unfeasible for large-scale transit systems.

Diesel and CNG have been the focus of the feasible and proven technologies debate. During the 1990’s CNG grew stronger and diesel was frequently stigmatized as the less-environmentally friendly fuel. However, during the last few years, new generations of diesel motors have raised questions about this. New diesel motors are able to comply with EURO III norm. In addition, recent findings seem to point that the carcinogenic effect of the particles is more related to their size than their number or mass;
the smaller they are, the greater their carcinogenic effect. This coupled with the still higher CNG costs and the recent diesel innovations resulting in cleaner emissions have brought diesel back to the preferred fuel option.

4.3.3.1 Boarding level

Boarding level is a variable resulting from both bus stop level and vehicle floor level. The best configuration is to achieve the same level on both, which we call free level boarding. In the mid region of the spectrum we can find solutions that provide close to level boarding and impose extra seconds of dwell time by lowering a ramp, kneeling a bus, or through the fact that there is a gap between the bus and the platform. In those cases we can assign the extra time either to the mean passenger boarding and alighting time or to the total overhead time per station.

Generally, low-floor buses are associated with BRT and even with free level boarding. As mentioned previously, the bus floor level means little without reference to the boarding platform, thus both high or low floor buses can achieve the ultimate characteristic of free level boarding. Free level boarding is achieved when the horizontal and vertical gap between platform and vehicles are small enough to allow wheelchair access and to avoid “extra care” for regular passengers. The dimensions are (Dejeammes, Coffin et al., 1999):

- Vertical gap: 5 cm (2 in. approximately) maximum
- Horizontal gap: 10 cm (4 in approximately)

Figure 4-13 Boarding level alternatives
Moving to the right, or diminishing boarding obstacles, we can expect:

(+)

- Reduced marginal boarding and alighting time per passenger
- Reduced overhead time per stop

(-)

- Small increase in infrastructure costs

Figure 4-14 shows a Curitiba high-platform bus lowering the ramp before the boarding and alighting process can begin. Figure 4-15 shows an L.A. Metro Rapid low-floor bus with a ramp. Figure 4-16 shows a low-floor bus next to the curb, where users still need to take a careful step to get onto the bus. Figure 4-17 shows an example of actual free level boarding, where platform and bus are matched, without the need for a ramp or without a foot-wide gap.
The main impact of free level boarding is the reduction of boarding time per passenger. However, free level boarding provides its greatest benefits when it is jointly implemented with off-vehicle fare payment. Usually, the critical path of boarding in CBS is paying the fare. Furthermore, implementing off-vehicle fare payment without free level boarding will not take full advantage of all the potential time-savings either. Both, the boarding level and payment method technologies should move forward side by side.
Many studies have measured boarding times under different boarding level and payment method configurations. Usually, CBS configurations, 3 steps and cash-back or ticket validation on the bus, have boarding times between 2 and 4 sec per passenger. BRT configurations, with level boarding and off-vehicle fare payment can achieve as little as 0.33 sec per passenger. However, it is very difficult to trace which of the benefits come from the boarding level configuration and which from the payment method.

4.3.3.2 Vehicle Capacity

Vehicle capacity is the number of passengers that can comfortably ride in the bus. The spectrum ranges from 20 passengers, which is a minibus, to 160 passengers, which is the approximate capacity of a bi-articulated bus. The final capacity will vary depending on the seating arrangement and service standards of each agency. In Latin America, some BRT systems operate with standards as high as 6 pass/m². The main impact of this variable will be on the route’s capacity. There is no typical BRT vehicle capacity since the right capacity depends on the demand and frequency desired. However, given the large investments involved on a BRT line, it is assumed that a large demand exists, thus high capacity buses are often used to meet the demand.

![Vehicle capacity alternatives](image)

**Figure 4-18 Vehicle capacity alternatives**
Moving to the right, or increasing vehicle capacity, we can expect:

\[ (+) \]
- Higher corridor capacity
- Less probability of passengers left behind
- Less labor - operator costs
- Rail-like appearance
- Lower peak fleet requirements

\[ (-) \]
- Higher per vehicle capital cost
- Higher maintenance costs
- Higher headways, and thus higher waiting and transfer times
- Less flexibility for real time intervention

4.3.3.3 No. of doors in the vehicle

![Figure 4-19 Number of doors](image)

Moving to the right, or increasing the number of doors, we can expect:

\[ (+) \]
- Reduced dwell time
- Reduced running time
- Reduced operating costs

\[ (-) \]
- Less flexibility for internal design
- Less seating capacity
- Higher vehicle costs
- Requires off-vehicle fare payment to achieve full benefits

4.3.4 Fare Collection

Fare collection involves two main decisions, which are highly related: the location of the transaction (vending and payment of fare), and the payment media. Combinations of both will produce different boarding rates.
4.3.4.1 Transaction location

Transaction location can be on-board or off-vehicle. The first class achieves different levels of service depending on the type of the transaction, which can range from paying the driver to paying into a fare-box. However, this last one ties into the second variable, payment media, because depending on it, fare box payment could take as long as 8 seconds per person, if using cash, or as little as 0.5 seconds if using contact less cards.

Moving to the right, or getting the fare vending process off the driver and the vehicle, we can expect:

( + )
- Reduced dwell time
- Reduced dwell time variability
- Potential improvement of operations information
- Less stressful work for driver

( - )
- Higher technology costs
- Potential increase of labor costs due to more personnel

Most systems, however, have a mix of all stages. For example in Chicago, users always pay on-board but they can use cash and get back a transfer card from the drivers, pay exact cash, insert a magnetic strip card into a fare-box reader, or bring their contactless SmartCard close to a sensor. Although some flexibility in terms of fare payment is desired for user convenience, mixed configurations like the one in Chicago, increase the variability of the boarding process, and thus the potential for unreliability on the route.
Substantial impact is usually observed when implementing general on-board contact less solution or off-vehicle fare collection.

Off-vehicle fare payment can be achieved with a variety of solutions: physical barriers solutions, like in Curitiba and Bogotá, where closed stations are built and the fare vending and payment process is moved to the station, before the bus arrives; or proof-of payment solutions, like the one being tested in Los Angeles, where users are just checked randomly on-board to control fare payment.

4.3.4.2 Payment media

Moving to the right, or increasing the technology of the fare media, we can expect:

(+)
- Reduced passenger boarding times
- Reduced dwell time variability
- Improvements on operations information
- Lower collection logistic costs

(-)
- Higher technology costs
- Higher distribution logistic costs
- Exclusion of some potential passengers may be possible

4.3.5 Signal System

4.3.5.1 Priority method

Signal priority relates to the ability of buses to move through signalized intersections with priority over private cars. The spectrum ranges from passive priority to active conditional priority. Passive priority means that signals are synchronized so that buses have a “green wave” along the corridor. However, due to the variable nature of bus
operations, this system seldom provides substantial benefits to buses, unless headways are large and stop spacing is high. Queue jumping requires a dedicated lane close to the intersection to allow the buses to overtake the queue of cars waiting at the intersection, and a separate traffic light that gives green to the buses a few seconds before the general traffic. Active priority is a system triggered by the presence of a vehicle. Several different technologies can be used to achieve this; however, they can be classified as either unconditional or conditional. Unconditional systems are always triggered when they sense a bus. Conditional might or might not give priority to a bus depending on the circumstances, for example, it would give priority to a bus only if it is late compared to its schedule or headway. Conditional priority, then, might be used as part of an operations control system.

![Figure 4-22 Signal priority methods](image)

Moving to the right, or increasing the priority given to buses at intersections, we can expect:

- **Reduced traffic signal delays**
- **Reduced running time**
- **Reduced operating costs**
- **Reduced headway variability**

- **Higher technology costs**
- **Potential delay to private cars**
- **Potential worsening of pedestrian crossing conditions**

### 4.4 Summary

This chapter studied the definitions, key attributes, and main components of BRT. At the end, the main decision variables that an agency faces in order to achieve the key
physical attributes were identified and their alternative solutions were described. Those
decision variables are:

- Degree of exclusivity in the right-of-way
- Degree of guidance in the right-of-way
- Stop spacing
- Boarding level
- Vehicle capacity
- No. of doors in the vehicle
- Fare collection location
- Fare collection media
- Signal priority method

The following chapter will focus on determining the relative importance of those
variables and how to prioritize them in an eventual staged implementation process.
The second step is to select the **BRT corridor** based on the understanding of the system goals and constraints from the previous step. As a result of this step we could select several BRT corridors, with the following steps being repeated for each of the selected corridors.

![Implementation process diagram](image)

**Figure 5-1 Implementation process**

The third step is to **assess the current corridor performance**, this step is crucial to accurately determine the potential impacts of BRT, and avoid overestimating benefits from the implementation of one or more components. As a result of this task, we should obtain a clear understanding of the corridor operation, its weaknesses, its strengths, and hence, a selection of areas for improvement.
The second step is to **select the BRT corridor** based on the understanding of the system goals and constraints from the previous step. As a result of this step we could select several BRT corridors, with the following steps being repeated for each of the selected corridors.

![Diagram of Implementation Process](image)

**Figure 5-1 Implementation process**

The third step is to **assess the current corridor performance**, this step is crucial to accurately determine the potential impacts of BRT, and avoid overestimating benefits from the implementation of one or more components. As a result of this task, we should obtain a clear understanding of the corridor operation, its weaknesses, its strengths, and hence, a selection of areas for improvement.
The fourth step is to **define the implementation strategy** based on the information gathered from the previous steps, budget information, and a sense of political will and community acceptance of the project. In several cases, the information collected from previous steps might not be sufficient to decide so early in the process the implementation strategy. In that case, the implementation strategy decision should be postponed and made after step 6 (prioritize components). The evaluation and prioritization of components should provide enough tools to judge whether the most appropriate implementation is incremental or all-at-once.

Should the implementation strategy selected be incremental, the next step is to **evaluate BRT components**. In this step, the potential impact of the agency decisions about each BRT component is evaluated. In the next step, **prioritize components**, that evaluation is considered to make decisions about the relative importance of implementing each component.

The next step is to **design** the BRT system. All previous steps provide crucial information to design a targeted BRT system that meets the needs and goals of the agency. Whether an all-at-once or incremental strategy has been decided, the critical design decisions for a BRT system is a result of simultaneous and iterative analysis of the different BRT components rather than a strictly sequential process. Figure 5-2 represents this design process schematically. Throughout the design process, we need to have an idea of the physical, service, and system components design because as discussed earlier, decisions made on one component are very likely to affect others. For example, decisions on right-of-way priority affect the service design options, in terms of headway and capacity; or vice versa, requirements set in terms of headway and capacity, are very likely to affect the choice of right-of-way configuration. Thus decisions need to be made in parallel in all components, then assess the resulting service configuration and refine as necessary the decisions made until a configuration that meets goals and requirements is reached. During the design process, in moving from one iteration to the next, it is very
likely that we would need to revisit previous steps as far back as the corridor selection step. Thus, the process might seem stationary at times, but when finished, a consistent system should result. Due to this iterative nature and the focus on decision making at all times, the design process needs to be led by people with access to agency information, with power to make decisions, and with the charisma necessary to gain buy-in from stakeholders.

Figure 5-2 Simultaneous and iterative design process of a BRT system

The final steps in the implementation process are to build and operate the system. The building step could be focused in time if an all-at-once strategy was adopted or spread over a longer period of time if an incremental strategy is adopted. A crucial task during operations is to perform ex-post evaluation to determine whether goals were met and understand why or why not, and provide input for future corridor planning and design.

The following sections contain a detailed analysis of steps 1 through 6 of the process presented above with the focus placed on steps 5 and 6.
5.2 Step 1: Understand transit system

The objective of this step is to understand the system in which the BRT corridor will be implemented. This understanding includes a clear vision of the system-wide goals and constraints, the motivation for BRT, and the expected ways in which BRT would contribute to those system-wide goals.

Both system goals and system constraints, will determine the scope of the BRT project objectives. For example, the current system could be large including other transit modes (e.g. New York City Transit) where a BRT corridor will be a small portion of the system or a feeder corridor to a rail line. Or the current system could be in a small city, which currently relies on CBS, and BRT is planned to be the backbone of the future transit network. Each city will have different needs and motivations for BRT, and therefore different system-wide goals and constraints. Identifying the system needs and expectations for BRT will lead to targeted solutions.

To understand the system, at least some basic data needs to be collected to determine:

- travel desires of citizens
- transit ridership and mode share
- transit costs
- transit service performance and quality of service delivered
- agency long-term goals and plans
- previous agency decisions that constrain the solutions

5.3 Step 2: Select BRT corridor

The information and understanding gained in the first step should clearly lead to the second step: selecting the BRT corridor. The selection of BRT corridors should reflect the system goals. Usually, in the US the top goal of a transit agency is ridership, which is
gained through improvements in the quantity and quality of the service. Where to make those improvements is the key question in this case. To answer that question a couple of criteria can be used, which help to narrow down the corridor alternatives. However, most of the time an effective use of the knowledge of the system that lies with the agency staff is sufficient to make a first cut selection of potential BRT corridors.

The following criteria are suggested to select BRT corridors through a quick and practical analysis.

1. **Select corridors with high expected ridership in the short term.** To identify those corridors we can look at current route ridership, densities in the corridors, current mode share in the zone, and mode share trends. By selecting corridors using this criterion we ensure high short term impact, which could be crucial to continue to develop a network of BRT corridors over time.

2. **Select corridors in areas with parallel CBS routes.** To select those corridors, we just need to look at a map of current bus routes and identify areas with high route density. This criterion, to some extent follows the same rationale as high ridership corridors, but also aims to create a less confusing system for the users. Generally, existing bus systems in the US are the result of bus service evolution over a century, adding, dropping, and modifying services to match the demand. This often creates a complicated network of routes for the user, with branching, short turns, and headways that depend on the time of day and day of the week.

3. **Select corridors with poor current performance.** This criterion can be applied by identifying routes in the system with low speed and/or low productivity. The rationale for this criterion is to implement BRT where most impact can be achieved.

4. **Select corridors with high expected ridership in the long term.** This criterion usually applies to corridors that are expected to develop transit supportive land uses, and thus requires a higher degree of analysis to accurately forecast the
expected demand and certainly of commitment from city officials to promote TOD. Strategically this is an excellent criterion for long-term impacts, however, short-term results may not be impressive, thus complicating the task of gaining political and community support.

5. **Select corridors with high market share loss rates.** This criterion aims at stopping decreasing market share trends through providing visible higher quality service. This criterion could be contentious since some experts would argue that in the US those decreasing trends are usually seen in lower income neighborhoods that are raising their purchasing power and buying cars for the first time. Given the social implications of owning a car for the first time and the freedom that represents, it may be unlikely that higher quality bus service would deter these potential users from buying their cars and using them as much as they can.

6. **Select corridors that could serve as a link between other rail and bus routes to increase transit network connectivity.** This criterion aims both at providing better service for existing transit users and generating new ridership from improved corridor connections.

Criteria 1, 2, and 3, are usually the most important with corridors that could satisfy more than one criteria more likely to be selected. Other strategic issues should also be considered, specifically continuity of the project and agency long term goals. BRT, as any other form of fixed route transit, provides exponential benefits when implemented as a network; therefore BRT plans should not include only one corridor but future extensions to cover more origins and destinations. Thus, success with the first corridor is particularly important.

Another strategic issue is to select corridors according to system-wide objectives. For example, if a key system goal were to increase connectivity among transit lines, a circumferential corridor connecting radial downtown rail lines should probably be
selected. If goals are to improve service quality in heavy downtown CBS routes, a congested corridor with potential for exclusive treatment would be selected. It is worth emphasizing that full BRT is a mass transportation system and corridors should be selected based on expected ridership and not on right-of-way availability. There are likely to be several goals for a transit system that could be satisfied with several BRT corridors. In this case, it is important to understand the objectives of each project, their connections and overlaps, to produce an integrated network that responds to these different needs.

5.4 Step 3: Assess current corridor performance

After we choose (at least) one corridor for the system, we move onto the next step: assessing the corridor’s performance. The objective of this step is to understand in detail the operations in the selected corridor to be able to later identify which of the BRT elements will contribute most to improving performance. When performing this task we must look ahead to the implementation strategy and to steps five and six to have an idea of the evaluation measures that should be used to prioritize BRT components. In this step the corridor must be assessed using the same evaluation measures that will be used later, in order to have a consistent basis for comparison. In this thesis, evaluation of the physical BRT components will be performed in terms of their contribution to user travel time and bus running time. Thus, the assessment of the corridor must produce a report on current travel time components on the corridor like the one shown in Figure 5-3 which is taken from the TCRP Report 26, *Operational Analysis of Bus Lanes on Arterials* (Jacques and Levinson, 1997). The figure breaks down total travel time into its components: running or moving time, dwell time, and traffic delay, which is in turn comprised of traffic signal delay, right turn delays, and congestion. The figure indicates that congestion and dwell time are proportionately greater in more congested areas.

Figure 5-3 is an average from various cities in the US and for different route types and settings and can be used as a guide, but specific data for the selected corridor should
be used when applying this process to specific routes. Information of this type suggests the type of components that will be of greatest impact in the corridor.

Figure 5-3 Bus travel time components

In addition to quantifying travel time components, other quantitative and qualitative observations should also be made to characterize all aspects of the corridor’s performance. These observations include current ridership, productivity, cost, land-use, network connectivity, and amenities. The result of this step should be a set of goals for the corridor to be addressed with BRT improvements.
5.5 Step 4: Define implementation strategy

To move from CBS to BRT, an agency can adopt either an all-at-once or incremental implementation strategies. Each strategy will be discussed in detail in the following two sections, including their advantages, shortcomings, and appropriate setting. It is worth noting that at this point we are addressing BRT implementation within one corridor, and distinguishing whether that project is implemented incrementally or all-at-once. Thus, the stages of the incremental strategy are the discrete implementation of BRT components (right-of-way, stops, vehicles, fare collection, etc) and not the discrete implementation of corridors.

5.5.1 All-at-once

All-at-once consists of implementing all components of the system at the same time. This strategy has both advantages and shortcomings. The primary advantages are:

- It is easier to have a consistent design across elements (i.e. vehicles, stops, user information) in terms of graphics, image, materials, etc, that provide a system-wide image to users.
- Impact is more easily perceived by the public due to greater scale changes; this is an advantage if, of course, the perceived impact is positive.
- As a large project, it creates momentum and once construction work has started it is difficult to stop it

The primary drawbacks of all-at-once implementation are

- Requires all funds in a short period of time
- It is likely to generate greater opposition as changes are larger, outside of control of the agency, and all obstacles must be faced at the same time
- Longer time for planning and approvals as project is larger
- Since all components are introduced during a short period of time, there is more potential for interfaces and overlap failures
An example of this type of implementation is the Transmilenio project in Bogotá. In this case the system was planned and implemented with all its new components (exclusive right-of-way, vehicles, stations, fare collection system, AVL system, control center, control agency, operators, street amenities, terminals, garages, etc) in three years. The system took advantage of this all-at-once implementation to design all its elements in an integrated manner to obtain a consistent system image. The service quality difference between the previous system and the new BRT system was large enough so that the positive impacts outweighed the negatives and the project was recognized as a benefit for the city. The principal negative impact was the failure of the fare collection system due to poor interface and overlap design with other components. Planning stage shortcomings such as greater opposition and longer time for approval were resolved thanks to skilled negotiators being in charge of the project and political will respectively.

The all-at-once strategy is recommended for cases in which one or more of the following situations exist:

- The current system provides extremely poor service compared to what would be delivered by the BRT system
- There is a strong political will to face opposition and carry out the project
- Availability of large amount of funds
- Large impacts are needed in a short period of time

5.5.2 Incremental

The incremental strategy recognizes that given the common roots of BRT and CBS a staged implementation is possible, adding components discretely as funds become available or the environment (i.e. agency, community, users) is ready for the change. As in the previous case, this strategy also has several advantages and shortcomings. The primary advantages are:

- Funding needs are spread over a longer period of time
Moving from Conventional Bus Service towards Bus Rapid Transit  Ch. 5. Analyzing the implementation process

- The agency faces obstacles and opposition discretely
- Deployment of each step is less burdensome as the risk of failure is smaller
- Components can be implemented to match demand needs more closely as improvements are made at a slower pace

The primary shortcomings of an incremental implementation are
- Due to the political changes the entire plan can be easily truncated after the first corridor
- Impact may not be easily perceived as changes occur incrementally

Los Angeles Metro rapid is a good example of a successful incremental implementation strategy. Two corridors were selected as the BRT pilot corridors and implementation was divided into two phases. Phase I was completed over three years and included the implementation of easier-to-implement components such as better stop amenities, next-bus real time information, branding, higher frequency, higher stop spacing and a dedicated fleet of low-floor vehicles. Phase II includes exclusive lanes, high capacity buses, off-vehicle fare payment, and multiple door boarding and alighting. The incremental strategy allowed LA MetroRapid to improve service quality with little opposition and make a successful case for continuation of the project into the more controversial Phase II. The incremental strategy is a wise one to try to get the support needed for larger changes.

The incremental strategy should be used when one or more of the following situations exist:
- Strong opposition is expected which could stop the project
- Improvements in one of the components will generate large impacts. For example if the corridor were to perform well except for the signal system, implementing a signal priority system as the first component could greatly improve service quality and gain buy in among the community to continue enhancements to other components.
• The public or the environment are not ready for large changes
• Funds are not available immediately but will be over a period of time
• Some impact is needed in the short term

There is no quantitative way to determine which of the two approaches, incremental or all-at-once, should be followed. Selecting an approach depends on a qualitative analysis of all aspects (social, economic, financial, technical, and political) of the current situation. In many cases, the previous step of assessing corridor performance provides sufficient information to decide which implementation strategy should be followed; however if the benefits of each strategy are uncertain, the decision should be postponed until the BRT elements have been prioritized and there is a better understanding of the benefits of implementing the elements discretely.

Some factors indicate that in the US an incremental approach may often be more appropriate than an all-at-once strategy. As mentioned before those reasons are the common roots of the two systems, the relatively low ridership levels, and the low political weight of public transit constituencies. As opposed to developing countries, the starting point in the US is an organized CBS and not a jitney operation, which generally need reform not only in terms of operations but also organization and institutions. Therefore, the starting point might be closer to the final configuration and improvements in some elements might produce significant impacts. In addition, since ridership levels and thus political weight of transit constituencies is lower in the US, the implementation of large transit projects is complex, difficult to obtain community buy-in, and extremely democratic, which induces a long term horizon for planning resulting in delayed positive impacts.

While under an all-at-once strategy, the process follows the conventional stages of design, build, and operate, under the incremental strategy, the planning process includes the next two steps of evaluating the components and prioritize them.
5.6 Step 5: Evaluate BRT components

If an incremental strategy is chosen, the next step is to evaluate the importance of each BRT component. The relative importance of the elements or their decision variables is assessed through their impacts and implementation costs. Impact or benefit and cost evaluation is a broad area and it contains a wide range of categories; including impacts on users, agency, and non-users or society in general. Within these categories, impacts range from quantitative ones such as travel time reductions, to very abstract and difficult to measure ones such as increased comfort, or increased perception of safety. There is a significant amount of literature on cost and impact evaluation, most of it describing all the different categories required for a comprehensive analysis of transportation alternatives (Litman, 2002); however, research is not well advanced on techniques to measure the subjective categories of impact evaluation.

This research will focus on user and agency impacts, and within those two categories, on quantifiable variables that represent how users and agency are affected by the decisions made on each component. The variable utilized for users is travel time, which is comprised by access time to the stop, waiting time for the vehicle, and in-vehicle time. The variable used for the agency is the running time, which is a proxy for operational costs in terms of revenue vehicle hours, and for capital costs in terms of fleet requirement. In addition, the infrastructure or technology costs required to implement every variable will be considered to evaluate the cost-effectiveness of components. Thus, the components will be evaluated by assessing how decisions on their critical variables affect the measures shown in Table 5-1.
Table 5-1 Selected evaluation measures

<table>
<thead>
<tr>
<th>Group</th>
<th>Category</th>
<th>Evaluation measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Users</td>
<td>Travel Time</td>
<td>Access Time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waiting Time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In-vehicle Time</td>
</tr>
<tr>
<td>Agency</td>
<td>Operation Costs</td>
<td>Running time</td>
</tr>
<tr>
<td></td>
<td>Capital costs</td>
<td>Infrastructure cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Technology cost</td>
</tr>
</tbody>
</table>

Table 5-2 presents a matrix that relates evaluation measures and critical variables. Cells marked with an X show the row of the evaluation measure that will be affected by decisions made on the critical variable of the corresponding column. In-vehicle time and running time are affected by all critical variables except bus capacity. The methodology used to evaluate these relationships has three stages. First analytical models of the impact time variables (e.g. travel time and running time) were developed. Second, using the resulting models the critical variables were varied over the range of alternatives shown in the previous chapter to observe changes in the impact variables. Finally, for the prioritization step the costs of its implementation were researched to compare the benefits achieved with the costs incurred.

The following sections will show the changes observed in each of the impact variables. A number of graphics follow; usually relating the critical variable as an independent variable on the x-axis and the travel or running time as the dependent variable on the y-axis. The x-axis reflects the range of possibilities for each variable discussed in section 4-3. More important than the actual numbers, we are interested in observing the tendencies and slopes of the curves to understand how decisions on each component affect travel and running time. For some variables, exact numbers are difficult to find, thus schematic figures are shown to illustrate the relationship. Also, in some
cases to illustrate the relationships graphically an example of a hypothetical bus route configuration was assumed reflecting a typical US CBS route. For specific analysis the assumed variables should be replaced by the real ones as will be shown in the next chapter. The assumptions for the route used as an example are presented in Appendix A. The graphics presented in the following sections assume these values unless otherwise stated.

Table 5-2 Relationship between evaluation measures and critical variables

<table>
<thead>
<tr>
<th>IMPACTS</th>
<th>CRITICAL VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lane exclusivity</td>
</tr>
<tr>
<td></td>
<td>Guidance</td>
</tr>
<tr>
<td></td>
<td>Spacing</td>
</tr>
<tr>
<td></td>
<td>Boarding level</td>
</tr>
<tr>
<td></td>
<td>Bus Capacity</td>
</tr>
<tr>
<td></td>
<td>No. doors</td>
</tr>
<tr>
<td></td>
<td>Transaction location</td>
</tr>
<tr>
<td></td>
<td>Fare Media</td>
</tr>
<tr>
<td></td>
<td>Priority method</td>
</tr>
<tr>
<td>Access Time</td>
<td>X</td>
</tr>
<tr>
<td>Waiting Time</td>
<td>X</td>
</tr>
<tr>
<td>In-vehicle time</td>
<td>X X X X X X X X X</td>
</tr>
<tr>
<td>Running time</td>
<td>X</td>
</tr>
<tr>
<td>Infrastruct. Cost (road &amp; vehicles)</td>
<td>X X X X X X X</td>
</tr>
<tr>
<td>Technology cost</td>
<td>X</td>
</tr>
</tbody>
</table>

5.6.1 Access time

The objective in this section is to study how access time is affected by decisions on critical BRT variables. Total travel time for a passenger is composed of access time, waiting time, and in-vehicle time. Access time refers to the time passengers spend moving from the starting point of the trip to the bus stop. Although that access portion of
the journey can be made by walking, cycling, driving, or by other means, this research will assume walking as the main mode to access the bus stop. As shown in Table 5-2, stop spacing is the only variable affecting access time.

Access time can be defined very simply as the distance between the starting point and the bus stop divided by the walking speed:

\[ AT = \frac{X_w}{V_w} \]  

(5.1)

where, \( AT \) = Mean Passenger Access Time  
\( X_w \) = Mean Passenger Walking Distance  
\( V_w \) = Mean Passenger Walking Speed

Pedestrian walking speeds vary depending on several factors including:
- Fitness: often correlated with age, speed tends to decline as age increases
- Gender: males typically walk faster than females
- Temperature: colder weather makes people walk faster
- Trip purpose: commuters going to work walk faster than off-peak passengers

Studies have shown that free-flow walking speeds range from 48 to 155 m/min (145 - 470 ft/min). Speeds below 48 m/min would be considered very slow motion, and speeds greater than 155 m/min would be considered running. A typical pedestrian walking speed used for design of pedestrian environments and transit station areas is 83 m/min (250 ft/min) ("Transit Capacity and Quality of Service Manual," 1999). Thus, we will assume \( V_w = 83 \) m/min as recommended by the Transit Capacity Manual, but if more specific information for a particular application is available, it should be used.

Walking distance to the bus stop depends heavily on the accessibility of the station, and the willingness of the user to walk. Both are highly correlated but are also influenced by:
• Stop location: having a bus stop near the trip starting point, increases accessibility for potential users
• Access to alternative modes of transportation: people with alternative modes of transport such as private auto have very low willingness to walk to a bus stop
• Purpose of the trip: willingness to walk for work-related trips is often higher
• Quality of the pedestrian environment: the more friendly the environment, the more willing are people to walk to stations, including weather.
• Culture: in some cultures there is a greater willingness to walk than in others

Bearing in mind all these qualitative considerations, we need to quantify walking distance ($X_w$). Usually, each stop is associated with a catchment area, which is defined as a circle of radius $R$ centered at the stop and representing the area from which people are willing to walk to the station. Figure 5-4 represents a portion of a bus corridor, with three stations and their respective catchment areas. $SS$ is the average distance between stations or stop spacing. Often, for bus routes, the catchment area is considered a corridor of width $R$ on each side of the bus route. This approximation is appropriate for short stop spacing. In this case, considering that the stop spacing spectrum for BRT could go as high as 1500 m, it is more appropriate to consider circular catchment areas around stops.

$R$ represents the maximum distance a person is willing to walk to a stop, which varies among cities and cultures, and among the type of transportation infrastructure. For example a heavy rail system often has a larger catchment or influence area than a conventional bus service. Often, if the system is perceived as permanent and its infrastructure reaches out to the community, the catchment area may be higher. As a rule of thumb, 400 – 600 meters is usually used for bus systems, and 800 – 1200 meters is often used for rail systems.
When \( SS \) is smaller than \( 2R \) we expect walking distance, and thus access time, to increase as stop spacing increases, (see Figure 5-5 a.). When \( SS \) increases beyond \( 2R \) we expect no further increase in \( X_w \) (see Figure 5-5 b), and therefore \( AT \), should remain constant when \( SS \) is \( 2R \) or greater. However, as stop spacing increases further, coverage and thus ridership would continue to decrease.

The mean walking distance also depends on two other factors, the probability of walking to the bus stop \( P_w \), and the way we calculate the distance, either grid distance or radial distance. In terms of the walking probability we have assumed two possible regimes
• Constant: assumes that all customers living within the catchment area have the same probability of walking to the stop, thus $P_w$ equals 1 for all customers

• Decreasing linearly: accounts for the fact that people who live closer to the stop are more willing to walk to the stop. Thus, we have assumed that $P_w$ can be represented with a linear function that equals 1 when the radial distance to the stop is 0, and equals 0 when the radial distance to the stop is $R$.

$P_w$ can then be described as

$$P_w = \begin{cases} 
1, & \text{under constant probability} \\
1 - \frac{r}{R}, & \text{under decreasing probability}
\end{cases}$$

(5.2)

In terms of the type of distance we have also defined two regimes:

• Radial distance: distances will be computed as radial from the stop

• Grid distance: distances will be computed as the sum of the movement along the bus corridor ($x$) and the movement perpendicular to the bus corridor ($y$).

Given the two regimes we have four cases for which to compute walking distance:

1. Radial distance with constant probability
2. Radial distance with linearly decreasing probability
3. Grid distance with constant probability
4. Grid distance with linearly decreasing probability

Now we compute the average walking distance to the stop as the weighted sum of possible walking distances to the stop in the catchment area, that is

$$X_w = \frac{\iint P_w(r) * D_w(r, \theta) * dA(r, \theta)}{A_{total}}$$

(5.3)

where, $P_w(r) =$ Probability of walking given a radial distance $r$ to the stop
Moving from Conventional Bus Service towards Bus Rapid Transit  

Ch. 5. Analyzing the implementation process

\[ D_w = \text{distance to stop (radial or grid distance)} \]

\[ dA = \text{Differential of area} \]

\[ A_{\text{total}} = \text{Total area of catchment region} \]

To calculate mean walking distance this further assumes

- constant population density throughout the catchment area, and
- people walk to the nearest station

Appendix B shows the complete derivation of the average walking distance \( X_w \) for each of the four cases. Substituting the resulting functions for \( X_w \) in Equation (5.1) we can compute Access Time for all cases for different values of \( R \) and \( SS \). Figure 5-6 shows how \( AT \) varies with stop spacing \( SS \), assuming \( R \) is fixed at 500 m.

![Mean Passenger Access Time](image)

**Figure 5-6** Impact of Stop Spacing on Access Time
The upper lines in this figure represent access time under the constant walking probability assumption, while the lower lines represent the linearly decreasing walking probability assumption. In each case, the top line represents the access time calculated with grid distances, while the bottom line represents the radial distances. As expected, $AT$ calculated with grid distances is slightly higher than that with radial distances. It is noticeable however, the 2 – 3 min difference in $AT$ between the constant and decreasing walking probabilities.

Both cases of walking probability to the station show two $AT$ regimes: first variable with SS and then constant. The change occurs at $SS = 2R = 1000$ m.

For the case of constant probability: before $SS$ reaches $2R$, $AT$ increases almost linearly. This result is intuitive since as stops are located farther apart, a larger mean walking time should be expected. For the case of decreasing probability, at the beginning $AT$ increases as stop spacing increases. However, a counterintuitive result of decreasing $AT$ is later observed. This phenomenon is a result of defining the probability of walking to the station as a decreasing linear function. This occurs because the incremental region introduced in the catchment area as $SS$ increases, brings a lower walking distance weight, due to its walking probability, than that of the catchment area before the $SS$ increase. This effect is more clearly understood if we think that after a certain threshold for $D_w$ the area being added to the station covers a population that is less likely to walk to the station, hence the weighted area increment is less than the added area.

In addition to this counterintuitive result, access time varies very little under the linearly decreasing walking probability assumption; the maximum difference is no higher than 0.5 min. This is a direct result of the model and does not seem very plausible; probably a less steep probability function should be used in the future. Therefore, to compare the changes in access time due to stop spacing changes, an intermediate value of both assumptions could be used or even the results from assuming constant probability.
When $SS$ exceeds $2R$, the walking distance, and thus $AT$, remains constant since the effective catchment area no longer depends on stop spacing. However, as $SS$ increases, the catchment regions decrease, and thus a reduction in ridership should be expected. Figure 5-7 presents the coverage curve for $R = 500$ m.

Coverage could be used as a proxy measure for the demand loss as we increase $SS$, assuming that people beyond the catchment areas will definitely not walk to this route’s stops. However they might choose to walk to other corridors, in which case system ridership loss might not be as sharp as in the corridor itself. However, $AT$ for the system would be expected to increase, and that could be considered as a reduction in overall quality of service. Figure 5-7 shows, for the case of $R = 500$ m, that coverage always decreases regardless of the behavior of $AT$. Thus, although $AT$ remains constant after a certain point, increasing $SS$ as much as possible to increase bus speed, is not recommended due to the reduced service quality and thus potential ridership loss.

![Access Time and Coverage](image)

Figure 5-7 Access Time and Coverage
In conclusion we can expect a small impact on access time if we consider a linearly decreasing probability of walking to the stop. Considerably higher impact is observed when a constant walking probability is assumed. However, a decreasing probability seems to reflect reality better. Probably a lower slope in the probability function could be a better fit to model walking probability. Although its impact does not seem to be great, coverage must also be considered to avoid extremely high stop spacing and potential ridership losses.

5.6.2 Waiting time

The objective of this section is to study how waiting time is affected by decisions on critical BRT variables. Table 5-3 lists the variables that affect waiting time from Table 5-2.

Table 5-3 Relationship between waiting time and critical variables

<table>
<thead>
<tr>
<th>CRITICAL VARIABLES</th>
<th>Lane exclusivity</th>
<th>Guidance</th>
<th>Spacing</th>
<th>Boarding level</th>
<th>Bus Capacity</th>
<th>No. doors</th>
<th>Transaction location</th>
<th>Fare Media</th>
<th>Priority method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waiting Time</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Since we are analyzing waiting time in the context of BRT, we will assume that corridors have sufficient demand to consider headways shorter than 15 min, and thus random passenger arrivals at stops can be also assumed\(^\text{18}\). Under this assumption, waiting time will be computed based on the following equation, presented in Chapter 2.

---

\(^\text{18}\) When conducting an application of this process, a true assessment is recommended about whether passengers will actually time their arrivals or not. For example, in many cases we assume that with 15 - 20
\[
E(W) = \frac{E(H)}{2} \left[ 1 + \frac{V(H)}{E(H)^2} \right]
\]

(5.4)

Most of the variables shown in Table 5-3 as affecting waiting time, enter into the previous equation within the headway variation \(V(H)\). Headway variation is a result of the various sources of unreliability on the route. These sources include traffic congestion and the boarding and alighting process at stops. Lane exclusivity and signal priority affect traffic congestion. Boarding level, number of doors, transaction location, and fare media, all help determine the boarding and alighting time per passenger and its variability.

Bus capacity is a variable that indirectly affects waiting time. Bus capacity partially determines route capacity and the probability of being left behind by a full bus, and thus the expected waiting time. However, in this case we will assume that capacity is not a binding constraint, thus bus capacity will not directly affect waiting time.

To calculate headway variance we use the model developed by (Adebisi, 1986). The theoretical model proposed by Adebisi to find the headway variation at stop \(i\) along a bus route is

\[
\text{var}(h_i) = 2(1 - \rho_i) \text{var}(t) \sum_{k=1}^{i-1} X_k \\
+ \sum_{k=2}^{i-1} \left[ 2p_k(1 - p_k)(c \cdot \bar{q}_k + l)^2 + 2(1 - p_k)c^2 \text{var}(q_k)(1 - \rho_q \cdot 1 - p_k) + c(1 - p_k) \cdot \text{cov}(\Delta q_k, h_k) \right]
\]

(5.5)

and \(\text{var}(q_k) = [\alpha_k \cdot \bar{h}_k + \alpha_k^2 \cdot \text{var}(h_k)]\); \(\text{cov}(\Delta q_k, h_k) = 2\alpha_k \cdot \text{var}(h_k)\)

where, \(h_k = \) headway at stop \(k\)

\(t = \) running time per unit distance

min-headway passengers would time their arrivals, however, if there is little or no communication to the public about bus schedule or reliability is poor, the probability of timed arrivals is likely to be low.
$X_k =$ distance between stop $k$ and stop $k-1$

$p_k =$ probability of skipping stop $k$

$c =$ boarding/alighting time per passenger

$q_k =$ passengers served at stop $k$

$\rho_t =$ correlation coefficient for successive buses running times

$\rho_l =$ correlation coefficient for passenger load among successive buses

$\alpha_k =$ passenger trips generated at stop $k$ in unit time

In Equation (5.5) the two major causes of headway variability can be identified:

- The route factor, which is the contribution of the road and traffic conditions upstream of the stop. Should there be identical loading conditions at all stops, this would be the only source of headway variance:

$$2(1 - \rho_l) \text{var}(t) \sum_{k=1}^{i-1} X_k$$

- The loading factor, which is the contribution of cumulative effects of variability in the loading situations at the upstream stops. This factor can be understood as the result of two effects

  - Alternate stops, which is the variation resulting from successive buses stopping alternately at some of the upstream locations, the effect of the $k$-th station is.

    $$2p_k(1 - p_k) \cdot (c \cdot q_k + l)^2$$

The contribution of this effect towards total headway variance is greatest when $p_k$ is 0.5. This means that having a constant high or low probability of skipping the stations is best to lower headway variance than mid-range probabilities. In real operations, we would prefer having constant low probability of skipping stations. Therefore, operations with buses stopping at all stops, regardless of the number of passengers, could reduce headway variance.
- Number of passengers, which is the variation caused by the variability in the number of passengers served by successive buses at upstream stops, the effect of the $k$-th station is

$$2(1 - p_k) \var(q_k) \cdot (1 - \rho_q \cdot 1 - p_k) + c(1 - p_k)^2 \cdot \text{cov}(\Delta q_k, h_k)$$

This effect suggests that the greater the variance of the number of passengers boarding at upstream stops, the greater the headway variance. Routes with fairly even loads at stops should result on lower headway variance than those with uneven passenger loads.

As expected, the alternate stops effect becomes zero when $p_k$ is zero; that is when the buses are expected to stop at all stations.

The values taken by the correlation coefficients, describe the conditions under which the buses are running. $\rho_t$ will usually have a value from 0 to 1. When it is close to 0, it means that running times of successive buses are independent, this happens when traffic conditions are unstable, and the running time of one bus does not necessarily indicate the running time of the following bus. When the correlation factor is closer to 1, it means that running times of successive buses are dependent, hence running time of successive buses are expected to be similar, which is usually associated with stable traffic conditions or uncongested streets.

$\rho_q$ usually have a value from $-1$ to 0. Values close to $-1$ indicate unevenness in loading distribution, a heavy loaded bus followed by a lightly loaded bus, that is negative correlation in the passenger distribution; values close to 0 indicates that passenger loads between successive buses are not correlated.

This model is convenient for the analysis required. Different configurations of the critical variables boarding level, number of doors, transaction location, and fare media...
will determine the boarding and alighting time per passenger $c$. The lane configuration and signal priority method will determine the value of the running time per unit distance $t$ and the values of the correlation coefficients $\rho_t$ and $\rho_q$.

To study the impacts of the critical variables on waiting time, we use the sample route characterized in the Appendix A. However, when applying the process to a real corridor, route-specific values should be used. The main assumptions used in the following evaluation are:

- Route length = 16 km
- Number of stops = 34
- Average stop spacing = 500 mts
- Average speed = 12 km/hr (7.5 mi/hr)
- $E(t) = 5$ min/km
- $\sigma(t) = 2.5$ min $\Rightarrow \text{var}(t) = 6.25$ min$^2$
- $E(h) = 10$ min (random passenger arrivals)
- Average boarding/alighting rate $c = 2$ secs/pass
- Passenger arrival rate $\alpha_t = 0.5$ pass/min
- $p_k = 0$ (buses stop at all stops)
- No capacity constraints
- Except for strict adherence to schedule at terminal dispatch, no other form of control takes place
- Roadway and traffic conditions are the same all along the route, this assumption could be overcome by dividing the route into different sub-routes with varying characteristics.
- Dwell time = overhead time ($l$) + passengers served ($q$) * boarding time/pass ($c$)

Figure 5-8 shows passenger waiting time along the route, at each stop varying each of the correlation coefficients in turn. The figure shows that passenger waiting time
increases along the route except when the running times are perfectly correlated. However the size of the effect varies with the correlation factors. Decreasing the running time correlation produces significant increases in waiting time, whereas increasing the passenger load correlation has no effect on passenger waiting time. This latter result seems implausible, we would expect to have varying passenger waiting times with uneven passenger loads in successive buses, which is typical of the bus bunching phenomenon. However, this result is directly produced by the analytical model, which does not allow $\rho_q$ to impact the headway variance as strongly as does $\rho_t$. This is aggravated by the fact that the loading factor of the headway variance in the sample route is small. To better model changes in passenger loads, we should vary $\rho_q$ along the route, and $\rho_t$ at the same time, because the loading factor (affected by $\rho_q$) of headway variance is dependent on the route factor; however route factor is independent of the loading factor.

Although the model allows studying waiting time along the route, with varying stop spacing, for the purposes of this thesis we will analyze one stop along the route. The selected point is close to the middle of the route where we expect demand to be significant (not too close to either terminal) and for there to be some headway variance, and thus higher waiting times than at the beginning of the route.
The first graph of this figure indicates that passenger waiting times may reach, in the later stops, twice the headway. This result seems implausible when compared to typical observed bus operations. This result may be explained by two factors. First, this model assumes no control along the route; whereas, most bus routes are controlled with
time points and supervisors. It may be possible that if a route this long had no control between its two ends, users on the latest stops would experience this kind of waiting time. To avoid this overestimation of waiting time under typical control techniques, we use waiting times estimated for mid-route stops, which may model real situations better. Second, it is possible that $\rho_t$ values may have a lower bound above 0 for mixed traffic operations. It is hard to establish specific $\rho_t$ values for each operation configuration; however, completely independent successive bus running times ($\rho_t = 0$) are implausible, even with heavy congested roads, thus $\rho_t$ values for mixed traffic operations could be limited to no less than 0.2 or 0.4.

The first critical variable that affects waiting time is lane exclusivity, which impacts expected running time $E(t)$, the variance of the running time, and the correlation coefficients, particularly $\rho_t$. The expected ranges of these variables for each degree of lane exclusivity are presented in Table 5-4. The running speed and running time standard deviation presented were obtained from various analytical and empirical studies (Okrent, 1974; Hendrickson, 1981; Levinson, 1983; Adebisi, 1986; Liu, 1995; Jacques and Levinson, 1997; Shen, Elbadrawi et al., 1998). The values for $\rho_t$ were assumed based on the findings and analysis of (Adebisi, 1986). Using the set of combinations resulting from the ranges of all variables, we obtain a set of possible passenger waiting times for each degree of lane exclusivity, which are presented in Figure 5-9.

The lowest level-of-service combinations for mixed traffic (i.e. speed of 5 – 10 km/hr, running time standard variation of 50 – 60% and $\rho_t$ of 0.3) result in expected waiting times higher than the headway (10 min). However, as mentioned in chapter 2, we will assume the highest feasible value of the cov(H) to be 1 (Adebisi, 1986), which results in a maximum average waiting time equal to the headway.
Table 5-4 Variables affected by degree of lane exclusivity

<table>
<thead>
<tr>
<th>Degree of lane exclusivity</th>
<th>Running speed [km/hr]</th>
<th>Running time $t$ [min/km]</th>
<th>$\sigma(t)^{19}$ [% of $t$]</th>
<th>$\rho_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed traffic</td>
<td>5 – 15</td>
<td>12.0 – 4.0</td>
<td>40% - 60%</td>
<td>0.30 – 0.50</td>
</tr>
<tr>
<td>Preferential lanes</td>
<td>10 – 20</td>
<td>6.0 – 3.0</td>
<td>30% - 50%</td>
<td>0.40 – 0.60</td>
</tr>
<tr>
<td>At-grade exclusive lanes</td>
<td>20 – 40</td>
<td>3.0 – 1.5</td>
<td>20% - 40%</td>
<td>0.60 – 0.70</td>
</tr>
<tr>
<td>Grade separated exclusive lanes</td>
<td>30 – 80</td>
<td>2.0 – 0.8</td>
<td>10% - 30%</td>
<td>0.70 – 0.80</td>
</tr>
</tbody>
</table>

Lane exclusivity impact on passenger waiting time

Figure 5-9 Lane exclusivity impact on passenger waiting time

This figure indicates that as we increase the degree of lane exclusivity, we can expect passenger waiting time not only to decrease but to become more consistent. The

$^{19}$ Running time standard deviation, expressed as a fraction of the mean running time, while 100% running time standard deviation indicates random running times, 0% indicates constant running times.
Moving from Conventional Bus Service towards Bus Rapid Transit  

Ch. 5. Analyzing the implementation process

area within the two dotted lines shows the region of feasible values for passenger waiting times at each configuration of lane exclusivity. As the degree of lane exclusivity increases, passenger waiting time approaches 5 min, which corresponds to half the fixed headway assumed for this exercise (10 min).

The impact on moving from mixed traffic to the higher end configurations depends on the current operating status. However, we consider that any improvement to mixed traffic operations in terms of lane exclusivity results in significant waiting time reduction. If current conditions place the system towards the upper dotted, we can expect passenger waiting time reductions of between 20% and 50%. If the current system although in mixed traffic, already operates at a good speed and without a lot of variation on the running time we can expect passenger waiting time reductions of between 10% and 20%.

The next variables that we had identified as influencing waiting time are boarding level, number of doors, transaction location, and fare media. Figure 5-10 reviews the range of alternatives for each of these variables. The configuration resulting from combining all these variables together affects the boarding/alighting time per passenger.

Some of the variables are plausible or make sense only under certain regimes for other variables. For example, the fare payment media impacts dwell time when we have on-board fare collection, otherwise fare payment media will not affect transit operations. Also, multiple door entry will only make sense when fares are collected off-board or there is the ability to collect fares on-board simultaneously at the multiple doors.
Moving from Conventional Bus Service towards Bus Rapid Transit

Ch. 5. Analyzing the implementation process

<table>
<thead>
<tr>
<th>Boarding Level</th>
<th>Steps (no level boarding)</th>
<th>Level boarding with extra overhead: ramp, kneeling, gap</th>
<th>Free Level boarding</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Doors</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Fare payment location</td>
<td>Driver</td>
<td>On-board vendor</td>
<td>On-board fare box</td>
</tr>
<tr>
<td>Fare payment media</td>
<td>Cash</td>
<td>Exact cash</td>
<td>Magnetic strip cards</td>
</tr>
</tbody>
</table>

Figure 5-10 Range of alternatives for some critical variables

The characteristics and magnitude of this service time have been researched extensively (Cundill and Watts, 1973; Kraft and Bergen, 1974; Okrent, 1974; Hoey and Levinson, 1975; Hendrickson, 1981; Levinson, 1983; Vandebona and Richardson, 1985; Levine and Torng, 1994; King, 1998; "Transmilenio Volumen V: Plan de Operación," 1999). Most studies agree that boarding times are usually higher than alighting times. Some studies consider separate rates for each of those activities and others have found combined service rates. Service times range between 0.5 secs/pass and 8 secs/pass. Figure 5-11 shows the expected impact on the hypothetical route as mixed (boarding and alighting) service rate varies.
Figure 5-11 Impact of boarding / alighting times on passenger waiting time

Figure 5-11 indicates that improving the service time per passenger at stops could reduce waiting time. The improvement could be conducted through any of the critical variables mentioned (boarding level, number of doors, fare payment location, fare payment media) taking into account the issues discussed above. One of the most straightforward ways to reduce passenger service time is the use of multiple doors, especially in the US, where the rear door seems to be underutilized, even for alighting purposes.

The last variable affecting waiting time is signal priority method. Signal priority, as lane exclusivity, could affect the mean and variance of running time between stops \( E(t) \) and \( \text{var}(t) \), and thus the correlation factors, due to its ability to control operations and re-establish degraded headways. However, we expect lane exclusivity to have a greater effect on the speed, and signal priority to have a greater effect on the variance of the running time. The values of the affected variables for the calculation of passenger waiting
times are presented in Table 5-5. While, under active unconditional priority we expect higher running speed since all vehicles regardless of their schedule adherence are given priority, under conditional priority we expect less variable running times due to the control on schedule adherence at traffic lights. Queue jumping produces slightly lower running times than normal mixed traffic operations. Overall we do not expect any of the forms of signal priority, assuming that no exclusive lanes are in place, to produce running times as low as those proposed for the higher degrees of lane exclusivity.

Table 5-5 Variables affected by signal priority method

<table>
<thead>
<tr>
<th>Method</th>
<th>Running speed [km/hr]</th>
<th>Running time [min/km]</th>
<th>$\sigma(t)$ [% of $t$]</th>
<th>$p_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive priority</td>
<td>5 – 15</td>
<td>12.0 – 4.0</td>
<td>40% - 60%</td>
<td>0.20 – 0.50</td>
</tr>
<tr>
<td>Queue jumping</td>
<td>10 – 20</td>
<td>6.0 – 3.0</td>
<td>30% - 50%</td>
<td>0.30 – 0.60</td>
</tr>
<tr>
<td>Active unconditional priority</td>
<td>20 – 40</td>
<td>3.0 – 1.5</td>
<td>20% - 40%</td>
<td>0.60 – 0.80</td>
</tr>
<tr>
<td>Active conditional priority</td>
<td>20 – 30</td>
<td>3.0 – 2.0</td>
<td>10% - 20%</td>
<td>0.70 – 0.80</td>
</tr>
</tbody>
</table>

The resulting waiting time, under the values assumed for each signal priority stage is shown in Figure 5-12. Again, waiting time was limited in the lowest level-of-service cases to be equal to the headway. The figure suggests that there is a higher possibility of achieving waiting time reductions through signal priority improvements when moving to unconditional or conditional priority than implementing queue jumpers. The impact of active priority is very similar in both conditional or unconditional priority cases, however, unconditional is more likely to increase total vehicular delays and its ability to enhance bus schedule adherence is limited (Furth and Muller, 2000).

---

20 Running time Standard deviation, seen as a portion of the running time, while 100% of running time standard deviation indicates highly variable running times, 0% indicates highly reliable running times
Moving from Conventional Bus Service towards Bus Rapid Transit Ch. 5. Analyzing the implementation process

Signal priority impact on passenger waiting time

Figure 5-12 Signal priority method impact on waiting time

5.6.3 In-vehicle time

The objective of this section is to assess how in-vehicle time is affected by critical BRT decision variables. Table 5-6 reviews the variables that affect in-vehicle time from Table 5-2.

In-vehicle time represents the portion of the passenger’s journey that is spent on the bus. For passengers, in-vehicle time starts when they board the bus and finishes when they alight the bus and is the sum of three major time components as follows

\[ IVT = IST + \text{No. stops} \times DT + \text{No. signals} \times ST \] (5.6)

where, \( IVT \) = In-Vehicle Time

\( IST \) = Inter-Stop Time

\( DT \) = Dwell Time per stop

\( ST \) = Traffic Signals Time per signal
Inter-stop time is the time spent between stops, whether the stops are caused by bus stops or traffic signals. Considering the critical variables, $IST$ is a function of lane exclusivity, guidance, stop spacing, and priority method.

Dwell time is the time spent at bus stops loading and unloading passengers. Considering the critical variables, $DT$ is a function of boarding level, number of doors, transaction location, and fare media. The number of stops can be estimated as the trip length divided by the average stop spacing. This assumes that all bus stops are served, which is plausible on a heavy route during the peak period.

Traffic time is the delay caused by traffic signal stops, and is a function of the signal priority method and lane exclusivity.

Total inter stop time can be defined as

\[ IST = \frac{X_v}{V_v} \tag{5.7} \]

where, $X_v =$ In-vehicle trip distance for a passenger

$V_v =$ Average moving speed of the vehicle
$X_r$ is the average distance traveled by a passenger on the bus. This information is usually available at a transit system level, although at the route level is desirable. For the evaluation we will assume an average trip length of 8 km (5 mi). $V_r$ is the average moving speed of the bus. Figure 5-13 shows a schematic profile of the speed of a bus as a function of distance along the route. Between stops, the bus accelerates until it reaches its cruise speed, then it maintains that speed until it is time to decelerate. The acceleration and deceleration rates depend largely on the vehicle characteristics and the traffic flow. The cruise speed varies and depends largely on the traffic volume. If the distance between stops is short, buses may not be able to reach the cruise speed.

The speed profile in black can be approximated by the gray dashed profile, where the acceleration and deceleration rates are incorporated into an average speed between stops. Furthermore, this profile can then in turn be approximated through a weighted average to a route average speed.

![Speed profile](image.png)

**Figure 5-13 In-vehicle speed profile**

As discussed previously, lane exclusivity, guidance, stop spacing, and priority all affect inter-stop time $IST$ and their impact is reflected in the speed profile. Higher degree of lane exclusivity allows higher acceleration and deceleration, and higher speed as buses
are less constrained by traffic. Also, a more consistent profile would be expected. The greatest impact of a higher degree of bus guidance is in the acceleration and deceleration rates as a guided system can allow less time-consuming docking processes and faster acceleration maneuvers. Longer stop spacing contributes to longer periods at the cruise speed and thus higher average speed. Similarly, unconditional signal priority improves average speed, as fewer stops are made. On the other hand, the benefits of conditional priority are not through increasing the average speed but by making it more consistent through its control capabilities.

Dwell time is the time spent at bus stops to unload and board passengers. Two definitions are usually found in the literature. The first one includes the time to open the doors, board and alight passengers, and close the doors. The second one also includes the time to decelerate, accelerate, and position the vehicle at the stop. Here we will use the first definition, as the time to decelerate and accelerate is already accounted for in the inter-stop time. Then, dwell time can be divided into two parts: fixed and variable. The fixed part \( l \) is the opening and closing of the doors. The variable part is a function of the number of alighting and boarding passengers. This function and the passenger service times have been widely studied (Cundill and Watts, 1973; Kraft and Bergen, 1974; Hoey and Levinson, 1975; Levinson, 1983; Vandebona and Richardson, 1985; Levine and Tornq, 1994; Liu, 1995; Aashtiani and Iravani, 2002). Given the focus in this thesis we are more interested in comparative than absolute values and so we will assume a simple linear function to model dwell time as a function of passenger service rates as follows.

\[
DT = l + q_i c_i + q_o c_o
\]  

(5.8)

where,  
\( l = \) time to open and close the doors  
\( q_i = \) number of passenger boarding  
\( c_i = \) service rate for boarding passengers  
\( q_o = \) number of passenger alighting
\( c_o = \text{service rate for alighting passengers} \)

The parameter \( l \) can vary depending on the activities to open and close the door (i.e. lowering an access ramp). Typical values are between 3 and 10 seconds. Passenger alighting times have been found to be consistently between 1 and 1.5 secs/pass for conventional buses. However, service times as low as 0.3 secs/pass have been recorded for situations with level boarding/alighting and multiple doors. Passenger boarding rates vary widely between 0.3 and 8 secs/pass. Mostly, this variation is due to fare payment media, location of fare payment, and boarding level.

The term for traffic signal delay in the in-vehicle time is composed of the number of stops and the delay at the stops. Each of the signal priority methods affects the terms as follows:

- Passive priority: slightly reduces the number of traffic signal stops
- Queue jumping: reduces the average delay at the stops
- Unconditional priority: greatly reduces the number of stops
- Conditional priority: slightly reduces the number of signal stops and introduces negative correlation with the segment running time

The average signal time \( ST \) depends on the current traffic signal cycles on the route and the level of congestion experienced. Typical red phases are between 20 and 50 seconds.

Given the previous discussions and substituting equations 1.6 and 1.7 in Equation 1.5 we obtain in-vehicle time as

\[
IVT = \frac{X_v}{V_v} + \text{No. stops} \times (l + q_i c_i + q_o c_o) + \text{No. signals} \times ST
\]

Using the example route for evaluation we can illustrate the impacts on varying the critical variables values on the previous equation of passenger in-vehicle time. The
impact observed from variations on the degree of lane exclusivity is shown in Figure 5-14. Varying the critical variable affects the speed, and thus \( IVT \).

This figure indicates how, for our example route, passenger in-vehicle time decreases as the degree of lane exclusivity increases. An increase in moving speed from 15 to 80 km/hr produces a reduction in IVT from 45 to 13 min. As shown the marginal benefits decrease as \( V_v \) increases, therefore achieving initial speed improvements might be more crucial than moving along the upper part of the spectrum.

More important than the degree of lane exclusivity configuration is the current and expected value of \( V_v \). For example, some mixed traffic routes might be able to achieve moving speeds usually associated with a high degree of exclusivity, for example above 40 or 50 km/hr. In that case higher levels of exclusivity should not be a priority as impacts will not be significant. In addition, in this case it is important to understand the causes of the observed speed, as this might be a criterion to avoid this as a BRT corridor or at least avoid moving to higher degrees of lane exclusivity.
The guidance impact is difficult to assess as its contribution to in-vehicle time depends on the current situation and the guidance mechanism acquired. Typically, the guidance system affects both the cruise speed and the acceleration/deceleration rates. When implementing a guidance system the goal is to use one that does not lower the cruise speed, however, there are some mechanisms that can reduce it. The acceleration/deceleration rates are usually higher with a guided system.

When using guidance only at stations, primarily the acceleration/deceleration rates will be affected. Rough estimates indicate that guidance at stations would reduce the time required to accelerate and decelerate by 10% to 25%, thus increasing speed by about 3% to 6%\(^{21}\).

Guidance all along the right-of-way can affect both cruise speed, and acceleration/deceleration rates. If the current system operates under mixed traffic, guidance will most likely increase the cruise speed, due more to the inherent lane exclusivity assumed than to the guidance system itself. If the current system already operates under some type of exclusivity, the guidance system needs to be chosen appropriately to avoid a reduced cruise speed. Acceleration / deceleration times are also expected to be reduced, although more so in the case of current mixed traffic operations. Expected movement time reductions from full-length guidance system are between 5% and 15%, assuming that current operations are in mixed traffic.

Stop spacing affects the inter-stop time through the speed and dwell time through the number of bus stops. As stop spacing increases, we expect higher speed \(V_s\), since the inter-stop distances are larger allowing the vehicles to reach the cruise speed more frequently and for longer periods of time. The other expected effect is to have fewer stops

\(^{21}\) This calculation assumes that no extra time is required for the vehicle to transition from a non-guided to guided regime close to the stations.
during the passenger trip, thus shorter total dwell time. Figure 5-15 shows the impact on IVT of increasing stop spacing.

![Stop spacing impact on passenger in-vehicle time](image)

**Figure 5-15 Impact of Stop Spacing in In-vehicle time**

Even more acutely than in the case of lane exclusivity, we observe that increasing stop spacing within the first 500 m results in significant in-vehicle time benefits, but as we move farther along the spectrum, marginal benefits decrease quickly. Therefore, the figure indicates that spacing stops more than 600 or 700 meters apart will not bring significant benefits from the IVT standpoint.

The next critical variables to study are those closely related to dwell time: boarding level, fare location, fare media, and number of doors. As in the case of waiting time, all these variables are evaluated through their contribution to the service times and the door opening/closing process. Figure 5-16 shows the impact on IVT of the main dwell time variables.

The alighting passenger service time $c_o$ varies between 2 sec and 0.5 sec, from a situation in which alighting occurs through one conventional door with steps to a
situation with free level boarding, without a gap. This variation has very little effect on IVT, which stay in a range of 23 to 24 min.

The boarding passenger service time $c_i$ varies from 8 sec to 0.5 sec. That is from conventional buses with steps and the driver giving change to off-vehicle fare payment, level boarding, and multiple doors. As observed from the figure, the impact on IVT from one end to the other is significant (from 28.2 min to 20.7 min). In addition, the marginal boarding service time benefits are the highest of all three variables presented.

The last variable presented in the previous figure is the time to open and close the doors, which varies between 4 sec and 12 sec. This variation basically depends on the opening mechanism and the activities required at the stop at the start and end of the loading and unloading process; for example lowering and raising a ramp as in Curitiba.

To assess the impact on specific cases we need to determine the current values of $I$, $c_i$, and $c_o$, and their expected values with the decisions made on the critical variables. To obtain those expected values, if no specific values are know or can be drawn for the
Moving from Conventional Bus Service towards Bus Rapid Transit

Ch. 5. Analyzing the implementation process

corridor being analyzed, the reader can find values in the literature (Cundill and Watts, 1973; Kraft and Bergen, 1974; Hoey and Levinson, 1975; Levinson, 1983; Vandebona and Richardson, 1985; Levine and Torng, 1994; Liu, 1995; Aashtiani and Iravani, 2002).

The last variable affecting dwell time, and thus IVT, is the number of doors that can be effectively used for boarding and alighting. The impact on in-vehicle time comes from a reduction in $c_i$ and $c_o$, the average boarding and alighting service times respectively. In situations where the current dwell time is significant, introducing multiple door boarding and alighting could have high benefits; not only to reduce in-vehicle time but to reduce route unreliability. Introducing more boarding doors produces a higher impact than more alighting doors; however, the latter is usually easier and hence more common.

5.6.4 Running time

Running time is the time spent by the bus to travel from one end of the route to the other. Unit distance running time is a normalized measure of the running time, which represents the time required to operate a unit distance, for example a kilometer or a mile.

Running time is a relevant measure for the agency as it represents a proxy variable for revenue vehicle hours (and thus operational costs) and is a significant component of the route cycle time, which determines peak fleet requirements (capital cost). The number of vehicles required for a route is the product of the cycle time and the frequency. Where the cycle time is the roundtrip running time plus the recovery time at each terminal. Reducing the running time significantly decreases cycle time and thus the number of buses required for a given frequency and thus represents a major saving for the agency.

Reductions in running time might also represent reductions in revenue vehicle hours or a more efficient operation, as passengers are transported more quickly and the agency uses its resources more effectively.
Running time can be calculated similarly to the passenger in-vehicle time, with the trip length replaced by the route length. Figure 5-17 show similar results as Figures 5-14 through 5-16, but for running time.

\[
RT = \frac{RL}{V_v} + \text{No. stops} \times \left( l + q_v + q_o \right) + \text{No. signals} \times ST
\]

(5.10)

where, \( RT \) = running time

\( RL \) = route length

The greatest running time savings will typically come from improvements to speed due to a higher degree of lane exclusivity, longer stop spacing or enhanced signal priority methods.
Moving from Conventional Bus Service towards Bus Rapid Transit  

Ch. 5. Analyzing the implementation process

Figure 5-17 Impacts on running time
5.7 Step 6: Prioritize BRT components

After evaluating the time benefits of the critical variables we move onto prioritizing them. This prioritization is based on a cost-benefit analysis using the time benefits obtained from the previous section, and the implementation costs required to achieve them. To prioritize the components we then follow a simple process:

1. Study the benefits identified in the previous section and disregard alternatives that are clearly unfeasible under the agency’s goals and constraints.
2. Determine the infrastructure and technology cost of the feasible improvement alternatives for each variable.
3. Identify the average time reduction as a percentage of current travel and running time based on the results of the previous section.
4. Calculate the average cost to achieve a reduction of one percentage point in travel time and running time in each of the variables.
5. Choose the prioritization criteria based on agency expectations and needs:
   - By users: prioritize alternatives more cost-effective in terms of travel time.
   - By agency: prioritize alternatives more cost-effective in terms of running time.
   - Both users and agency: prioritize alternatives that are more cost-effective in terms of both travel and running time.
6. Establish a priority list according to the results of the previous step.

The previous process will be applied in the following chapter for the Chicago Western Avenue corridor.

Sometimes, passenger travel time is mistakenly thought of as simply in-vehicle time, overlooking the importance of access time and waiting time. In fact, many studies have shown that waiting and access time are valued more highly by passengers than in-vehicle time. For example, usually customers value waiting time twice as highly as in-vehicle time, which means that users perceive one minute of waiting time as equivalent to
two minutes of in-vehicle time, or that users are willing to pay the same amount of money to have their trip reduced by 2 in-vehicle minutes as by 1 waiting minute. Therefore, in prioritizing by travel time we should consider a weighted average of the different components of travel time.
6  APPLICATION: WESTERN CORRIDOR IN CHICAGO

The objective of this chapter is to apply the process presented in Chapter 5 to a real situation. The selected application is the city of Chicago (Illinois, USA) specifically the Chicago Transit Authority (CTA) North-South Western Avenue transit corridor. The chapter is divided into three main sections. The first one is the application of the process, which consists of six sub-sections, each one corresponding to steps one through six of the process. The second section contains the recommendations for the CTA resulting from the application of the process. The final section contains other findings and recommendations for the city of Chicago that might not be a direct result of the process but became apparent while conducting the research for this thesis.

6.1  Applying the process: establishing priorities

6.1.1  Step 1: Understand current transit system

The CTA is responsible for providing transit service for the city of Chicago and 38 neighboring suburbs. It is the nation’s second largest transportation system, serving more than 1.5 million riders each day. The two main streams of CTA riders use CBS and rapid rail transit with the basic operations statistics shown in Table 6-1.

<table>
<thead>
<tr>
<th></th>
<th>Bus</th>
<th>Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicles</td>
<td>1,900 buses</td>
<td>1,100 cars</td>
</tr>
<tr>
<td>Routes</td>
<td>~ 134 routes</td>
<td>7 lines</td>
</tr>
<tr>
<td>Route-miles</td>
<td>1937 route-miles</td>
<td>222 track-miles</td>
</tr>
<tr>
<td>Ridership</td>
<td>~ 1,000,000 pass/day</td>
<td>~ 500,000 pass/day</td>
</tr>
<tr>
<td>Stops</td>
<td>12,000</td>
<td>143</td>
</tr>
</tbody>
</table>

CTA rail lines follow a radial alignment while bus routes generally operate either East-West or North-South on the city’s well-defined grid street network. The rail lines
transport users from the North, West, and South neighborhoods to the downtown area known as the loop. Figure 6-1 shows a transit service map of the North, Central, and South parts of Chicago. Rail lines are shown on thick lines and thinner gray lines represent bus routes. Western Avenue, the application corridor is shown as a dashed black line.

Overall, CTA ridership during the past 5 to 7 years has been growing. A closer look at CTA’s ridership figures indicate that the growth is due to increases in rail ridership, while bus ridership has in fact been decreasing\(^{22}\). Furthermore, rail ridership is approaching capacity during the peak periods. Currently, the main goals for the CTA system are to increase bus ridership and maintain ridership growth on the rail side. The methodology to accomplish the objectives for rail are clear: to re-build currently used rail infrastructure, which is almost 100 years old, and for the longer-term, extend the Blue and Red lines towards the northwest and south respectively. However, the strategy to increase bus ridership is not as clear, instead a group of loosely linked initiatives are underway throughout the agency seeking to improve bus quality. One of the initiatives, although still in its early stages, is to convert some of today’s CBS corridors into BRT routes.

Thus, the main system-wide objective for the CTA is to increase ridership. In the case of rail, longer-term strategies are being implemented given the existing growth pattern. In the case of bus, shorter-term strategies are desired to show positive impacts on constituencies as soon as possible.

\(^{22}\) Analysis performed from CTA’s website information, published Bus and Rail ridership reports, and CTA budget documents.
Figure 6-1 Map of North, Central, and South CTA transit network
Other system-wide initiatives that will affect BRT and thus should be considered are:

- New compo-buses. CTA is acquiring new 45-foot composite materials buses. Those buses are supposed to be the dedicated fleet for express routes X49 (on Western Avenue), X80, and X55 to enhance these routes’ image.

- Bus Stop Spacing project. CTA’s standard for bus stop spacing is currently 1/8 mi (660 ft). However, many routes violate this standard by having shorter average stop spacing. In an effort to reduce travel time, CTA is engaged in a project to bring average stop spacing up to standard on the five routes of each garage that are in greatest violation of this standard, for a total of 40 routes. One of the routes is the local service 49 on Western Avenue.

- Smart Cards. In an effort to reduce dwell time, 3 years ago CTA started a pilot project to introduce contact-less Smart Cards for fare payment. The pilot project proved positive impacts after a deployment of 3,500 trial cards. A larger wave of SmartCards is expected to be introduced at the beginning of next year.

### 6.1.2 Step 2: Select BRT corridor

Given the current CTA situation, in which short-term ridership increase or at least reduction of market share loss is sought, two of the BRT corridor selection criteria should be used:

- Criterion 1: Select corridors with high expected ridership both in the short and long term
- Criterion 5: Select corridors with high market share loss rates

The first one is to introduce BRT in places where demand is already high enhancing a large number of customers’ journeys, and generating large impacts. The second one is to introduce BRT on routes where bus ridership is dropping the fastest and attempt to retain those customers.
In the case of CTA, a decision has been made following the argument of Criterion 5. Market share losses are most pronounced on cross-town routes rather than conventional downtown oriented routes, and thus CTA has already initiated a set of efforts to study, understand, and intervene on cross-town bus routes to improve their service quality and to increase ridership. Efforts have focused on Western Avenue, which has been identified as the BRT pilot project for Chicago (FTA, 1998).

In fact, in addition to criterion 5, the selection of Western Avenue also fits criterion 4\(^\text{23}\) and criterion 6\(^\text{24}\). Western Avenue is expected to have higher ridership levels in the future due to the densification and gentrification of the near west Chicago area. In addition, western Avenue crosses 6 of the 10 rail lines serving downtown, and it is an important route in terms of connectivity both with rail lines and East-West bus routes.

Because of the strong CTA interest and existing initiatives for Western Avenue, this was selected as the application corridor for this thesis. Thus, this thesis did not conduct an extensive corridor selection task and accepted as a given Western Avenue and its Limited Stop Service X49.

Western Avenue service 49 has been one of the best performing bus routes in the CTA system. Given the high level of ridership along this route, as well as the role Western Avenue plays in regional mobility, in December 1998 the CTA introduced a new service, the X49 Express. This service eliminated three-fourths of the local bus stops and increased travel speeds by 24% to 25 MPH. It gave long-distance, cross-town riders a faster alternative to the local Western bus service. (CTA, 2002)

\(^{23}\) Criterion 4: Select corridors with high expected ridership in the long term

\(^{24}\) Criterion 6: Select corridors that could serve as a link between other rail and bus routes to increase accessibility within the transit network
6.1.3 Step 3: Assess corridor current performance

Western Avenue is a North – South Street approximately 3 miles west of downtown Chicago. Currently, CTA runs four routes within this corridor:

- Local service 49
- Local service 49A.
- Local service 49B
- Express service X49

Figure 6-2 shows a schematic of the four routes running on Western Avenue, including their length and daily ridership.

As observed, ridership on the express service X49, which was implemented to provide higher quality service to riders due to its higher speed, is in fact much lower than that of the parallel local service 49. This fact is of concern to the CTA in terms of the readiness to move forward to a BRT like operation. Therefore, this thesis uses the X49
service as the base route to determine what are the potential benefits from moving towards a BRT type of operation in Western Avenue. The other three routes, specially local route 49, are also considered in the analysis, as improvements to the X49 will certainly affect the other routes in the corridor.

To assess the current corridor performance, data and information about the routes were collected as follows:

1. Review of published literature and internal CTA reports on the corridor
2. Formal and informal interviews with CTA staff in the planning and operation departments as well as in the garage.
3. Field visits to stops on service X49 to make mostly qualitative observations on performance.
4. On-board travel time data collection for route X49.

In element 3, field visits were conducted at all X49 stops in order to collect descriptive information about the stops and identify issues that need to be addressed. During the field visits the following information was collected

- Name of crossing street with Western Avenue
- Location of stop (i.e. near-side, far-side, mid-block)
- Shelter availability
- Availability of route information for users
- Bus routes and rail lines to which passengers could transfer
- Observed bus operational issues
- Type of intersection (i.e. 4-way, 5-way, 6-way, or other)
- Traffic signals (i.e. Traffic light, Stop sign)
- Vehicular flow: main directions, flow issues
- Cross section: No. of lanes, road width, turns allowed, sidewalk width, on-street parking (where present)
• Sidewalk amenities: benches, vending machines, trashcans, phones, bike racks, lighting, trees, and others
• Types of land use: residential, commercial, industrial, special (hospital, school), car-related, parking, empty lot.
• Demand patterns: potential demand generators, pedestrian flows

In element 4, activities focused on collecting sufficient information to determine the travel time components on route X49, that is how much time is currently spent moving, dwelling, and delayed at traffic lights. This information helps to analyze which BRT component will have the greatest impact on travel and running time. Data collection took place on Western Avenue, on the X49 bus route during the following days and peak periods:

- Monday, July 22, 2002 PM peak
- Tuesday, July 23, 2002 AM Peak, PM peak
- Wednesday, July 24, 2002 AM Peak, PM peak
- Thursday, July 25, 2002 AM Peak

Each segment between two stops has at least 3 records. The information gathered consists of:

- Arrival time at stop
- Number of passengers alighting (front door and rear door distinguished)
- Number of passengers boarding
- Departure time from stop
- Arrival time at traffic lights
- Departure time from traffic lights

Some facts about the data collection process are worth noting to understand the implications on future results. Western Avenue has been undergoing re-paving work for several months now, at the time of the data collection, construction work was being done
between Madison St. and Archer St.; that segment only had one lane in service in each direction. Thus, lower speeds are expected in this part of the route. In addition, low demand was observed during the fieldwork, with very few instances of standees and general availability of empty seats. CTA staff, regular users of the route, noted that during the summer months, demand drops given several large high schools along the corridor. Ridership reports for summer and non-summer months of previous years were analyzed, and it was concluded that during the summer, ridership is consistently 10% below fall, winter, and spring levels. Therefore, ridership recorded, and thus dwell time might be underestimated compared to typical operations during the rest of the year.

The following paragraphs characterize the route and its performance based on the information collected as described above. Figure 6-3 shows a schematic of the X49 service.

**Right-of-way**

X49, as well as the local 49 service, run in mixed traffic. The cross-section of the street is wide. All segments have at least three lanes in each direction; usually one for parking and two moving lanes. There is no bus guidance system in place.

**Stops**

The service has 32 stops southbound and 33 stops northbound. To identify the stops, each intersection containing a bus stop was identified with the consecutive ID numbers shown in Figure 6-3. Each intersection contains one Southbound and one Northbound stop, except for intersection 11, which has two Northbound stops (Cortland and Milwaukee). These two stops are 100 ft apart and are both shown in the figure as part of intersection 11. Although Figure 6-3 is a schematic, it does represent the true stop location to scale. As observed average stop spacing in the southern portion of the route is considerably larger than in the northern part of the route.
Average stop spacing for the northern portion of the route is approximately 2,200 ft, while for the southern portion it is almost twice as great: 4,000 ft. Overall average stop spacing is 3,100 ft. Average stop spacing for the local service 49 by contrast is currently

---

25 Madison St is considered the boundary between North and South
460 ft, which the bus stop spacing project is aiming at increasing to 620 ft by removing 34 (25%) Southbound stops and 22 (17%) Northbound stops. As opposed to the X49 service, the 49 service does not have a significant difference in stop spacing north and south; both segments have very similar average stop spacing.

Table 6-2 shows basic information on the stops including the location of the stop, the type of stop, amenities, special land uses, etc. As seen most stops are near-side, however, most of them are being re-located to the far-side under the current re-paving project. The new locations are being given concrete bus pads for the buses.

**Vehicles**

The existing boarding level in the route is a mix of the first two types: step-boarding (conventional high floor buses with steps) and somewhat level boarding (low-floor buses with a gap to board).

The vehicles serving Western Avenue are conventional 40-feet buses, with two doors and seating capacity as follows:

- Flxible (high-floor): 42 seats and crush load of 95
- Nova (low-floor): 37 seats and crush load of 90

However, CTA standards establish an average maximum load of 60 pass/bus during any half-hour period.
### Table 6-2 Intersection inventory

<table>
<thead>
<tr>
<th>ID</th>
<th>Intersection</th>
<th>Position</th>
<th>Distance to last [ft]</th>
<th>Bus routes</th>
<th>Transfers</th>
<th>Shelter</th>
<th>Shop info</th>
<th>Rail transfer</th>
<th>Car</th>
<th>Pedestrian/ Special use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BERWYN</td>
<td>SB</td>
<td>0</td>
<td>647</td>
<td>49,49A,49</td>
<td>490</td>
<td>1</td>
<td>Y</td>
<td></td>
<td>Medical Center</td>
</tr>
<tr>
<td>2</td>
<td>POSTER</td>
<td>NS</td>
<td>647</td>
<td>1994</td>
<td>49,49A,49</td>
<td>92</td>
<td>246</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>LAWRENCE</td>
<td>FS</td>
<td>1995</td>
<td>1995</td>
<td>49,49A,49</td>
<td>61</td>
<td>786</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>BROWN LINE - LELAND</td>
<td>NS</td>
<td>603</td>
<td>1459</td>
<td>11,49A,49,49</td>
<td>400, 11, Pace</td>
<td>1,167</td>
<td>Y</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>5</td>
<td>MONTROSE</td>
<td>NS</td>
<td>1392</td>
<td>1997</td>
<td>49,49A,49</td>
<td>78</td>
<td>461</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>RIVIER PARK</td>
<td>NS</td>
<td>1997</td>
<td>1995</td>
<td>49,49A,49</td>
<td>50, 630</td>
<td>457</td>
<td>Y</td>
<td></td>
<td>Medical Center</td>
</tr>
<tr>
<td>7</td>
<td>ADDISON</td>
<td>FS</td>
<td>2066</td>
<td>2034</td>
<td>49,49A,49</td>
<td>152</td>
<td>235</td>
<td>Y</td>
<td></td>
<td>High School</td>
</tr>
<tr>
<td>8</td>
<td>BELMONT</td>
<td>NS</td>
<td>1923</td>
<td>1976</td>
<td>49,49A,49</td>
<td>77</td>
<td>555</td>
<td>Y</td>
<td></td>
<td>Court</td>
</tr>
<tr>
<td>9</td>
<td>HOMEROY</td>
<td>NS</td>
<td>1943</td>
<td>1973</td>
<td>49,49A,49</td>
<td>76</td>
<td>444</td>
<td>Y</td>
<td></td>
<td>High School</td>
</tr>
<tr>
<td>10</td>
<td>FULLERTON</td>
<td>NS</td>
<td>2047</td>
<td>2265</td>
<td>49,49A,49</td>
<td>74</td>
<td>732</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>BLUE LINE CHASE - MILWAUKEE</td>
<td>-</td>
<td>107</td>
<td>49,49A,49</td>
<td>56</td>
<td>1,881</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>CORTLAND</td>
<td>NS</td>
<td>2478</td>
<td>1620</td>
<td>49,49A,49</td>
<td>56</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>NORTH AVENUE</td>
<td>NS</td>
<td>1514</td>
<td>1995</td>
<td>49,49A,49</td>
<td>72</td>
<td>829</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>DIVISION</td>
<td>NS</td>
<td>1997</td>
<td>1992</td>
<td>49,49A,49</td>
<td>70</td>
<td>457</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>CHICAGO</td>
<td>NS</td>
<td>1992</td>
<td>1594</td>
<td>49,49A,49</td>
<td>66</td>
<td>601</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>GRAND</td>
<td>NS</td>
<td>1394</td>
<td>2597</td>
<td>49,49A,49</td>
<td>66</td>
<td>212</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>MADISON</td>
<td>FS</td>
<td>2597</td>
<td>1355</td>
<td>49,49A,49</td>
<td>70</td>
<td>721</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>ROOSEVELT</td>
<td>MB</td>
<td>1500</td>
<td>2501</td>
<td>49,49A,49</td>
<td>7</td>
<td>767</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>SHANGHAI</td>
<td>FS</td>
<td>2487</td>
<td>3309</td>
<td>27,49,49A,</td>
<td>12, 37</td>
<td>531</td>
<td>Y</td>
<td></td>
<td>Medical Center</td>
</tr>
<tr>
<td>20</td>
<td>BLUE LINE CEDAR - 1st</td>
<td>MB</td>
<td>3491</td>
<td>654</td>
<td>49,49A,49</td>
<td>455</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>URBAN</td>
<td>FS</td>
<td>521</td>
<td>1969</td>
<td>49,49A,49</td>
<td>21</td>
<td>380</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>24TH STREET</td>
<td>NS</td>
<td>1961</td>
<td>3274</td>
<td>49,49A,49</td>
<td>60</td>
<td>119</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>MCGREGOR</td>
<td>FS</td>
<td>5197</td>
<td>4761</td>
<td>49,49A,49</td>
<td>53</td>
<td>691</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>25TH STREET</td>
<td>NS</td>
<td>4809</td>
<td>849</td>
<td>49,49A,49</td>
<td>47, 94, 48</td>
<td>802</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>GRAND</td>
<td>NS</td>
<td>3155</td>
<td>1995</td>
<td>49,49A,49</td>
<td>55</td>
<td>633</td>
<td>Y</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>26</td>
<td>30TH STREET</td>
<td>NS</td>
<td>1948</td>
<td>2063</td>
<td>49,49A,49</td>
<td>59</td>
<td>176</td>
<td>Y</td>
<td></td>
<td>Park</td>
</tr>
<tr>
<td>27</td>
<td>OSWEGO</td>
<td>NS</td>
<td>2063</td>
<td>2973</td>
<td>49,49A,49</td>
<td>76</td>
<td>1,043</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>31ST STREET</td>
<td>NS</td>
<td>2973</td>
<td>4796</td>
<td>49,49A,49</td>
<td>67</td>
<td>391</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>32ND STREET</td>
<td>TM</td>
<td>4851</td>
<td>5480</td>
<td>49,49A,49</td>
<td>49, 784</td>
<td>8179</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>33RD STREET</td>
<td>NS</td>
<td>5480</td>
<td>5500</td>
<td>49A, 49,49A,</td>
<td>765</td>
<td>Park</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>34TH STREET</td>
<td>FS</td>
<td>5500</td>
<td>2518</td>
<td>49A, 49,49A,</td>
<td>955</td>
<td>Pace 348, Pace 36</td>
<td>55</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>32</td>
<td>EVERGREEN PLAZA</td>
<td>MB</td>
<td>0</td>
<td>549A,49,9,60</td>
<td>0</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>Mail</td>
</tr>
</tbody>
</table>

SB: Southbound; NB: Northbound
FS: Far side; NS: Near side; MB: Middle Block; TM: Terminal
Y: Yes

### Fare collection

The transaction location is always on-board with a fare box; however sometimes driver interaction is needed to issue a transfer card or a card with the change value.\(^\text{26}\)

---

\(^\text{26}\) Drivers do not provide change, but passengers can pay more than the exact fare amount, for example two dollar bills for a $1.50 fare, in which case the driver issues a card to be used again in the system with the remaining value on it.
The payment media is basically a mix of cash and transit cards, which are magnetic-stripe cards. Although some Smart Cards are used, they are so few that they are not yet worth considering as a payment medium.

**Signal system**

The signal system is at the lower end of the priority spectrum, basically providing only passive priority. However, when carrying out the running time data collection it was observed that buses repeatedly fell into green waves for long segments. Drivers and street supervisors, feel however, that green waves are achieved only by experienced drivers that know Western Avenue well, and that green waves are not well calibrated for CTA buses.

**Land use**

The corridor crosses various neighborhoods with a wide range of urban, social, and economic characteristics. However, the entire corridor can be considered auto-oriented, given its poor urban public space, and car-related land uses such as auto dealers, auto repair shops, and parking lots.

**Demand**

As mentioned, daily demand in the Western Avenue service is approximately

- Local service 49: 25,000 pass
- Local service 49A: 600 pass
- Local service 49B: 5,200 pass
- Express service X49: 6,000 pass

Load profiles are not collected by the CTA in a regular basis. However, detailed data on daily transfers by stop from March 2001 is available. Given that total number of transfers to and from routes 49 and X49 (25,500 transfers/day) is approximately 82% of combined ridership (31,000 pass/day), we can expect transfer figures to be a reasonable
Moving from Conventional Bus Service towards Bus Rapid Transit

Ch. 6. Applications

proxy for total demand at each stop. Figure 6-4 shows transfers at each X49 stop. Of the 25,500 transfers/day recorded, 1,455 were not identifiable\(^\text{27}\), and 3,690 occurred between the Western Avenue services themselves making it impossible to determine at which stop they occurred. Thus, the figure below presents a total of 20,355 records, still a good representation of the universe of transfers on Western Avenue.

![Transfers at X49 stops](image)

**Figure 6-4 Daily transfers between 49 and X49 and all other CTA routes**

Figure 6-5 presents the transfers that occurred only for route X49. Both figures show a consistent set of stops with highest numbers of transfers: Blue Line O’Hare, Orange Line, 79th street, Brown Line, 63rd street, and Chicago Street.

---

\(^{27}\) Transfers were not identifiable either because the trip started at a downtown rail station that does not have a unique connection to Western Avenue, or because the previous or next trip is shown in a bus route that does not have a direct connection with Western Avenue.
Moving from Conventional Bus Service towards Bus Rapid Transit

Ch. 6. Applications

Figure 6-5 Daily transfers to/from X49 from/to all CTA routes

**Speed and travel time**

With the data collected in element 4, we are able to characterize the travel time components of the X49 service. Figure 6-6 shows the cumulative time for each of the three major components of travel time (moving, dwell, signals) for the X49 route, from Berwyn in the north to 95th St in the South. As observed, dwell time is 10 to 15%, and signal time about 20 to 30% of total travel time, the remainder is moving time.

In the figure, a steeper line for total travel time represents lower speed, as more time is required to advance a given distance. As observed, travel speed for the first or northern part of the route is lower than for the southern part. To study in detail speed variations, Figure 6-7 shows the operational and moving speed profiles for the route. The operational speed accounts for moving time, dwell time, and traffic delays. Moving speed considers only the time the vehicle was running or delayed in normal congestion.
As expected due to construction work, Figure 6-7 shows lower speed between Madison and 26th street. Operational speed ranges mostly between 10 mi/hr and 17 mi/hr. Moving speed could be seen as an upper bound for speed under the existing degree of lane exclusivity (mixed traffic) but with improved signal priority system and fare collection system that significantly reduces boarding and alighting service times. Thus, the difference between the moving and operational speed lines represent the potential for improvement in travel times without engaging in exclusive lane treatments. Furthermore, from Figure 6-6, we can conclude that there is more room for improvement from reducing signal time than from dwell time. However, as mentioned before, dwell time could be underestimated due to the lower ridership without high schools operating.
In Figure 6-7, the black line represents the average speed that could be obtained from aggregating similar segments.

- **Berwyn to Montrose:** ~7 mi/hr, lowest average speed, potentially due to short stop spacing, higher demand, and narrower cross section.

- **Montrose to Belmont:** ~13 mi/hr, average operation in the north portion, speed degrades as the route approaches Diversey.

- **Belmont to Cortland:** ~10 mi/hr, lower speed probably due to congestion, high demand, and heavy intersections, especially those with Diversey and Milwaukee.

- **Cortland to 79th St.:** ~15 mi/hr, average operation although construction work in this particular case lowers speed between Madison and 26th St., performance during regular operations will probably be like its neighbor segments.
• 79th St. and 95th St.: ~28 mi/hr, exceptionally high speed probably achieved due to the relatively lower traffic and larger stop spacing

Figure 6-7 also points to a correlation between stop spacing and speed; specifically very short distances between stops resulting in very low speeds. Figure 6-8 studies this relationship more specifically. The x-axis in this figure shows the distance between two stops and the y-axis the average speed observed during the data collection process for that same distance\(^{28}\). The figure indicates that a positive power function could relate stop spacing and speed.

![Relationship between Stop Spacing and Speed](image)

Figure 6-8 Relationship between stop spacing and operational speed

**Boarding and alighting service time**

During the fieldwork dwell time and number of passengers boarding and alighting were counted. A total of 128 observations were recorded for dwell time. Some general observations follow:

\(^{28}\) The values for segments affected by construction have been removed from the data set shown in this figure
• Rear door usage is low. 93 of the records included at least one person getting off the vehicle, of those, only 24 (26%) included any alighting through the rear door. The overall service time, that is the dwell time divided by the total number of boarding and alighting passengers is:
  - 3.0 sec/pass for the cases in which the rear door was used
  - 4.0 sec/pass for the cases in which only the front door was used for alighting
  - 6.2 sec/pass for the cases in which only boardings (front door) were recorded

• This suggests that greater rear door usage could reduce the alighting portion of the dwell time by around 25%, and if this door could also be used for boarding savings could be even higher.

• The lowest dwell time observed was 4 sec, and a constant overhead time $t$ to open and close the doors of 3 sec is assumed.

• The average service time $c$ to be used in Equation (5.6) to find headway variation was identified as 3.0 sec/pass

During the data collection exercise, the buses were never close to capacity; seats were always available. Boarding/Alighting data show that the heaviest load observed on the buses was 29 passengers. Thus, although there is room for improvement in the current boarding/alighting service times ($\sim 3.0$ sec/pass), the dwell time component appears to have the lowest potential to impact travel time due to low ridership levels.

**Signal system**

Figure 6-9 allows us to analyze the potential savings from improvements to the signal system. The figure again shows the operational and moving speed profiles, as well as a line that represents the speed profile if the bus had received unconditional priority.

---

29 These times include overhead time for opening and closing the doors

30 Does not include overhead time because it is accounted for as a separate variable.
and thus no traffic signal delay. Thus in any given segment between two stops, the vertical distance between the blue (bottom) and red (middle) lines represents the potential increase in operational speed when improving the signal system to reduce signal delays. The vertical distance between the red (middle) and green (top) lines represents the potential speed increment coming from dwell time reduction. This figure confirms that dwell time improvements seem to offer lesser potential impact on travel time. This seems to be due to the low level of passengers observed, rather than an existing fast boarding and alighting process.

![Signal priority potential impact on operational speed](image)

*Figure 6-9 signal system*
The signal time component is more significant in some areas than in others, notably, the north seems to have greater potential than the south\textsuperscript{31}.

In the five segments noted above, the upper bound for increase in operational speed due to reductions on traffic signal delays are as follow:

\begin{itemize}
  \item \textbf{Berwyn to Montrose}: 36\% from 7.2 mi/hr to 9.9 mi/hr
  \item \textbf{Montrose to Belmont}: 27\% from 13.5 mi/hr to 17.1 mi/hr
  \item \textbf{Belmont to Cortland}: 34\% from 7.5 mi/hr to 10.1 mi/hr
  \item \textbf{Cortland and 79th St.}: 18\% from 14.6 mi/hr to 17.3 mi/hr
  \item \textbf{79th St. and 95th St.}: 9\% from 29.1 mi/hr to 31.6 mi/hr
\end{itemize}

These maximum improvements are, as noted, an upper bound, and in reality might never be fully achievable.

The signal spacing found in the corridor is approximately 350 mt (\textasciitilde 1151 ft). The average signal delay in the corridor is 30 sec, with a hit ratio of 57\%. The hit ratio means that in average buses stop at 5.7 of every 10 signals in the route.

\textbf{6.1.4 Step 4: Define implementation strategies}

Given the current situation on the Western Avenue routes, an incremental approach is recommended for the following reasons.

First, the CTA is already taking discrete actions to improve service on Western Avenue and raise the profile of transit in the corridor. To this end, the CTA is currently undertaking six major initiatives:

\begin{itemize}
  \item \textbf{Stops re-location on Express route}. Recommendations to relocate many stops to the far side of intersections were developed by the CTA in January 2002 to
\end{itemize}

\textsuperscript{31} Without considering the segment Madison – Archer because due to the construction, traffic delays were higher than usual.
correspond with the repaving of Western Avenue. This aims to improve travel time for the Express route and allow for more effective use of Transit Signal Priority technology in the future.

- **Streetscape improvements.** Overall improvements to the pedestrian areas directly adjacent to the stops are planned. This should help improve passenger comfort and convenience and will enhance the neighborhoods along Western Ave. Improvements include better lighting, wayfinding, gateway treatments, and sidewalk conditions.

- **Dedicated Express fleet.** The CTA is considering buying new 45-foot low-floor buses for use on the Western Express and other neighborhood Express routes. This fleet may be "branded" with non-standard paint colors to increase Express visibility. This is being done with the belief that BRT can become more competitive with rail service if "brand recognition" is established by creating a dedicated, recognizable fleet.

- **Bus stop amenities.** The City's street furniture program is expected to allow for installation of shelters and benches at Western Express stops.

- **Transit Signal Priority (TSP) Technology.** The Regional Transportation Authority, the City of Chicago, and the CTA are currently exploring a TSP system for several regional corridors including two segments of Western Avenue. CDOT also completed a feasibility study in 2001 that showed promising findings for TSP on Western Avenue. Although the preferred system requires GPS technology and a schedule adherence system that the CTA does not currently have, there are plans for a limited application of intelligent technology for Western Avenue on an accelerated timeframe.

- **Balance between local and Express service.** The CTA conducted an analysis of the Western local and Express routes in order to achieve a better balance of service between the two routes. Starting with the summer 2002 pick, headways on the local service were increased from 5 to 8 min and express service headways were reduced.
from 15 to 10 min in the peak. Increased headways are expected to further improve perceptions of BRT on Western Avenue.

- **Intersection design.** The CTA is writing the RFP to hire a consultant to design improved prototypical intersections, to be applied to Western Avenue and other express corridors in the system.

  Through interviews, we researched the rationale behind this incremental strategy already being followed by the CTA. In general, there is a sentiment that implementing small enhancements is safer for the CTA given the unbalanced ridership currently observed in local 49 and express X49 services. Also, there is some feeling that Western Avenue might not need full BRT until several years in the future.

  Second, the land uses along the corridor, except perhaps the most northern part, are still car-oriented and not transit supportive. For an all-at-once strategy to be successful, land use development, zoning rules, etc should be applied, which not only requires agencies other than CTA to be involved but also supportive land uses, which will probably not exist in the near future.

  Third, most neighborhoods along Western Avenue, are lower income but with a population eager to be first-time car buyers as their purchasing power increases. For these reasons it is doubtful that the trend of increasing motorization can be stopped quickly, as explained earlier.

  Fourth, the implementation of the X49 service and its resulting low ridership compared with the 49, may indicate a small time elasticity for users on Western Avenue. Thus the expected ridership of a full BRT service is difficult to predict, and thus a strategy that allows incrementing capacity at a pace matching demand is preferable.

  Fifth, the joint ridership of the 49 and X49 service does not necessarily require a total transformation of CBS operations. Current loads can be handled without any operational concern without a full BRT system.
Sixth, the corridor performance assessment showed that there is some room for improvement in some elements including the fare collection system and potentially the signal system.

Seventh, impacts are required in the short term, which is very difficult to obtain with all-at-once implementation.

Finally, the success of full BRT, implemented all-at-once in Western Avenue is uncertain, and CTA should not run the risk of the first BRT being viewed as less than a complete success: The success of the first line will largely determine the prospects for further BRT lines throughout the city.

6.1.5 Step 5: Evaluate BRT components

The main objective at this point is to quantify the time saving benefits when improving the current configuration of each variable. The following sections study each of the critical variables of the components discussed. To identify the impact on time we first quantify the travel and running time for the current configuration of the application corridor.

Base case values can be obtained through direct measurement or modeling. In this case some basic variables were measured directly from operations, but the final figures resulted from applying those measured values to the models described in the previous section. The following base case values were the found for each time component. The assumptions for the calculations are also presented below.

- **Average Access Time: 3.7 min**
  - Average Stop Spacing 2953 ft (~900 m)
  - Catchment area radius R 0.25 mi (~400 m)

  The two contiguous bus lines are 0.5 mi (800 m) away on either side, and thus we assume that people distribute evenly to each corridor.

- Walking configuration Grid distance
- Walking probability Constant

- **Waiting time: 6.0 min**
- Average Operational Speed (weighted) 13 mi/hr (~ 20 km/hr)
- Expected unit distance running time \( E(t) = 4.8 \) min/mi (~ 3.0 min/km)
- Running time standard dev. \( \sigma(t) = 0.4 \) E(t) 1.9 min/mi (~ 1.2 min/km)
- Expected Headway \( E(h) = 10 \) min
- Length 18 mi (~ 29 km)
- Average boarding/alighting rate \( c = 3 \) sec/pass
- Dwell time Overhead \( (l) = 3 \) sec
- Passenger arrival rate \( \alpha_t = 0.6 \) pass/min
- Running time correlation factor \( \rho_r = 0.6 \)
- Loading correlation factor \( \rho_q = -0.4 \)

Traffic conditions are mostly stable, usually not very congested streets.

Some unevenness in loading distribution was observed, however it was not significant.

The operational speed of 13 mi/hr is the weighted average speed in the corridor, which considers distances for which the speed was achieved, and all time components (i.e. moving, dwell, and traffic delays). However, this operational speed does not consider the last two segments of the route (i.e. 79th – 87th – 95th) because while this stretch increases the average speed of the corridor significantly, the vast majority of the passengers in the direction being analyzed do not benefit from it. Considering the last two segments in the speed calculation would overestimate the actual speed experienced by a typical passenger.
Figure 6-10 shows the estimated waiting time for each stop along X49 for a bus from Berwyn to 95th street\textsuperscript{32}. The dashed line in the figure represents the resulting headway coefficient of variation (cov) for each stop. As expected, this coefficient of variation increases along the route, since it is assumed that no control is performed along the route. Its variation (ranging from 0.1 to 0.7) indicates that in fact the loading distribution in the buses should not be expected to be the same all along the route, thus for a more detailed analysis along the route, a varying $\rho_q$ should be applied.

![Waiting Time per stop for X49](image)

**Figure 6-10 Current waiting times along service X49**

In this case only one value of waiting time must be chosen to represent waiting time in the route, rather than using an average value, we have selected a representative

\textsuperscript{32} Waiting times estimated with equation 5.4 and the Adebisi model for headway variance, based on data characteristics collected on the field.
stop to evaluate and compare its variations on waiting time when varying the configuration of BRT components. The Madison St. stop was selected; it represents a stop with a fair number of transfers, and while its distance from the terminal allows for some headway variance to be observed, it is not very close to a supervisor point where the model will not reflect reality very accurately given the difference in control strategies—that assumed by the model and the real situation in Western Avenue, where supervisors control the route performance in between terminals.

- **In-vehicle time: 16.0 min**
  - Passenger trip length 3 mi (~4.8 km)
  - Moving speed $V_r$ 17.5 mi/hr (~28 km/hr)
  - Dwell time Overhead ($I$) 3 secs
  - Boarding passengers 4 pass/stop
  - Boarding service time 4 sec/pass
  - Alighting passengers 2 pass/stop
  - Alighting service time 1 sec/pass
  - No. of effective boarding doors 1
  - No. of effective alighting doors 1
  - Boarding/Alighting regime Consecutively
  - Traffic signal spacing 1152 ft (~350 m)
  - Average signal delay 30 sec
  - Traffic signal hit ratio 57%

Moving Speed is the weighted average speed that considers only the portions of the trip in which the bus is moving, it does not consider time spent at stops or at traffic signals. Similarly to the operational speed in waiting time, this speed does not consider the last two segments of the route, to avoid overestimation of the speed experienced by the typical user.
• **Total travel time** = access time + waiting time + in-vehicle time: 26 min

• **Running time**: 90 min
  - Trip length 18 mi (~29 km)
  - Moving speed $V_r$ 20 mi/hr (~32 km/hr)

In this case, all the segments are considered in the moving speed, and as expected its value is higher than the $V_r$ used for passengers. The resulting modeled running time is consistent with the scheduled running time for the route during peak periods of about 85 min.

**Degree of lane exclusivity**

This variable affects travel time -through waiting and in-vehicle time- and running time. Improving lane exclusivity from a mixed traffic configuration to preferential or exclusive lanes affects three specific variables in the waiting time model: operational speed, running time variation, and the running time correlation factor. The first three graphics of Figure 6-11 show the variation of waiting time as a result of changes in those variables. The thick black points represent the current configuration of X49 on Western Avenue. The last figure presents the range of waiting times that could be expected in each lane exclusivity configuration.

As observed, the expected impact on waiting time from increasing the operational speed beyond 20 km/hr is relatively small. In fact, the current speed of the X49 service is good in comparison with usual urban operations. Indeed, it is similar to that achieved on many of the exclusive lane buses in the Curitiba network.

Improvements in running time variation and correlation factor tend, as operational speed, to lower the 6-min waiting time to 5 min (1/2 the headway), which is the theoretical lower bound for 10-min-headway operations.
The impact on in-vehicle time comes from the improvement in moving speed. Figure 6-12 shows the expected reduction in in-vehicle time as moving speed increases. As in the waiting time vs operational speed case, it seems that the additional benefits given the base speed are relatively modest.

The in-vehicle time savings due to speed increments beyond 30 km/hr are small and in this particular case, the moving speed achieved in the corridor is already high, in fact it is typical of preferential or exclusive treatments rather than mixed traffic operations. Thus, moving towards a preferential lane would not provide significant in-vehicle time savings.
Figure 6-12 Impact of lane exclusivity on in-vehicle time

Current running time (~ 90 min), considering the length of the route is again more representative of preferential lanes treatment than a typical mixed traffic configuration. The magnitude of impact on running time is similar to that of in-vehicle time, as is shown in Figure 6-13.

Figure 6-13 Impact of lane exclusivity on running time
The combined effects of the variables presented result in the travel and running times presented in Table 6-3 for each higher degree of lane exclusivity.

Table 6-3 Expected reductions from lane exclusivity improvements

<table>
<thead>
<tr>
<th></th>
<th>Mixed traffic</th>
<th>Preferential lanes</th>
<th>Exclusive lanes at-grade</th>
<th>Grade separated exclusive lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access-time</td>
<td>3.7 min</td>
<td></td>
<td></td>
<td>No effects</td>
</tr>
<tr>
<td>Waiting Time</td>
<td>6.0 min</td>
<td>0% - 11%</td>
<td>11% - 13.5%</td>
<td>13.5% - 14%</td>
</tr>
<tr>
<td>In-vehicle Time</td>
<td>16.0 min</td>
<td>0% - 13%</td>
<td>13% - 34%</td>
<td>34% - 42%</td>
</tr>
<tr>
<td>Travel time</td>
<td>26 min</td>
<td>0% - 11%</td>
<td>11% - 25%</td>
<td>25% - 29%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26 - 23 min</td>
<td>23 - 20 min</td>
<td>20 - 18 min</td>
</tr>
<tr>
<td>Running time</td>
<td>90 min</td>
<td>0% - 5%</td>
<td>5% - 28%</td>
<td>28% - 36%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 - 85 min</td>
<td>85 - 64 min</td>
<td>64 - 57 min</td>
</tr>
</tbody>
</table>

In the table, reductions in running time differ from those observed in in-vehicle time. This effect is produced by the different speed assumed for each variable. As mentioned earlier, the route has a significantly higher speed between 79th street and 95th street. That segment was not considered to calculate in-vehicle time reductions for users because most of the passengers do not ride that segment in their typical trip. However, running time speed should include the segment, as it is part of every trip. As a result to impact running time in the same proportion of in-vehicle time a higher net absolute reduction is needed.

As observed in the previous table, improving the degree of lane exclusivity, especially to exclusive lanes, would have a significant impact (between 25% and 35%) on travel time and running time. However the costs of these enhancements are high, most likely the highest of all variables. Financial costs could vary from almost zero to about $10 M (at grade) – $30 M (intersection free) per mile. In the case of almost zero financial cost, we assume that the exclusive lane would be taken from one of the existing lanes on the Western Avenue and no further infrastructure work would be done. This option is
likely to have very high political cost, especially in this auto-oriented corridor, and in fact has never been followed in the US. In the case of $10M per mile, we are assuming that an at-grade lane would be built without mayor property acquisition but using some left turns, and parking space. In the case of $30M per mile we assume land acquisition and underpasses to avoid traffic lights.

In addition to the cost of the infrastructure it is difficult to justify the technical need for exclusive lanes on a corridor with 31,000 pass/day; the figure still appears to be low to justify a system that could carry 5 to 10 times as much. Furthermore, when current travel speeds are high compared to typical urban routes.

Intermediate options in terms of financial cost and opposition should be sought. The main alternative is to use low cost lane exclusivity interventions, such as the one described above, using existing lanes with some potential refurbishments, but dedicating them only partially to buses, such as the preferential lanes treatment, to avoid strong political opposition. Preferential lanes may reduce X49 passengers travel time by around 5%, but will have lower impact on running time. However, a preferential treatment will provide the express route with some image and permanence that may be able to attract more riders from the local 49 route. In that case, the average travel time reduction per passenger would be higher.

Degree of guidance

Guidance would only become a feasible option under an exclusive lane configuration, which is not strongly recommended for Western Avenue given the current speed and ridership. In case of defining the need for exclusive lanes, guidance systems could reduce the cross-section needed by 3 feet for each bus lane.

Stop Spacing
Stop spacing affects all variables considered; however its effect on waiting time is small and also depends more on the regularity of stop spacing than the average spacing itself, and thus we consider it negligible in this analysis.

The effect on access time is shown in Figure 6-14. The continuous line shows the effect when incrementing stop spacing from current value of 900 meters, the dashed line shows the impact when reducing stop spacing. As observed in the figure, increasing stop spacing will not affect average access time since the catchment areas assumed are not overlapping due to the high spacing; however increasing stop spacing will reduce corridor coverage even further. In fact, the area covered by the catchment areas of X49 stops is only 60% of the corridor that would be covered by closer stations (400 – 500 meters) or lower like the 49 service. Increasing stop spacing, from an access time standpoint is not recommended in this case.

![Impact of Stop Spacing on Access Time](image)

**Figure 6-14 Impact of stop spacing on access time**

Reducing the stop spacing, which may seem counterintuitive when CTA is carrying out a project to increase stop spacing in many of its routes, might in fact be a better
strategy to improve ridership levels on the X49; as long as it does not increase travel time significantly. The impact of stop spacing on in-vehicle time is presented in Figure 6-15.

![Stop spacing impact on passenger in-vehicle time](image)

**Figure 6-15 Impact of Stop Spacing in In-vehicle Time**

As observed in the previous figure increasing stop spacing would not affect in-vehicle time significantly, which reinforces the recommendation of not increasing stop spacing. On the other hand, reducing stop spacing from 900 meters to 400 meters increases in-vehicle time from 16 min to 18.3 min. In this case, the benefits would come from lower access times and greater coverage.

Impact on running time is similar to that on in-vehicle time and is shown on Figure 6-16. The marginal running time saving from increasing stop spacing beyond 900 meters is very small.
Table 6-4 summarizes the expected impact on travel time and running time from increasing stop spacing to 1200 and 1500 meters, and decreasing it to 600 and 300 meters. A negative sign in the table indicates that instead of a reduction in time, an increment should be expected. The values in the table indicate that increasing stop spacing further will not have significant benefit on travel time and running time and will further reduce coverage. Reducing stop spacing to 600 meters, would reduce access time by 21% and increase coverage while increasing in-vehicle time by 6%, which results in a negligible effect on total travel time of 0.6%. Running time, however, is expected to increase by 7%. Impacts when stop spacing is reduced to 300 meters are too significant (10% on travel time and 27% on running time) to consider it a viable strategy.
Table 6-4 Expected time reductions from changes on stop spacing

<table>
<thead>
<tr>
<th>Stop Spacing (m)</th>
<th>Access-time (%)</th>
<th>Waiting Time</th>
<th>In-vehicle Time</th>
<th>Travel Time</th>
<th>Running Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>34%</td>
<td>Negligible effects</td>
<td>-23%</td>
<td>28 min</td>
<td>114 min</td>
</tr>
<tr>
<td>600</td>
<td>21%</td>
<td>Negligible effects</td>
<td>-6%</td>
<td>25.8 min</td>
<td>96 min</td>
</tr>
<tr>
<td>900</td>
<td>0%</td>
<td>Negligible effects</td>
<td>16.0 min</td>
<td>26 min</td>
<td>90 min</td>
</tr>
<tr>
<td>1200</td>
<td>0%</td>
<td>Negligible effects</td>
<td>3%</td>
<td>25.1 min</td>
<td>87 min</td>
</tr>
<tr>
<td>1500</td>
<td>0%</td>
<td>Negligible effects</td>
<td>5%</td>
<td>24.9 min</td>
<td>85 min</td>
</tr>
</tbody>
</table>

The infrastructure cost of reducing stop spacing is very low for the CTA, since it only involves signage cost. If shelters are desired, the new stops could be part of the shelter deployment program led by the city.

**Boarding level**

Boarding level is the first of the “dwell time variables”, which also include the number of effective doors in the vehicle for boarding and alighting, the transaction location, and the payment media. All of them affect waiting time, in-vehicle time, and running time, and have negligible effect on access time.

As shown in Figure 6-6, route X49 dwell time represents a small portion of total travel time, thus we should not expect a great impact on travel time or running time from improvements in these variables.

From a boarding level standpoint, currently the route is served by some buses with vertical and horizontal gap (High-floor Flexible), and by some with only horizontal gap (Low-floor Flyer). Feasible potential improvements to this variable would be to achieve a 100% low-floor fleet, or to upgrade to full level boarding or no-gap (either vertical or horizontal). The latter option is reasonable under a pre-payment configuration, otherwise the bottleneck is still the payment transaction and we could not take full advantage of the
benefits of level boarding. In fact, the first option is actually the one currently being followed by the CTA; a dedicated fleet for the express corridors is under way, which features low floor amongst its characteristics.

Alighting service time has been consistently measured at between 1 and 1.5 sec/pass for both conventional high-floor buses and low-floor buses (Cundill and Watts, 1973; Kraft and Bergen, 1974; Vandebona and Richardson, 1985; King, 1998). Level boarding and alighting measurements for buses are rare but Bogotá and Curitiba systems have achieved alighting times of 0.35 and 0.5 sec/pass, respectively ("Transmilenio Volumen V: Plan de Operación," 1999) with multiple doors.

Boarding service times range more widely within the three possible configurations. Step boarding times are usually between 8 and 3 sec/pass (Cundill and Watts, 1973; Kraft and Bergen, 1974; Hoey and Levinson, 1975; Vandebona and Richardson, 1985). Reductions in boarding times due to the use of low-floor instead of high-floor vehicles have been reported between 0.2 and 1.0 sec (King, 1998). For level boarding in buses, alighting times of 0.35 sec/pass have been reported in Transmilenio, with pre-payment and multiple doors used. Level boarding times could be modeled using boarding times observed in rapid rail systems, which vary between 1.0 and 2.0 sec/pass("Transit Capacity and Quality of Service Manual," 1999). With the previous information and data collected from X49 service, we assume the following service times, to analyze boarding level impact:
Table 6-5 Service times assumed for X49 boarding level improvements

<table>
<thead>
<tr>
<th></th>
<th>Step boarding &amp; Level boarding with gap</th>
<th>All Level boarding w/ gap (Horizontal gap)</th>
<th>Level boarding* (No gap)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boarding $c_i$</td>
<td>4.0 sec/pass</td>
<td>3.0 – 3.8 sec/pass</td>
<td>0.4 - 1.0 sec/pass</td>
</tr>
<tr>
<td>Alighting $c_o$</td>
<td>1.0 sec/pass</td>
<td>same</td>
<td>0.4 - 1.0 sec/pass</td>
</tr>
<tr>
<td>Mixed $c$</td>
<td>2.4 sec/pass</td>
<td>2.0 – 2.4 sec/pass</td>
<td>0.4 - 1.0 sec/pass</td>
</tr>
<tr>
<td>Overhead $/\ell$</td>
<td>3.0 sec/stop</td>
<td>same</td>
<td>same</td>
</tr>
</tbody>
</table>

* Assumes other improvements as well like pre-payment and multiple boarding doors

Table 6-6 summarizes the impact on travel and running time from changes in the boarding level. The values indicate that, with everything else being equal, an implementation of a 100% low-floor fleet will not have significant impact on travel and running time. The benefits from such implementation would come from more qualitative perceptions of the users than real time savings. Moving forward, towards a full level boarding configuration, impact although still not very significant are around 5 and 8%. However, the higher end of those savings assumes other features as well, such as pre-payment and multiple door boarding.

Table 6-6 Expected impact from boarding level improvements

<table>
<thead>
<tr>
<th></th>
<th>Step boarding &amp; Level boarding with gap</th>
<th>All Level boarding w/ gap (Horizontal gap)</th>
<th>Level boarding* (No gap)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access-time</td>
<td>3.7 min</td>
<td>No effects</td>
<td></td>
</tr>
<tr>
<td>Waiting Time</td>
<td>6.0 min</td>
<td>0 % - 1%</td>
<td>3% - 4%</td>
</tr>
<tr>
<td>In-vehicle Time</td>
<td>16.0 min</td>
<td>0.4% - 2.2%</td>
<td>6.6% - 8%</td>
</tr>
<tr>
<td>Travel time</td>
<td>26 min</td>
<td>0.3% - 1.5%</td>
<td>5% - 6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.5 – 25.0 min</td>
<td>24.5 – 24.0 min</td>
</tr>
<tr>
<td>Running time</td>
<td>90 min</td>
<td>0.5% - 2.5%</td>
<td>7.0% - 8.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>89 – 88 min</td>
<td>83 – 82 min</td>
</tr>
</tbody>
</table>
**Transaction location**

Transaction location is also a variable affecting dwell time. Its original spectrum included the alternative of a collector on-board, however that alternative is not considered in the following analysis because it is an infeasible option given the already high personnel costs for the CTA and the projects under way that seek to upgrade the fare collection process through technology. Therefore, the potential improvements for the X49 service, from a transaction location standpoint, are to move to a 100% on-board farebox (eliminating the alternative of obtaining cards with value from the driver) or moving to off-vehicle fare payment.

Table 6-7 shows the values assumed for passenger service times to analyze impacts from payment location improvements. The times are based in previous studies and experiences (Cundill and Watts, 1973; Kraft and Bergen, 1974; Okrent, 1974; Hoey and Levinson, 1975; Hendrickson, 1981; Levinson, 1983; Vandebona and Richardson, 1985; Levine and Torng, 1994; King, 1998; "Transmilenio Volumen V: Plan de Operación," 1999).

**Table 6-7 Assumed passenger service times for payment location improvements**

<table>
<thead>
<tr>
<th></th>
<th>Driver and On-board farebox</th>
<th>On-board farebox</th>
<th>Off-vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boarding $c_t$</td>
<td>4.0 sec/pass</td>
<td>2.5 – 4.0 sec/pass</td>
<td>0.4 – 2.5 sec/pass</td>
</tr>
<tr>
<td>Alighting $c_o$</td>
<td>1.0 sec/pass</td>
<td>same</td>
<td>0.4 - 1.0 sec/pass</td>
</tr>
<tr>
<td>Mixed $c$</td>
<td>2.4 sec/pass</td>
<td>1.6 – 2.4 sec/pass</td>
<td>0.4 - 1.6 sec/pass</td>
</tr>
<tr>
<td>Overhead $/l$</td>
<td>3.0 sec/stop</td>
<td>same</td>
<td>same</td>
</tr>
</tbody>
</table>

Table 6-8 summarizes the impact from fare payment location on travel and running time. As with the previous variable, maximum time reductions are about 6% for travel time and 8% in running time. The feasible short to medium term improvement for CTA would be to encourage more cash users to pay exact fares on-board or use the cards, in which case the impact would be a reduction in travel and running time of only about 3%.
### Table 6-8 Expected impact from fare payment location improvements

<table>
<thead>
<tr>
<th></th>
<th>Driver and On-board farebox</th>
<th>On-board farebox</th>
<th>Off-vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access-time</td>
<td>3.7 min</td>
<td>No effects</td>
<td></td>
</tr>
<tr>
<td>Waiting Time</td>
<td>6.0 min</td>
<td>0% - 3%</td>
<td>3% - 8%</td>
</tr>
<tr>
<td>In-vehicle Time</td>
<td>16.0 min</td>
<td>0% - 3%</td>
<td>3% - 8%</td>
</tr>
<tr>
<td>Travel time</td>
<td>26 min</td>
<td>0% - 2.5%</td>
<td>2.5% - 6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26 - 25 min</td>
<td>25 - 24 min</td>
</tr>
<tr>
<td>Running time</td>
<td>90 min</td>
<td>0% - 3.6%</td>
<td>7.0% - 8.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 - 87 min</td>
<td>87 - 82 min</td>
</tr>
</tbody>
</table>

**Payment media**

Payment media is another "dwell time variable". Its spectrum of alternatives includes contact smart-cards, which will be excluded from this analysis because the CTA has already made the decision to move forward with contact-less smart-cards. In addition, passenger service rates resulting from contact smart-cards operations are very similar to magnetic stripe rates. Currently CTA operates with cash and magnetic stripe cards. Its potential improvements consist on implementing 100% magnetic cards, a mix of magnetic cards and contact-less smart cards, or 100% smart cards. As mentioned earlier, CTA is deploying contact-less smart cards in the system (without discontinuing the use of cash), and thus in the medium-term, the expected fare collection media will be a mix of cash, magnetic cards, and contact-less smart cards.

For this variable, in addition to the studies of the impact of fare-collection systems in transit operations, we rely on an internal CTA study conducted to determine the boarding rates when using different payment media. The results shown in Table 6-9 measured transaction times through two methodologies. Methodology a measured the time required to complete 30 transactions; methodology b measured total transactions in
one minute. The rates resulting from test method b are more consistent with other literature results and with the data collected for this thesis. It is worth noting the small difference found between magnetic cards and contact-less SmartCards when most literature argues that boarding rates resulting from each media are significantly different. These figures, however, are not surprising because everything else being equal – that is the boarding level, the number of doors, and the transaction location- we should not expect great effect in boarding rates. Contact-less SmartCards are usually identified with higher rates, however that is generally assuming at least level boarding, but also often pre-payment and multiple doors.

**Table 6-9 CTA boarding rates (transactions per minute) by fare media**

<table>
<thead>
<tr>
<th></th>
<th>Cash</th>
<th>Magnetic Cards</th>
<th>Contact-less SmartCards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test a&lt;sup&gt;(a)&lt;/sup&gt;</td>
<td>12.5</td>
<td>16.4</td>
<td>17.5</td>
</tr>
<tr>
<td>Test b&lt;sup&gt;(b)&lt;/sup&gt;</td>
<td>14.2</td>
<td>26.1</td>
<td>28.1</td>
</tr>
</tbody>
</table>

(a) Measurement method: time required to achieve 30 transactions  
(b) Measurement method: Total transactions per minute

Based on the previous information, Table 6-10 shows the service times assumed to analyze impacts from payment media improvements.

**Table 6-10 Assumed passenger service times for payment media improvements**

<table>
<thead>
<tr>
<th></th>
<th>Cash/Magnetic Cards</th>
<th>Magnetic Cards</th>
<th>Contact-less SmartCards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boarding $c_i$</td>
<td>4.0 sec/pass</td>
<td>3.0 – 4.0 sec/pass</td>
<td>2.0 – 3.0 sec/pass</td>
</tr>
<tr>
<td>Alighting $c_o$</td>
<td>1.0 sec/pass</td>
<td>same</td>
<td>same</td>
</tr>
<tr>
<td>Mixed $c$</td>
<td>2.4 sec/pass</td>
<td>2.0 – 2.4 sec/pass</td>
<td>1.5 – 2.0 sec/pass</td>
</tr>
<tr>
<td>Overhead $l$</td>
<td>3.0 sec/stop</td>
<td>same</td>
<td>same</td>
</tr>
</tbody>
</table>

Table 6-11 summarizes the impact expected from changes in the payment media. In general, savings are not significant, typically up to 3.5% for travel time and 5% for running time.
Table 6-11 Expected time reductions from payment media improvements

<table>
<thead>
<tr>
<th></th>
<th>Cash/Magnetic Cards</th>
<th>Magnetic Cards</th>
<th>Contact-less Smart-Cards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access-time</td>
<td>3.7 min</td>
<td>No effects</td>
<td></td>
</tr>
<tr>
<td>Waiting Time</td>
<td>6.0 min</td>
<td>0% - 1%</td>
<td>1% - 2%</td>
</tr>
<tr>
<td>In-vehicle Time</td>
<td>16.0 min</td>
<td>0% - 2%</td>
<td>2% - 4.5%</td>
</tr>
<tr>
<td>Travel time</td>
<td>26 min</td>
<td>0% - 1.5%</td>
<td>1.5% - 3.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26 – 25 min</td>
<td>25 – 24 min</td>
</tr>
<tr>
<td>Running time</td>
<td>90 min</td>
<td>0% - 2.4%</td>
<td>2.4% - 4.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 – 87.5 min</td>
<td>87.5 – 85.5 min</td>
</tr>
</tbody>
</table>

**Vehicle Capacity**

Vehicle capacity is a critical variable for service components such as frequency. In terms of infrastructure components, it should only affect waiting time significantly, and that is when passengers are left behind due to lack of capacity in the bus. For the X49 routes there are no vehicle capacity issues, since it is a route with a 10-minute headway, 6,000 pass/day, and 40-feet buses.

As mentioned earlier, the CTA is planning on deploying a dedicated fleet on all express corridors including Western Avenue. The new composite-material buses are 45-feet long and with a slightly higher capacity.

In conclusion, vehicle capacity is not a constraining variable for routes X49 and 49. In addition, a decision has already been made regarding the type of fleet that will soon operate on the route, which from a travel and running time perspective will have little impact.
No. of doors

The number of doors in the vehicle refers specifically to those doors that are effectively being used for boarding and alighting. Since boarding rates are usually higher than alighting rates, introducing an additional boarding door is usually more effective in reducing dwell time than introducing an additional alighting door. However, adding a boarding door usually represents a more complicated change in terms of the fare-collection strategy (i.e. pre-payment or proof of purchase).

Despite its relatively low impact, introducing an additional alighting door is a strategy that could be implemented at very little cost in US operations, since the rear door exists but is seldom used.

The number-of-doors could go as high as 4 or 5 doors, however, short and medium term strategies in the CTA should use the fixed resources available, which are 2-door vehicles. The analysis then is performed for a 2-door potential boarding and/or alighting operation. The assumed values are presented in Table 6-12. Although CTA buses have 2 doors, we consider the current situation closer to one door for both alighting and boarding, since the rear door is seldom used on low ridership routes such as X49.

Table 6-12 Assumed passenger service times for No. of doors improvements

<table>
<thead>
<tr>
<th></th>
<th>1 boarding and alighting</th>
<th>1 boarding and alighting + 1 alighting</th>
<th>2 boarding and alighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boarding $c_i$</td>
<td>4.0 sec/pass</td>
<td>3.5 - 4.0 sec/pass</td>
<td>2.0 - 2.5 sec/pass</td>
</tr>
<tr>
<td>Alighting $c_o$</td>
<td>1.0 sec/pass</td>
<td>0.7 - 0.8 sec/pass</td>
<td>0.7 - 0.8 sec/pass</td>
</tr>
<tr>
<td>Mixed $c$</td>
<td>2.4 sec/pass</td>
<td>2.2 - 2.4 sec/pass</td>
<td>1.2 - 1.8 sec/pass</td>
</tr>
<tr>
<td>Overhead $I$</td>
<td>3.0 sec/stop</td>
<td>same</td>
<td>same</td>
</tr>
</tbody>
</table>

Table 6-13 summarizes the impact on travel and running time from changing the effective number of doors used for boarding and alighting. Similar to previous “dwell time variables” its isolated implementation results in a negligible impact. It is worth...
noting that a more consistent use of the rear door in this case does not produce significant time savings. Despite a significant reduction in individual service times, ridership is not sufficient to produce a large impact on dwell time.

Table 6-13 Expected time reductions from changes to the number of doors

<table>
<thead>
<tr>
<th></th>
<th>1 boarding and alighting</th>
<th>1 boarding and alighting + 1 alighting</th>
<th>2 boarding and alighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access-time</td>
<td>3.7 min</td>
<td>No effects</td>
<td></td>
</tr>
<tr>
<td>Waiting Time</td>
<td>6.0 min</td>
<td>0% - 0.5%</td>
<td>1.5% - 2.8%</td>
</tr>
<tr>
<td>In-vehicle Time</td>
<td>16.0 min</td>
<td>0% - 1.1%</td>
<td>3.3% - 4.4%</td>
</tr>
<tr>
<td>Travel time</td>
<td>26 min</td>
<td>0% - 0.8%</td>
<td>2.4% - 3.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26 - 25.4 min</td>
<td>25 - 24.7 min</td>
</tr>
<tr>
<td>Running time</td>
<td>90 min</td>
<td>0% - 1.2%</td>
<td>3.6% - 4.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 - 88.6 min</td>
<td>86.5 - 85.4 min</td>
</tr>
</tbody>
</table>

**Signal priority method**

Changing the signal priority method would affect four variables: operational speed, the running time variation, the average signal delay, and the signal hit ratio. Table 6-14 presents the values assumed for these variables under each of the potential signal priority configurations.

Table 6-14 Values assumed for signal priority variables

<table>
<thead>
<tr>
<th></th>
<th>Passive priority</th>
<th>Queue jumping</th>
<th>Unconditional priority</th>
<th>Conditional priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational Speed</td>
<td>20 km/hr</td>
<td>20 - 25 km/hr</td>
<td>25 - 35 km/hr</td>
<td>25 - 30 km/hr</td>
</tr>
<tr>
<td>Running time standard deviation</td>
<td>0.4 E(t)</td>
<td>0.4 E(t)</td>
<td>0.4 E(t)</td>
<td>0.1 - 0.3 E(t)</td>
</tr>
<tr>
<td></td>
<td>1.2 min/km</td>
<td>1.2 min/km</td>
<td>1.2 min/km</td>
<td>1.2 min/km</td>
</tr>
<tr>
<td>Average signal delay</td>
<td>30 sec</td>
<td>15 - 25 sec</td>
<td>20 - 25 sec</td>
<td>20 - 25 sec</td>
</tr>
<tr>
<td>Signal hit ratio</td>
<td>57%</td>
<td>57%</td>
<td>2% - 10%</td>
<td>30% - 50%</td>
</tr>
</tbody>
</table>
Table 6-15 summarizes the expected reductions in travel and running time resulting from an improvement to the current signal priority method. As observed, the impact is more significant than that observed with the previous variables.

### Table 6-15 Expected impact from improvements to signal priority method

<table>
<thead>
<tr>
<th></th>
<th>Passive priority</th>
<th>Queue jumping</th>
<th>Unconditional priority</th>
<th>Conditional priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access-time</td>
<td>3.7 min</td>
<td>No effects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waiting Time</td>
<td>6.0 min</td>
<td>0% - 5%</td>
<td>5.2% - 9.8%</td>
<td>9.3% - 14%</td>
</tr>
<tr>
<td>In-vehicle Time</td>
<td>16.0 min</td>
<td>14% - 21%</td>
<td>29% - 32%</td>
<td>16% - 24.5%</td>
</tr>
<tr>
<td>Travel time</td>
<td>26 min</td>
<td>9% - 15%</td>
<td>19% - 22%</td>
<td>12% - 18.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23 – 22 min</td>
<td>21 – 20 min</td>
<td>22.5 – 21 min</td>
</tr>
<tr>
<td>Running time</td>
<td>90 min</td>
<td>7% - 16%</td>
<td>24.5% - 27.6%</td>
<td>9.7% - 19.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>83 – 76 min</td>
<td>68 – 65 min</td>
<td>81 – 72 min</td>
</tr>
</tbody>
</table>

Queue jumping itself offers an average reduction of 12% on travel and running time. However, its implementation may incur a high infrastructure cost to provide the jumper or high political costs to use infrastructure currently utilized by cars. In addition, its operation faces enforcement problems.

As expected unconditional priority results in more time savings than conditional priority. However, the advantage of conditional priority is its ability to control vehicles and improve schedule adherence.

The results are similar to that of a transit signal priority study performed in Western Avenue in 2001 ("Western Avenue Traffic Signal Priority Feasibility Study," 2001), which found average travel time savings of 15%.
6.1.6 Step 6: Prioritize BRT components

The main objective of this step is to create an implementation priority list of components based on the benefits identified in the previous section and their infrastructure and technology costs. The components are:

- Exclusive lanes
- Guidance system
- Stop spacing
- Boarding level
- Transaction location
- Payment media
- Vehicle capacity
- Number of doors
- Signal priority method

Based on the results from the previous section, two these variables will not be considered for further analysis or implementation: guidance system, and vehicle capacity. The guidance system is not considered for further analysis because its impacts are uncertain at this time, and furthermore, its implementation depends largely on the degree of exclusivity recommended, which at this point does not appear to be high. Vehicle capacity is not a concern in the route, and furthermore, it is a decision the CTA already made, which will have little impact on travel and running time.

Stop spacing will not be analyzed under the same framework as the other variables because the benefit analysis in this thesis focuses on travel time savings, and the recommendation, although counterintuitive at first, would be to reduce stop spacing and thus most probably increase travel time slightly. This recommendation follows from the findings that increasing stop spacing in the X49 service will not reduce significantly travel time and at the same time will decrease coverage further. Ridership being one of
the main concerns for this route, improving the catchment area of the route may be one of the most effective short-term improvements to tackle this issue. The exact benefits obtained from reducing stop spacing need further research and more exact evaluation of the corridor. These benefits would materialized in the form of higher ridership and thus it would be difficult to compare with the time-savings framework developed in this thesis.

Figure 6-17 shows the impact on travel and running time from each identified variable alternative. Each variable alternative has two associated columns, one for travel time and the other for running time. The columns represent the change from the current time that would result from such an implementation.

![Impact of different BRT variables on Travel and Running Time](chart)

Figure 6-17 Summary of travel and running time impact from feasible variables

As observed, lane exclusivity and signal priority present the highest potential for time reduction – 20% to 35% reductions from current time. Dwell time variables (i.e.
boarding level, payment location, payment media, and no. of doors) result in travel time reductions of less than 10%. Two issues are worth noting on the dwell time variables impact. First their isolated impact is low as shown in the figure, however, their combined effect might be more significant. For example, combining off-vehicle fare payment, level boarding, and multiple door boarding. Second, the low impact in this particular route also results from the low ridership levels of the route, and thus the small portion of time that is taken by dwell activities, compared to moving or signal time. Dwell time improvements do not affect local 49 service. Lane exclusivity and signal priority have the potential to have greater impact than that indicated here because they would also affect local 49; signal priority by giving local service 49 the possibility of having signal priority at low marginal cost. Lane exclusivity because the impact would be so significant that we would expect some ridership shift between services.

The final prioritization of components, however, must consider the costs required in each case to achieve the expected time benefits. There are many costs that could be accounted for in the implementation of these components; however, since many of them (e.g. political, social) are intangibles, we will only consider the financial costs of the infrastructure and technology.

Table 6-16 shows the costs calculated for each variable alternative. These costs are not for general use since they consider and reflect the specific situation for CTA and on Western Avenue. For example the cost of moving to contact-less smart cards does not consider the cost of the readers since all CTA buses already have them.

The lane exclusivity variable assumes new lanes for the improvement alternatives, at a cost of $8 M/mile for preferential lanes, $10 M/mile for exclusive lanes at grade, and $30 M/mile for grade separated exclusive lanes.

For boarding level we used a cost per low-floor bus of $300,000 assuming that all 21 buses that serve the route would be newly bought for the route. However, CTA could
decide to implement these measures without buying new equipment but ensuring that only existing low-floor buses would be schedule for the route. In the first case only the cost of the buses is considered. In the second case (level boarding) in addition to the buses the cost includes renovating the sidewalks and creating modest platforms to ensure level boarding at $18,000 per stop.

For some variables (use of on-board farebox, use of magnetic cards, use of contactless smart cards, and use of the rear door) the only costs assumed were those of enforcement and marketing initiatives since the infrastructure and technology already exists at CTA.

**Table 6-16 Costs to implement feasible variable alternatives in Western corridor**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Alternative</th>
<th>Cost</th>
<th>% reduced travel time</th>
<th>% reduced running time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane exclusivity</td>
<td>Preferential lanes</td>
<td>144,000,000</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>Excl. lanes at grade</td>
<td>180,000,000</td>
<td>18%</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>Grade separated excl. lanes</td>
<td>540,000,000</td>
<td>27%</td>
<td>32%</td>
</tr>
<tr>
<td>Boarding level</td>
<td>Low-floor with horizontal gap</td>
<td>6,300,000</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Level boarding</td>
<td>7,452,000</td>
<td>5%</td>
<td>8%</td>
</tr>
<tr>
<td>Payment location</td>
<td>Farebox</td>
<td>500,000</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Off-vehicle</td>
<td>N/A</td>
<td>6%</td>
<td>5%</td>
</tr>
<tr>
<td>Payment media</td>
<td>Magnetic card</td>
<td>500,000</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Contact-less card</td>
<td>500,000</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>No. of doors</td>
<td>1 on &amp; off + 1 off</td>
<td>500,000</td>
<td>0%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>2 on &amp; off</td>
<td>N/A</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>Signal priority</td>
<td>Queue jumping</td>
<td>19,400,000</td>
<td>12%</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>Unconditional priority</td>
<td>1,037,667</td>
<td>21%</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>Conditional priority</td>
<td>1,086,000</td>
<td>15%</td>
<td>15%</td>
</tr>
</tbody>
</table>

The cost of off-vehicle fare payment and the use of two boarding doors are difficult to establish, since there are different paths to implement them with a wide range of costs.
depending on their nature. For example some paths could depend on labor and others on technology to achieve the improvements. A more detailed study would be needed to determine the magnitude of the costs of such initiatives at the CTA.

To establish queue jumping costs, we assumed a cost of $200,000 for each signalized intersection. However, the queue jumpers could be implemented only at critical intersections. The cost of unconditional priority are based on the cost estimates for transit signal priority for Western Avenue ("Western Avenue Traffic Signal Priority Feasibility Study," 2001), which indicates an average of $4,000 per intersection and $31,000 per bus to implement the system. In the case of conditional priority, the cost of the intersection equipment is slightly higher.

The cost of reducing travel and running time by 1% through each of the variable alternatives is presented in Table 6-17 and shown graphically in Figure 6-18. In Figure 6-18 the cost axis was cut at $14 M to have a more appropriate scale for the lower cost variables. In this figure a shorter bar indicates a more cost-effective measure since less money is needed to reduce travel or running time by 1%. 

209
### Table 6-17 Cost of reducing travel and running time by each alternative

<table>
<thead>
<tr>
<th>Variable</th>
<th>Alternative</th>
<th>Cost of 1% reduction in</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Travel Time</td>
</tr>
<tr>
<td>Lane exclusivity</td>
<td>Preferential lanes</td>
<td>27,197,089</td>
</tr>
<tr>
<td></td>
<td>Excl. lanes at grade</td>
<td>10,245,108</td>
</tr>
<tr>
<td></td>
<td>Grade separated excl. lanes</td>
<td>20,040,932</td>
</tr>
<tr>
<td>Boarding level</td>
<td>Low-floor with horizontal gap</td>
<td>4,343,937</td>
</tr>
<tr>
<td></td>
<td>Level boarding</td>
<td>1,383,389</td>
</tr>
<tr>
<td>Payment location</td>
<td>Farebox</td>
<td>225,675</td>
</tr>
<tr>
<td></td>
<td>Off-vehicle</td>
<td>N/A</td>
</tr>
<tr>
<td>Payment media</td>
<td>Magnetic card</td>
<td>453,224</td>
</tr>
<tr>
<td></td>
<td>Contact-less card</td>
<td>187,480</td>
</tr>
<tr>
<td>No. of doors</td>
<td>1 on &amp; off + 1 off</td>
<td>1,222,414</td>
</tr>
<tr>
<td></td>
<td>2 on &amp; off</td>
<td>N/A</td>
</tr>
<tr>
<td>Signal priority</td>
<td>Queue jumping</td>
<td>1,662,236</td>
</tr>
<tr>
<td></td>
<td>Unconditional priority</td>
<td>50,077</td>
</tr>
<tr>
<td></td>
<td>Conditional priority</td>
<td>70,203</td>
</tr>
</tbody>
</table>
The extremely high cost of the exclusive lane alternatives could be lowered dramatically by using existing lanes, and thus trading infrastructure cost for political cost. Furthermore, the political cost could also be offset in the case of preferential lanes by allowing some use of the lane by certain vehicles, such as right turning vehicles, vehicles accessing the parking lane, other public transportation vehicles, such as taxis, and emergency vehicles. This alternative will be included in the following analysis, of lower cost, intermediate strategies.

As mentioned earlier the high cost of the boarding level alternatives could also be decreased by using existing low-floor fleet. Considering the previous observations, Figure 6-19 presents a smaller set of alternatives, which we consider more plausible for the current conditions of the route and constitutes the basis for the priority list.
Figure 6-19 Cost of reducing running and travel time by 1% (alternative 2)

Figure 6-19 includes two preferential lane alternatives: Alternative 1 assumes an investment of US$250,000 per mile and Alternative 2 assumes twice as much (US$500,000). The first alternative represents a low-cost preferential lane investment to repave the road and do minor civil works and curb corrections. The second alternative includes additionally public space enhancements and stop amenity improvements. Both alternatives would be able to achieve travel time reductions of about 5% and running time reductions of approximately 6%. However, the second alternative would certainly provide benefits which are difficult to quantify such as image, permanence, style, which usually result in higher ridership.

A 1% reduction on travel time represents a savings of 16 seconds per trip and a 1% reduction on running time represents a savings of 1 min per trip on the X49 corridor.
However, implementing some of the strategies will have an effect on the local 49 route as well, and thus its prioritization should reflect this. For example, a preferential lane treatment is a strategy that will most probably encourage a shift from local 49 users, as it is a clear visual improvement. On the other hand, using all low-floor buses, encouraging contact-less smart card usage, or allow rear door entry, are strategies that could be implemented to affect only one of the routes.

If an incremental and discrete approach were to be followed by the CTA to improve service on route X49, two groups of actions can be identified. The first group is a shorter term (1 – 3 years) strategy, the second group represents the higher cost variables which would be implemented in 3 – 6 years.

1. First phase
   - Stop spacing: reduce stop spacing to at least 500 meters
   - Low-floor buses: assign only low-floor buses to the route
   - Fare collection: encourage users to use the farebox -without interacting with the driver- as much as possible
   - Signal priority: implement conditional or unconditional priority, the best alternative from a time savings standpoint would be unconditional priority; however more detailed analysis for each should be made to account for the schedule adherence capabilities of conditional priority.
   - Implement preferential treatment on existing lanes
   - Improve the payment media, the first option would be to use contact-less smart cards as much as possible, and then magnetic card

2. Second phase
   - Off-vehicle fare payment: establish mechanisms to collect fares prior to boarding the vehicle. It could be done with infrastructure or proof-of-payment, but the second is preferred
Exclusive lanes: in the long-term and depending on the success and ridership of the preferential lanes, exclusive lanes implementation should be analyzed

6.2 Recommendations

From a pure travel time savings standpoint, signal priority measures appear to be the most cost-effective BRT component to improve service in the X49 route. However, considering other benefits not strictly included in this framework, such as coverage and the ability to benefit riders from the local 49 service as well, and the feasible implementation feasibility time frame of each variable, two phases are recommended to move towards better quality bus service in the Western Corridor.

The first or short term phase which corresponds to variables that could be implemented within 1 – 3 years. First are those within the control of the agency and likely to affect only X49 users, unless they are also applied to the local 49 route. In the first phase, the recommended variables to be implemented are:

- Reduced stop spacing. This would increase the market for the X49 and increase overall benefits. It does not apply to the local 49 service.
- Low-floor buses
- Expedite the fare collection process by encouraging wider use of transit cards

The second group for the first implementation phase involve more complex implementation strategies because they require system-wide changes (smart-cards), are likely to encounter opposition (preferential lanes) or require a significant amount of inter-agency coordination. The recommended actions are:

- Signal priority
- Preferential lanes running on existing lanes
- Contact-less smart cards

The second implementation phase corresponds to variables that could be implemented in the medium term, 3 – 5 years and include:
- Off-vehicle fare payment
- Exclusive lanes

A more detailed analysis is needed to establish the specific cost effectiveness of travel time savings for two measures: off-vehicle fare payment and multiple door boarding. Specific design information on the methodology to achieve these attributes would be necessary. However, given the small contribution of dwell time to total time they are not expected to have a different magnitude of impact than the other dwell time variables, unless they are implemented in the local 49 route as well.

Improvements to the signal priority system, could produce benefits at a low marginal cost to local route 49. Therefore, those benefits should be accounted for in an evaluation of the implemented measure.

BRT components might be desired features for Western Avenue, however, current condition points to smaller actions that could be taken to improve service in the corridor

- With current stop spacing, the X49 stops cover only 60% of the influence area of Western Avenue. Thus reducing stop spacing to increase coverage could increase ridership and produce shift of some passengers from local 49 to X49.
- Even though construction work was taking place at the corridor, running times still seemed to be high, and drivers needed to slow down below their potential speed to meet the time points. Therefore, adjusting running times, and have fewer and/or tighter time points may improves route speed and decreases travel and running time.
- X49 drivers consistently stay behind local 49 buses, as a result the express service is not as fast as it could be. We recommend to provide special training to X49 drivers to pass local 49 buses
- Buses are very often caught on extra red phases at signals due to boarding or alighting passengers. Hence implementing far side stops could help reduce signal delay.
• There is a lack of information at stops about the service, users constantly ask the driver whether the X49 stops at their destination stop. We recommend conducting a review of the user information status in the corridor and updating it, improving the amount of information and its quality.

• The corridor has a non-conventional demand pattern that is not clear within the agency, thus we recommend to perform a study of Origins and Destinations on the corridor to match supply and demand and increase productivity.

Although focus was placed on X49 the productivity difference between routes 49A and 49B is worth noting. While 49A runs for 7 miles carrying only 600 passengers daily, 49B runs for 3.5 miles carrying 5,200 passengers daily. It might be worth studying the turn around points of the express service, intuitively, it seems that the service should start and end farther north in both directions.

People usually take the first bus that shows up, either 49 or X49. They certainly do not wait for the X49 route, although some passengers may wait for the 49. There is little competitive advantage in waiting for the X49 since significant travel time-savings are not perceived. The in-vehicle time savings are not enough compared to the extra waiting time, whether real or perceived.
7 CONCLUSIONS

This thesis has presented a process to study incremental implementation of BRT components and applied that process to the specific case of the Express service on Western Avenue in Chicago, IL.

Through the study of five existing BRT cases we identified the key attributes of successful BRT systems to be:

- Right of way priority
- Expedited boarding and alighting
- Knowledge-based planning and operations
- High frequency
- High reliability
- Distinct image
- Connectivity
- Land use integration

We focused on the study of how to achieve the first two key attributes through the improvement of infrastructure components including the right-of-way, the stops, the vehicles, the fare collection system, and the signal system. Within these five infrastructure components we identified the most important variables and analyzed their potential range of alternatives. To determine the implementation priority of each variable, we studied their benefits in terms of time savings and their costs in terms of the infrastructure and technology required to achieve the benefits.

To evaluate the time savings, we used analytical models to determine access time, waiting time, in-vehicle time, and running time. The access time model was developed for this thesis and its core problem is to find the average walking distance to the station. The model considers circular catchment areas around the stations instead of a rectangular corridor along the alignment, and a function for the probability of walking to the station.
Although a linearly decreasing probability, which seems more plausible than a constant function, resulted in somewhat counterintuitive results, the model is a basic stepping stone for further research given the limited extent of literature in the topic.

The waiting time was based on a simple commonly accepted model and a somewhat more recently developed analytical model for headway variance. The model was consider an appropriate analytical expression for this thesis; it allowed quantifying waiting time impact as a result of variations in the different BRT components, except by passenger load variations.

In-vehicle and running time models are deterministic models that rely on basic variables measured in the field. Despite their simplicity and reliance on average values, they predicted current times accurately.

The process developed was applied to a specific route in Chicago, the express service in Western Avenue: X49. For this route signal priority measures appear to be the most cost-effective BRT component to improve service. The variables that help to reduce dwell time (boarding level, transaction location, payment media, number of doors), which are usually critical in BRT systems due to the ridership levels, do not appear to provide significant improvements in the X49 service. However, these variables would have a greater impact if implemented in the 49 service or if a shift from the local 49 route to the new express 49 service is achieved.

Costly interventions to the infrastructure to achieve lane exclusivity do not seem to be a cost-effective measure given the existing fairly high speed of the route, the current ridership on the corridor, and the high opposition that is likely to occur. An intermediate solution was proposed to create certain degree of exclusivity under a preferential lane treatment. The preferential lane operation could reduce travel time by 4 – 10% and running time by 4 – 12%.
Reducing the stop spacing in the X49 route was recommended. This may seem counterintuitive when CTA is carrying out a project to increase stop spacing in many of its routes. However, for the X49 case, increasing it is in fact be a better strategy to improve ridership levels on the X49, since the coverage, a proxy for demand, would increase, without affecting significantly travel time.

Finally two implementation phases were recommended as follows

1. First phase: implemented in 1 to 3 years.
   - Reduce stop spacing
   - Use only low-floor buses in the X49 route, using current low-floor fleet
   - Expedite fare collection process by encouraging wider use of transit cards
   - Implement active signal priority, still to be determined whether it should be unconditional or conditional priority
   - Use existing lanes as preferential lanes for the X49 service
   - Spread the use of contact-less smart cards in the system

   - Introduce mechanisms to pay fare prior to board the vehicle, either proof-of-payment or closed stations with paid areas.
   - Depending on the ridership and success of the preferential lanes, implement exclusive lanes.

This thesis lays the foundations for future research on both improving the work done and extending to topics not covered in this thesis. In the first case there are some shortcomings of the process followed and the models used, which could be improved.

A potential area for improvement in the travel time model comes from the fact that the impacts on access time, waiting time and in-vehicle time were computed separately. But people usually make decisions optimizing total travel time. For example, a person may not walk to the nearest stop but to the one that minimizes the walking + riding time.
Thus, a passenger may walk to a station slightly farther downstream when boarding or farther upstream when alighting to trade off walking time with riding time.

In addition, the analysis performed in this thesis considered isolated improvements, however, due to synergies between variables, implementation in parallel of two or more variables may result in higher benefits than the sum of benefits resulting from isolated implementation. For example, improvements to dwell time configurations are usually made in parallel such as off-vehicle fare payment and multiple door use. Therefore, simultaneous improvements may create synergies generating greater impacts than those anticipated based on isolated analyses.

In the second case, further research could be performed to study how to best achieve the BRT attributes that were not analyzed on this thesis, including:

- Knowledge-based planning and operations
- High frequency
- High reliability
- Distinct image
- Connectivity
- Land use integration

Also, an extended evaluation framework could be developed to be able to include other benefits besides travel time savings, for example potential ridership increase resulting from coverage improvements or image, style, and permanence enhancements.
REFERENCES


14. CTA, (2002). "Western Avenue Bus Rapid Transit Intersection Design Project". Chicago, IL,


32. HalcrowFox, Halcrow Fox (2000). "Mass Rapid Transit in Developing Countries". London,


54. "MTA.NET". Los Angeles County Metropolitan Transportation Authority (2002). (www.mta.net)


71. Texas Transportation Institute (1999). Washington, D.C.,


75. Vaughn, R. J. and E. A. Cousins (1977). "Optimum location of bus stops on a bus route". 7th international symposium on transportation and traffic theory.


85.
### Appendix A: Configuration of Example Route

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking Speed $V_w$</td>
<td>83 m/min (250 ft/min)</td>
</tr>
<tr>
<td>Station Catchment Area Radius $R$</td>
<td>500 m</td>
</tr>
<tr>
<td>Stop Spacing $SS$</td>
<td>500 m</td>
</tr>
<tr>
<td>Length</td>
<td>16 km long</td>
</tr>
<tr>
<td>Number of stops</td>
<td>34</td>
</tr>
<tr>
<td>Average speed</td>
<td>12 km/hr (7.5 mi/hr)</td>
</tr>
<tr>
<td>Expected unit distance running time $E(t)$</td>
<td>5 min/km</td>
</tr>
<tr>
<td>Standard deviation of running time $\sigma(t)$</td>
<td>2.5 min/km = 50% $E(t)$</td>
</tr>
<tr>
<td>Expected Headway $E(h)$</td>
<td>10 min</td>
</tr>
<tr>
<td>Average boarding/alighting rate $c$</td>
<td>2 secs/pass</td>
</tr>
<tr>
<td>Passenger arrival rate $\alpha_i$</td>
<td>0.5 pass/min</td>
</tr>
</tbody>
</table>
Appendix B: Finding average walking distances

Average walking distance to the stop is the weighted sum of possible walking distances to the stop in the catchment area, that is

$$X_w = \frac{\int \int P_w(r) * D_w(r, \theta) * dA(r, \theta)}{A_{total}}$$

(1.1)

where,

- $P_w (r) =$ Probability of walking given a radial distance $r$ to the stop
- $D_w =$ distance to stop (radial or grid distance)
- $dA =$ Differential of area
- $A_{total} =$ Total area of catchment region

Calculations are done for four cases as follows

1. Radial distance with constant probability
2. Radial distance with linear decreasing probability
3. Grid distance with constant probability
4. Grid distance with linear decreasing probability

The following figure details the variables defined for the calculations.
Two areas result of the drawing \( QyT \), thus

\[
X_w = \frac{X_w^Q A^Q + X_w^T A^T}{A^Q + A^T}
\]

\[
X_w^{Q,T} = \int_A \left[ P_w^{Q,T}(r) D_w^{Q,T}(r, \theta) \right] dA^{Q,T}(r, \theta)
\]

and

\[
A^T = \frac{1}{2} \left( \frac{SS}{2} H \right) = \frac{SS \cdot H}{4}
\]

\[
A^Q = \int_{\theta_\phi}^{\pi/2} \int_{r_0}^{r} r \ dr \ d\theta = \int_{\theta_\phi}^{\pi/2} \frac{R^2}{2} \ d\theta = \frac{R^2}{2} \left( \frac{\pi}{2} - \phi \right)
\]

\[
SS = 2 \cdot \cos \phi
\]

\[
H = R \cdot \sin \phi
\]
Case 1. Radial distance with constant probability

\[
X^Q_w = \frac{\int_{\theta=0}^{\phi} \int_{r=0}^{\rho} r \, r \, dr \, d\theta}{A^Q}
\]

\[
X^Q_w = \frac{\int_{\theta=0}^{\phi} \frac{\pi}{3} R^3 \, d\theta}{A^Q}
\]

\[
X^Q_w = \frac{2R}{3A^Q}
\]

\[
X^\tau_w = \frac{\int_{\theta=0}^{\phi} \int_{r=0}^{\rho} r \cos \phi \, r \, dr \, d\theta}{A^\tau}
\]

\[
X^\tau_w = \frac{4}{SS.H} \int_{\theta=0}^{\phi} \left[ \frac{R^3}{3} \cos \phi \right] \, d\theta
\]

\[
X^\tau_w = \frac{4}{SS.H} \int_{\theta=0}^{\phi} \left[ \frac{1}{3} \cos \phi \right] \, d\theta
\]

\[
X^\tau_w = \frac{4.R^3 \cos^3 \phi}{3.\cos^3 \theta} \left\{ \sin \theta \left( \frac{\cos \theta}{2.\cos^2 \theta} \right) + \frac{1}{2} \ln \left[ \tan \left( \frac{\pi}{4} + \frac{\theta}{2} \right) \right] \right\}_0^\phi
\]

\[
X^\tau_w = \frac{2.R^3 \cos^3 \phi}{3.\cos^2 \phi} \left\{ \frac{\sin \phi}{\cos^2 \phi} + \ln \left[ \tan \left( \frac{\pi}{4} + \frac{\phi}{2} \right) \right] \right\}
\]

\[
X^\tau_w = \frac{R.\cos \phi}{3.\sin \phi} \left\{ \frac{\sin \phi}{\cos^2 \phi} + \ln \left[ \tan \left( \frac{\pi}{4} + \frac{\phi}{2} \right) \right] \right\}
\]
\[ X_w^r = \frac{R}{3} \left[ 1 + \frac{\sin \phi}{\cos^2 \phi} \ln \left[ \tan \left( \frac{\pi}{4} + \frac{\phi}{2} \right) \right] \right] \]
Case 2. Radial distance with linear decreasing probability

\[
X_w^T = \frac{\int_0^{R \cos \phi} \int_0^{\cos \theta} (1 - \frac{r}{R}) r \, r \, dr \, d\theta}{A^T}
\]

\[
X_w^T = \frac{4}{SS \cdot H} \int_0^{\phi \cos \theta} \int_0^{\cos \theta} \left( r^2 - \frac{r^3}{R} \right) \, dr \, d\theta
\]

\[
X_w^T = \frac{4}{SS \cdot H} \int_0^{\phi \cos \theta} \left( \frac{R^3 \cos^3 \phi}{3 \cos^3 \theta} - \frac{R^3 \cos^4 \phi}{4R \cos^4 \theta} \right) \, d\theta
\]

Replacing SS and H and solving the integral

\[
X_w^T = \frac{2R}{\sin \phi \cos \phi} \left[ \cos^3 \phi \left( \frac{\sin \phi}{\cos^2 \phi} \right) + \ln \left( \tan \left( \frac{\pi}{4} + \frac{\phi}{2} \right) \right) \right] - \frac{\sin \phi \cos \phi}{12} \left( 1 + 2 \cos^2 \phi \right)
\]

\[
X_w^T = \frac{R}{3} \left[ 1 + \frac{\cos^2 \phi}{\sin \phi} \ln \left( \tan \left( \frac{\pi}{4} + \frac{\phi}{2} \right) \right) \right] - \frac{1}{6} R \left( 1 + 2 \cos^2 \phi \right)
\]

\[
X_w^T = \frac{R}{6} \left[ 1 - 2 \cos^2 \phi + \frac{2 \cos^2 \phi}{\sin \phi} \ln \left( \tan \left( \frac{\pi}{4} + \frac{\phi}{2} \right) \right) \right]
\]
Case 3. Grid distance with constant probability

\[
X_w^{\varphi} = \frac{\int_{\theta=\varphi}^{\pi/2} \int_{r=0}^{R} \left( r \cos \theta + r \sin \theta \right) dr d\theta}{A^Q}
\]

\[
X_w^{\varphi} = \frac{\int_{\theta=\varphi}^{\pi/2} \int_{r=0}^{R} \left( r \cos \theta + r \sin \theta \right) dr d\theta}{A^Q}
\]

\[
X_w^{\varphi} = \frac{\int_{\theta=\varphi}^{\pi/2} \left[ \frac{R^3}{3} (\cos \theta + \sin \theta) \right] d\theta}{A^Q}
\]

\[
X_w^{\varphi} = \frac{R^3}{3} (1 - \sin \varphi + \cos \varphi)
\]

\[
X_w^{\varphi} = \frac{2R(1 - \sin \varphi + \cos \varphi)}{3\left(\frac{\pi}{2} - \varphi\right)}
\]

\[
X_w^T = \frac{\int_{y=0}^{H} \int_{x=0}^{SS/2} \left[ \frac{1}{2} (x + y) \right] dx dy}{SS/2 H}
\]

\[
X_w^T = \frac{1}{SS.H} \int_{y=0}^{H} \int_{x=0}^{SS/2} (x + y) dx dy
\]

\[
X_w^T = \frac{1}{SS.H} \int_{y=0}^{H} \left( \frac{SS^2}{8} + \frac{SS}{2} y \right) dy
\]
\[ X_w^\tau = \frac{1}{SS \cdot H} \left( \frac{SS^2}{8} H + \frac{SS \cdot H^2}{2} \right) \]

\[ X_w^\tau = \frac{SS}{8} + \frac{H}{4} \]
Case 4. Grid distance with linear decreasing probability

For the assumption that probability of walking decreases with distance to stop we recalculate $X_w^T$ and $X_w^Q$.

\[
X_w^Q = \frac{\int_{\theta = \phi}^{\pi/2} \int_{r=0}^{R} \left[ P_w(r) \cdot X_w(r, \theta) \cdot A(r, \theta) \right]}{A^Q}
\]

\[
X_w^Q \cdot A^Q = \int_{\theta = \phi}^{\pi/2} \int_{r=0}^{R} \left[ \left( 1 - \frac{r}{R} \right) \cdot (x+y) \cdot r \right] dr \, d\theta
\]

\[
X_w^Q \cdot A^Q = \int_{\theta = \phi}^{\pi/2} \int_{r=0}^{R} \left[ \left( 1 - \frac{r}{R} \right) \cdot (r \cos \theta + r \sin \theta) \cdot r \right] dr \, d\theta
\]

\[
X_w^Q \cdot A^Q = \int_{\theta = \phi}^{\pi/2} \left[ (\cos \theta + \sin \theta) \int_{r=0}^{R} \left( r^2 - \frac{r^3}{R} \right) \right] dr \, d\theta
\]

\[
X_w^Q = \frac{R^3}{12} \int_{\theta = \phi}^{\pi/2} (\cos \theta + \sin \theta) \, d\theta
\]

\[
X_w^Q = \frac{R^2}{12} (1 - \sin \Phi + \cos \Phi)
\]

\[
X_w^Q = \frac{R^3 (1 - \sin \Phi + \cos \Phi)}{12 \cdot \frac{R^2}{2} \left( \frac{\pi}{2} - \phi \right)}
\]

\[
X_w^Q = \frac{R^3 (1 - \sin \Phi + \cos \Phi)}{6 \left( \frac{\pi}{2} - \phi \right)}
\]
\[ X_w \hat{r} = \int_{r=0}^{R \cos \phi} \int_{\theta=0}^{\cos \theta} \left[ P_w(r, X_w(r, \theta), A(r, \theta)) \right] \] 

\[ X_w \hat{r} \cdot A^\top = \int_{r=0}^{R \cos \phi} \int_{\theta=0}^{\cos \theta} \left[ \left(1 - \frac{r}{R}\right)(x + y) \right] r \, dr \, d\theta \]

\[ X_w \hat{r} \cdot A^\top = \int_{r=0}^{R \cos \phi} \int_{\theta=0}^{\cos \theta} \left[ \left(1 - \frac{r}{R}\right)(r \cos \theta + r \sin \theta) \right] r \, dr \, d\theta \]

\[ X_w \hat{r} \cdot A^\top = \int_{\theta=0}^{\phi} \left( \cos \theta + \sin \theta \right) \int_{r=0}^{R \cos \phi} \left( r^2 - \frac{r^3}{R} \right) r \, dr \, d\theta \]

\[ X_w \hat{r} \cdot A^\top = R^3 \cos^3 \phi \int_{\theta=0}^{\phi} \left( \cos \theta + \sin \theta \right) \left( \frac{1}{3 \cos^3 \theta - \frac{\cos \phi}{4 \cos^4 \theta}} \right) \, d\theta \]

\[ X_w \hat{r} \cdot A^\top = R^3 \cos^3 \phi \int_{\theta=0}^{\phi} \left( \frac{\sin \theta}{3 \cos^3 \theta} - \frac{\cos \phi \sin \theta}{4 \cos^4 \theta} + \frac{1}{3 \cos^2 \theta} - \frac{\cos \phi}{4 \cos^3 \theta} \right) \, d\theta \]

\[ X_w \hat{r} \cdot A^\top = R^3 \cos^3 \phi \left\{ \tan^2 \phi - \frac{\cos \phi}{6} - \frac{1}{12} \left[ \frac{1}{\cos^3 \phi} - 1 \right] + \frac{\tan \phi}{3} - \frac{\cos \phi}{4} \left[ \frac{\sin \phi}{2 \cos^2 \phi} + \frac{1}{2} \ln \left( \tan \left( \frac{\pi}{4} + \frac{\phi}{2} \right) \right) \right] \right\} \]

\[ X_w \hat{r} = \frac{4 R^3 \cos^3 \phi \left\{ \tan^2 \phi - \frac{\cos \phi}{6} - \frac{1}{12} \left[ \frac{1}{\cos^3 \phi} - 1 \right] + \frac{\tan \phi}{3} - \frac{\cos \phi}{4} \left[ \frac{\sin \phi}{2 \cos^2 \phi} + \frac{1}{2} \ln \left( \tan \left( \frac{\pi}{4} + \frac{\phi}{2} \right) \right) \right] \right\}}{SS \cdot H} \]