Simulation based Analysis of Bus Lane Operation and Bus Signal Priority in Urban Streets

(シミュレーションを用いた都市内のバス優先レーン及びバス優先信号の分析)

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Abstract

As the world population keeps growing, the demand for using cars traveling in transportation system becomes outstripping the current limited supply of road facility. Although there are many transportation modes recognized as the key of the future sustainable transportation system, bus system plays an important role because of its flexibility, easy navigation and low costs. It can be said that improving bus service to attract more bus users switching from private car to bus is an indispensable trend to relieve traffic congestion, traffic accident as well as excessive dependence on car mobility in the current overpopulation society.

Although current bus priority systems can perform well its functionality, there are some weak points needed to be improved to enhance convenience for users as well as to encourage more users of the public transportation. For example, the huge delay that a traffic system has incurred due to priority calls at signalized intersections, the reduction in road capacity for cars in the cases of bus priority lanes, etc. are problems related to negative effects of priority treatment. In this research, the author investigates into bus lane operation and proposes improved models for bus signal priority for the sake of enhancing the efficiency of bus service. The scope of the study covers not only isolated intersections, arterial roads with multi-intersections but also traffic networks. The details are as follows.

For bus lanes, the research firstly comparatively analyzes the operation of three popular bus lane types, including ordinary lane, exclusive bus lane and bus priority lane in Japan. The result of a case study shows that although the exclusive bus lane type can improve bus service, its negative impacts on other types of vehicles are significant. Meanwhile, because of the flexibility in choosing lane in the scenario of bus priority lane, the bus priority lane can reduce bus travel time and relieve negative effects on other types of vehicle simultaneously. Converting all the vehicle delays to passenger delay, the research conducts a sensitivity analysis in choosing bus lane types under various conditions of the main traffic volume and the number of passengers in buses. The analysis concludes the roles of main traffic volume and the number of passengers in buses in determination of the bus lane type. More specifically, the increase in the number of passengers in buses decides the tendency of choosing exclusive bus lanes. Meanwhile the increase in the main traffic volume benefits the decisions on ordinary lanes. The tendency of choosing bus priority lanes plays an intermediate role that finds rooms between the choice of exclusive bus lanes and that of ordinary lanes.

The research secondly investigates the behaviour of passenger cars under the bus effects in the scenario of bus priority lane by proposing a new car lane-changing model. Unlike any previous car lane-changing model, this model consists of three steps: looking-back threshold determination, gap acceptance model and execution model. These three steps are represented for the philosophy of a lane-changing manoeuvre of passenger cars under the influence of oncoming buses. The estimation result confirms the compulsory lane-changing behaviour of cars under bus priority-lane effects. As soon as a car recognises oncoming buses, it would rather pay attention to the speed of the lag vehicle than concern that of the lead vehicle in finding acceptable gaps. Because of the compulsory lane changing behaviour in this situation, the research would like to send a message on warnings of traffic accident to car drivers when changing lane to give space to buses.
After investigating the proposed car lane changing model, the research thirdly integrates the proposed model into simulation models and evaluates the effect of bus priority lanes in comparison with that of exclusive bus lanes based on the current ordinary lane in Nagaoka traffic network. The results show that the bus priority lane and exclusive bus lane can reduce the bus travel time on the treatment segment significantly. However, in terms of entire the bus routes, the bus priority lane and the exclusive bus lane may benefit some bus routes and bring disadvantages to several ones as well. In terms of the effect intensity of exclusive bus lane and bus priority to the traffic network, the research suggests that bus priority lanes should be considered as a transitional treatment before the exclusive bus lane deployments.

For bus signal priority at isolated intersections, the research firstly proposes a prediction model to predict bus arrival time. The proposed model that utilizes the measured data from image processing sensor and signal database can improve the accuracy of the prediction on bus arrival time. Based on the proposed prediction model, the research investigates the intersection performance under different schemes of bus priority, including bus signal priority, bus preemption without exclusive bus lanes, and bus preemption with exclusive bus lanes. The result shows that the more increase the bus priority level is, the more decrease the bus travel time is and the more negative effect on non-bus vehicles is. In terms of delay reduction at intersections, the bus priority level is directly proportional to the role of bus occupancy in this study. The research secondly proposes an improved genetic algorithm (GA) for optimization in adaptive bus-signal priority control at isolated signalized intersections by applying the compensation rule between signal cycles in adaptive control. The proposed algorithm can increase the convergence rate to reach the optimal solutions compared with conventional ones. The time saving is important to the smooth running of any simulation model as well as real time control systems.

For bus signal priority in arterial roads with multi-intersections, the research proposes a model to improve the efficiency of bus service. The model involves the coordination between bus speed guidance and signal timing techniques to give priority to buses in arterial roads. The coordination allocates the proper recommended bus speed as well as minimizes the traffic delays simultaneously. The results show that the proposed model which be integrated into simulation models is more efficient than the conventional one in terms of delay reduction.

The dissertation is organized into six chapters as follows:

- **Chapter 1 - Introduction**: This chapter states general introductions about public transport as well as bus priority treatments in urban streets. Several concepts of bus treatment are introduced. At the end of the chapter, problem identifications unveil necessary tasks for future researches and the research recognition in this dissertation.

- **Chapter 2 - Literature review**: This chapter presents a state of art of the existing studies about bus lanes and bus signal priority as well. Based on the literature review, this chapter presents and concretizes in details the objectives of the research.

- **Chapter 3 – Methodology**: This chapter mainly describes the common methodology used for investigation of bus lane and development of signal priority models in this research. The common methodology goes through main steps, including proposal of improved model, calibration of the proposed models, integration into simulation models in PARAMICS, creations of traffic networks in PARAMICS as well as the
way to calibrate and validate simulation models, and the criteria for evaluation of model performance. The general information on model development and the detail of simulation in PARAMICS are the main target of this chapter. The specific details for each studied system, bus lane system and bus signal priority system, will be presented in the following corresponding chapters.

- Chapter 4 - Bus lane system: This chapter firstly comparatively analyzes the three popular bus lane types in Japan, including ordinary lane, bus priority lane and exclusive lane with simple assumptions on lane changing behavior. The purpose of the comparative analysis is to find criteria for bus lane determination in terms of delay reduction. Secondly, the chapter proposes a car lane-changing model under bus effects for the scenario of bus priority lane. The characteristic of a lane changing behavior is identified in this part. The proposed car-lane changing model is then integrated again into simulation models in PARAMICS to evaluate the effect of bus priority lanes in comparison with that of exclusive bus lanes based on the current ordinary lane in Nagaoka traffic network.

- Chapter 5 – Bus signal priority system: This chapter focuses on signal priority control at levels of isolated intersection and arterial road with multi-intersection. For the isolated intersection level, the research firstly proposes a prediction model by employing Image Processing Sensor to predict bus arrival time. The proposed model is then utilized to investigate the intersection performance under different bus priority levels at a signalized intersection. In addition, the research also proposes an improved genetic algorithm to increase the convergence rate in a system of adaptive bus signal priority control. The increase in convergence rate means reducing computation time enhances the applicability of real time control applications. For the arterial road level, the research proposes a model to improve the efficiency of bus service based on coordinating bus speed guidance and signal timing techniques in arterial roads. The proposed model is then investigated in two approaches: analytical approach and simulation approach. The good performance of the proposed model in terms of total traffic delay reduction is the target of this part.

- Chapter 6 - Conclusions and recommendations: A review of the current research work and some conclusions for further studies are discussed in this chapter.
Acknowledgement

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# TABLE OF CONTENTS

ABSTRACT ...........................................................................................................................i
ACKNOWLEDGEMENT .........................................................................................................iv
TABLE OF CONTENTS .......................................................................................................v
GLOSSARY ..........................................................................................................................ix
LIST OF FIGURES ...............................................................................................................x
LIST OF TABLES ..................................................................................................................xiii

1. INTRODUCTIONS ........................................................................................................1
   1.1. General background. ..............................................................................................1
   1.1.1. The role of bus system ...................................................................................1
   1.1.2. Types of bus priority treatments ....................................................................2
   1.2. Bus lane priority system. .....................................................................................4
   1.3. Bus signal priority system. ....................................................................................4
   1.4. Problem identifications .......................................................................................5

2. LITERATURE REVIEW ................................................................................................8
   2.1. Related studies about bus lane. ............................................................................8
   2.2. Related studies about bus signal priority. ............................................................10
       2.2.1. Research studies on travel time prediction ............................................10
       2.2.2. Research studies on bus signal priority control .......................................10
   2.3. Research objectives. ..........................................................................................12

3. METHODOLOGY ..........................................................................................................13
   3.1. Proposal of models .............................................................................................14
       3.1.1 Bus lane system ..........................................................................................14
       3.1.2 Bus signal priority system ..........................................................................14
           3.1.2.1. For isolated signalized intersection .............................................15
           3.1.2.2. For arterial with multi-intersections .............................................17
   3.2. Data collection ......................................................................................................18
   3.3.1 Analysis technique ............................................................................................18
   3.3.2 Collected data ...................................................................................................19
   3.3. Integration into simulation models .......................................................................19
       3.3.1 Bus lane system ..........................................................................................20
       3.3.2 Bus signal priority system ..........................................................................21
           3.3.2.1. Bus signal timing technique .......................................................21
           3.3.2.2. Modification of the car following model ......................................22
   3.4. Simulation in PARAMICS ...................................................................................23
       3.4.1 The functionality of PARAMICS modules ................................................23
       3.4.2 Traffic network built in PARAMICS ..........................................................24
       3.4.3 Calibration process ......................................................................................24
           3.4.3.1. Control of fixed parameters .........................................................24
           3.4.3.2. Control of traffic operation parameters .......................................24
5. BUS SIGNAL PRIRORITY SYSTEM .................................................................64
   5.1. General introduction ............................................................................64
   5.2. Objectives ............................................................................................65
   5.3. Image Processing sensor and Infrared beacon ....................................66
      5.3.1. Image Processing sensor .................................................................66
      5.3.2. Infrared beacon ............................................................................67
   5.4. Study on isolated signalized intersections ............................................67
      5.4.1. Introduction ....................................................................................67
      5.4.2. Bus arrival time prediction model ....................................................68
         5.4.3.1. Formulation ............................................................................68
         5.4.3.2. Results and analyses ...............................................................70
      5.4.3. Bus signal priority strategy comparisons ........................................72
         5.4.3.1. Four scenarios of bus signal priority strategy ..........................72
         5.4.3.2. Results and analyses ...............................................................74
      5.4.4. Genetic algorithm for adaptive bus signal priority control .............78
         5.4.4.1. An overview on optimization approach .....................................78
         5.4.4.2. Adaptive bus signal priority control .........................................79
         5.4.4.3. Evolution algorithm .................................................................82
         5.4.4.4. A simple numerical test ...........................................................84
         5.4.4.5. Results and analyses ...............................................................85
      5.4.5. Conclusions ....................................................................................89
         5.4.5.1. Comparative analysis at isolated intersections .......................89
         5.4.5.2. The GA improvement ...............................................................90
   5.5. Study on arterial roads with multi-intersections ......................................91
      5.5.1. Introduction ....................................................................................91
      5.5.2. Model development .......................................................................92
         5.5.2.1. Bus arrival time prediction .......................................................92
         5.5.2.2. An improved model .................................................................93
      5.5.3. Analytical approach .......................................................................94
         5.5.3.1. Assumed input parameters ......................................................94
         5.5.3.2. Results and analysis ...............................................................94
      5.5.4. Simulation approach .......................................................................96
         5.5.4.1. Study site ................................................................................96
         5.5.4.2. Modification of the car following model .................................97
         5.5.4.3. Simulated scenarios .................................................................97
         5.5.4.3. Results and analyses ...............................................................97
      5.5.5. Conclusions ....................................................................................99

6. CONCLUSIONS AND RECOMMENDEDATIONS ......................................100
   6.1. Conclusions .........................................................................................100
      6.1.1. Bus lane system ...........................................................................100
      6.1.2. Bus signal system .........................................................................101
   6.2. Recommendations ...............................................................................102
      6.2.1. Bus lane system ...........................................................................102
6.2.2. Bus signal system ........................................................................................................103

References ..........................................................................................................................104
## Glossary

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVL</td>
<td>Automatic Vehicle Location</td>
</tr>
<tr>
<td>UTMS</td>
<td>Universal Traffic Management Society of Japan</td>
</tr>
<tr>
<td>ITS</td>
<td>Intelligent Transport Systems.</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>BSP</td>
<td>Bus Signal Priority</td>
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<tr>
<td>APC</td>
<td>Automatic Passenger Counting</td>
</tr>
<tr>
<td>ANN</td>
<td>Arterial Neural Network</td>
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<tr>
<td>API</td>
<td>Application Programming Interface</td>
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<tr>
<td>TSP</td>
<td>Transit Signal Priority</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
</tr>
</tbody>
</table>
List of Figures

<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Road space required by 50 persons driving motorcycles (left), cars (middle) and bus (right)</td>
<td>2</td>
</tr>
<tr>
<td>Figure 1.2</td>
<td>Signal timing techniques and delay reduction</td>
<td>5</td>
</tr>
<tr>
<td>Figure 1.3</td>
<td>An exclusive bus lane</td>
<td>6</td>
</tr>
<tr>
<td>Figure 1.4</td>
<td>A bus priority lane</td>
<td>6</td>
</tr>
<tr>
<td>Figure 1.5</td>
<td>An ordinary lane</td>
<td>6</td>
</tr>
<tr>
<td>Figure 1.6</td>
<td>Public transportation priority systems</td>
<td>7</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>General methodology</td>
<td>13</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>The structure of the lane changing behavior</td>
<td>14</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Studied signalized intersection</td>
<td>15</td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>Algorithm to create DLL in PARAMICS for bus lane</td>
<td>15</td>
</tr>
<tr>
<td>Figure 3.5</td>
<td>Delay of buses and general vehicles</td>
<td>16</td>
</tr>
<tr>
<td>Figure 3.6</td>
<td>A hypothetical arterial road</td>
<td>17</td>
</tr>
<tr>
<td>Figure 3.7</td>
<td>Algorithm to create a plugin in PARAMICS for BSP</td>
<td>17</td>
</tr>
<tr>
<td>Figure 3.8</td>
<td>Diagram of data collection and extraction using video techniques</td>
<td>19</td>
</tr>
<tr>
<td>Figure 3.9</td>
<td>The process for integration into simulation models</td>
<td>20</td>
</tr>
<tr>
<td>Figure 3.10</td>
<td>Algorithm to override the car lane changing model</td>
<td>21</td>
</tr>
<tr>
<td>Figure 3.11</td>
<td>Execution of signal control</td>
<td>22</td>
</tr>
<tr>
<td>Figure 3.12</td>
<td>Algorithm for bus speed adjustment</td>
<td>22</td>
</tr>
<tr>
<td>Figure 3.13</td>
<td>General process of executing traffic simulation in PARAMICS</td>
<td>23</td>
</tr>
<tr>
<td>Figure 3.14</td>
<td>Procedure for OD estimation</td>
<td>26</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>Bus priority-lane (left) and exclusive bus lane (right)</td>
<td>28</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Lead gaps and lag gaps</td>
<td>30</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Vehicle changes lane to give space for prioritized bus</td>
<td>31</td>
</tr>
<tr>
<td>Figure 4.4</td>
<td>Camera’s locations for data collection</td>
<td>32</td>
</tr>
<tr>
<td>Figure 4.5</td>
<td>Location of camera for data collection</td>
<td>32</td>
</tr>
<tr>
<td>Figure 4.6</td>
<td>The study site (left) and network built in PARAMICS (right)</td>
<td>32</td>
</tr>
<tr>
<td>Figure 4.7</td>
<td>The studied traffic arterial</td>
<td>33</td>
</tr>
<tr>
<td>Figure 4.8</td>
<td>Traffic proportion</td>
<td>33</td>
</tr>
<tr>
<td>Figure 4.9</td>
<td>Bus routes at the study site from 7:30 to 9:30</td>
<td>35</td>
</tr>
<tr>
<td>Figure 4.10</td>
<td>Traffic flow validation</td>
<td>36</td>
</tr>
<tr>
<td>Figure 4.11</td>
<td>Road segment for travel time collection</td>
<td>37</td>
</tr>
<tr>
<td>Figure 4.12</td>
<td>Travel time validation for bus and other vehicles</td>
<td>37</td>
</tr>
<tr>
<td>Figure 4.13</td>
<td>Road segment for traffic comparison among the cases</td>
<td>38</td>
</tr>
<tr>
<td>Figure 4.14</td>
<td>Bus travel time comparison</td>
<td>39</td>
</tr>
<tr>
<td>Figure 4.15</td>
<td>Non-bus vehicle travel time comparison</td>
<td>39</td>
</tr>
<tr>
<td>Figure 4.16</td>
<td>Comparison of passenger travel times</td>
<td>40</td>
</tr>
<tr>
<td>Figure 4.17</td>
<td>Decisions on bus lane type</td>
<td>41</td>
</tr>
<tr>
<td>Figure 4.18</td>
<td>The structure of a car lane-changing process</td>
<td>45</td>
</tr>
<tr>
<td>Figure 4.19</td>
<td>Looking-back threshold distribution</td>
<td>46</td>
</tr>
</tbody>
</table>
Figure 4.20  Lead gap and lag gap at the studied site  46
Figure 4.21  The studied site in Niigata, Japan  48
Figure 4.22  A snapshot of using SEV to collect data  49
Figure 4.23  Studied cases for lane-changing behavior  51
Figure 4.24  Critical lead gap comparison  51
Figure 4.25  Critical lag gap comparison  52
Figure 4.26  The structure of the lane changing behavior  54
Figure 4.27  Comparison in terms of vehicle travel time  56
Figure 4.28  Comparison in terms of area distribution  56
Figure 4.29  Bus punctuality in Nagaoka city  57
Figure 4.30  The studied traffic network (left) and the network in PARAMICS (right)  58
Figure 4.31  Traffic flow validation  58
Figure 4.32  Traffic count validation at the connecting bridges  59
Figure 4.33  Travel time validation  59
Figure 4.34  Bus travel times on the treatment segment  60
Figure 4.35  The effects on the bus routes  61
Figure 4.36  Observed and simulated traffic flows at the bridges  61
Figure 5.1  Spatial area measured by processing sensor  66
Figure 5.2  Queue length measured by image Processing sensor  66
Figure 5.3  The communication zone of an Infrared beacon  67
Figure 5.4  Studied signalized intersection  68
Figure 5.5  Algorithm for bus arrival time prediction  69
Figure 5.6  Bus arrival time prediction validation  71
Figure 5.7  Predicted error distribution  71
Figure 5.8  Absolute errors of bus arrival time prediction  71
Figure 5.9  The studied intersection  72
Figure 5.10  Preemption cases  73
Figure 5.11  Flow rate validation.  74
Figure 5.12  Vehicle travel time validation  74
Figure 5.13  Changes in travel time  76
Figure 5.14  Bus trajectory comparisons  76
Figure 5.15  Turn delays caused by the intersection  77
Figure 5.16  The role of bus occupancy  78
Figure 5.17  Standard NEMA phases, rings and barrier  79
Figure 5.18  Considered consecutive signal cycles  80
Figure 5.19  Early green time technique  81
Figure 5.20  The process of GA type determination  82
Figure 5.21  Crossover operator  82
Figure 5.22  Mutation operator  83
Figure 5.23  Conventional GA for optimization  83
Figure 5.24  Population space improvement  84
Figure 5.25  The studied intersection  85
Figure 5.26  The convergence speed comparison  85
Figure 5.27  The results with different random seeds  86
Figure 5.28  The fluctuation areas  86
Figure 5.29  The computation time comparison  87
Figure 5.30  The demand based efficiency  88
Figure 5.31  A new public transport system  91
Figure 5.32  Hypothetical arterial roads with its mechanism  92
Figure 5.33  Space and velocity relationship  93
Figure 5.34  Combination between bus guidance and signal techniques  94
Figure 5.35  Compared with the base scenario  95
Figure 5.36  Compared with the conventional adaptive model  95
Figure 5.37  The studied street (above) and PARAMICS (below)  96
Figure 5.38  Traffic flow validation  97
Figure 5.39  Bus speed under speed guidance mechanism  98
Figure 5.40  Comparison of the average link delay  98
# List of Tables

<table>
<thead>
<tr>
<th>Table No.</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 4.1</td>
<td>The number of buses on each bus route during 7:30-9:30</td>
<td>34</td>
</tr>
<tr>
<td>Table 4.2</td>
<td>Estimated parameters</td>
<td>50</td>
</tr>
<tr>
<td>Table 5.1</td>
<td>Traffic signal at the study intersection (8AM-9AM)</td>
<td>72</td>
</tr>
<tr>
<td>Table 5.2</td>
<td>Definitions of phases, rings and barrier</td>
<td>79</td>
</tr>
<tr>
<td>Table 5.3</td>
<td>Traffic signal at the studied intersection</td>
<td>84</td>
</tr>
<tr>
<td>Table 5.4</td>
<td>Assumed input parameters</td>
<td>94</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1. GENERAL BACKGROUND

1.1.1. The role of bus system

Many environmental problems and severe urban problems such as traffic congestion, accidents on the roads, etc are hot issues whose deep reason is excessive dependence on car mobility. These problems affect significantly every aspect of society and become burden problems in many countries throughout the world. According to researches or experts in the field of transportation engineering, the tendency of switching from private mode to public transport mode is an indispensable trend to avoid the above problems. However, considering public transport, there are many kinds of mode: airline, bus, coach, tram, etc. So what kind of mode is suitable for a traffic network for short-term periods or long-term views? Because of unaffordable investments and construction time, railroad cannot be considered as a solution for short-term periods. Although rail is the safest, quite punctual and the form of transport, there is a lack of accessibility to any location due to the inflexibility of rail’s tracks. In other words, rail transport cannot provide door-to-door service as taxi, bus or paratransit does. It needs huge time, money to construct as well as operate and maintain. It is just suitable for some cases and for long-term periods at macroscopic levels.

In fact, a less expensive, easier to navigate and more frequent mode is bus system. This is a suitable choice for short-term solutions and an answer for local area problems. There are many examples of cities in developed countries that have developed noteworthy bus systems even before the rapid motorization progress began. Transport planners adopt a variety of strategies to cope with situations that impede the bus movement. An innovative form of bus transport system is Bus Rapid Transit (BRT), which is indispensable part in modern societies. This is a car competitive service that public-transport planners have tried in their attempts to win back customers. A BRT system becomes more and more popular nowadays because of its huge benefit. Due to the advantages of lower construction costs and greater flexibility, BRT systems can be regarded as an alternative to railway systems with superior features of the high speed and safety. In the world of rapid motorization and economic growth that the public transport looses its competitiveness, hence BRT is accepted as an effective public transport mode in many aspects. As shown in Figure 1.1, this is a comparison the road spaces obtain by 50 persons driving motorcycles, cars and buses. The road space required for motorcycles is smaller than that for car. However, motorcycles travel disordered, not follow any lane as cars do. All of them, the road space required by 50 persons driving bus is the smallest. This proves the advantage of ridding buses compared with other modes. This advantage becomes significant if there are good ways to control, manage as well as to improve the efficiency of bus networks.
The positive role of public transportation, especially bus system has been clearly proved in previous works. The improvement of bus service can relieve traffic congestion, improve traffic quality as well as attract more people to switch from using private cars to riding buses. Many things to improve bus service are considered not only special policies for bus users but also some priority treatments to bus at bus stops, bus lanes, or signalized intersections. Although improving the performance of public transport usually causes unfavorable conditions for non-bus operations, this is an indispensable way to deal with the current burning problems in urban streets such as traffic congestion, the increase of private car, accidents, environmental pollutions, etc.

1.1.2. Types of bus priority treatments

Bus priority is defined as any scheme that gives buses preferential treatment over other road users (Priscilla, 2002). Therefore, the efficiency of bus service will increase when applied with any priority treatment. However, this efficiency usually has a negative impact on other traffic users. The literature review on bus priority can divide the priority treatment into three categories. They are lane system, signal priority system and traffic management (Priscilla, 2003; HCM, 2010). Concerning traffic management, this category includes demand management, parking restrictions, access or tuning restriction, etc. These policies affects the positively bus operation in direct or indirect ways. For bus lane system or bus signal priority system, there are many types of treatment, which have been deployment in the world. The popular treatments can be named as exclusive bus lane, queue jump lane, queue bypass, boarding island, curb extensions, parking restriction, signal priority, etc. The benefit as well as disadvantage of each priority treatment was identified clearly. For example, according to HCM 2000, the comparison of bus preferential treatments is shown in Table 1.1:

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**Figure 1.1** Road space required by 50 persons driving motorcycles (left), cars (middle) and bus (right)
<table>
<thead>
<tr>
<th>Treatment</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Priority</td>
<td>• Reduces delay</td>
<td>• Risks interrupting coordinated traffic signal operation</td>
</tr>
<tr>
<td></td>
<td>• Improves reliability</td>
<td>• Risks lowering intersection LOS, if intersection is close to capacity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Requires ongoing interjurisdiction coordination</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Buses on cross streets may incur added delay greater than the time saved by the favored route</td>
</tr>
<tr>
<td>Queue Bypass</td>
<td>• Reduces delay from queues at ramp meters or other locations</td>
<td>• Bus lane must be available and longer than the back of queue</td>
</tr>
<tr>
<td>Queue Jump</td>
<td>• Reduces delay to queues at signals</td>
<td>• Right lane must be available and longer than the back of queue</td>
</tr>
<tr>
<td></td>
<td>• Buses can leapfrog stopped traffic</td>
<td>• Right-turn or special transit signal required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Reduces green time available to other intersection traffic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Bus drivers must be alert for the short period of priority green time</td>
</tr>
<tr>
<td>Curb Extensions</td>
<td>• Reduces delay due to merging back into traffic</td>
<td>• Requires at least two travel lanes in bus direction of travel to avoid blocking traffic while passengers board and alight</td>
</tr>
<tr>
<td></td>
<td>• Increases riding comfort because buses don’t need to pull in and out of stops</td>
<td>• Bicycle lanes require special consideration</td>
</tr>
<tr>
<td></td>
<td>• Increases on-street parking by eliminating need for taper associated with bus pullouts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Increases space for bus stop amenities</td>
<td></td>
</tr>
<tr>
<td>Boarding Islands</td>
<td>• Increases bus speed by allowing buses to use faster-moving left lane</td>
<td>• Requires at least two travel lanes in bus direction of travel and a significant speed difference between the two lanes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Requires more right-of-way than other treatments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pedestrian and ADA accessibility, comfort, and safety issues must be carefully considered</td>
</tr>
<tr>
<td>Parking Restrictions</td>
<td>• Increases bus and auto speeds by removing delays caused by automobile parking maneuvers</td>
<td>• May significantly impact adjacent land uses (both business and residential)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Requires ongoing enforcement</td>
</tr>
<tr>
<td>Bus-Stop Relocation</td>
<td>• Uses existing signal progression to bus’s advantage</td>
<td>• May increase walking distance for passengers transferring to a cross-street bus</td>
</tr>
<tr>
<td>Turn Restriction Exemption</td>
<td>• Increases bus speed by eliminating need for detours to avoid turn restrictions</td>
<td>• Potentially lowers intersection LOS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Safety issues must be carefully considered</td>
</tr>
<tr>
<td>Exclusive Bus Lanes</td>
<td>• Increases bus speed by reducing sources of delay</td>
<td>• Traffic and parking effects of eliminating a travel or parking lane must be carefully considered</td>
</tr>
<tr>
<td></td>
<td>• Improves reliability</td>
<td>• Requires ongoing enforcement</td>
</tr>
<tr>
<td></td>
<td>• Increases transit visibility</td>
<td></td>
</tr>
</tbody>
</table>

Source: Portland Office of Transportation.
1.2. BUS LANE SYSTEM

In terms of bus lane, it is easy to find out many definitions for bus lane from literature reviews. Indeed, with-flow bus lanes, contra-flow bus lanes, bus ways are defined as link based measures to give priority to buses (Kevin, G., 2009). Specifically, with-flow bus lane is defined as a roadside reserved traffic lane for the use of buses and may accommodate bicycles (DETR, London, 1997). Meanwhile, contra-flow bus lane is a lane where buses are allowed to travel against the main direction of traffic flow. Being segregated from general traffic, bus-ways are designed for the exclusive uses of buses. This bus lane type can protect buses from congestion and make the trip faster as well. In a different aspect, HCM (2010) categorizes bus lanes into three types. For type 1, bus lanes have no use of adjacent lane. In type 2, bus lanes have partial use of the adjacent lane, which is shared with other traffic. Lastly for type 3, bus lanes are provided for exclusive use of two lanes by buses. It can be seen that, the category was based on the degree of exclusivity of bus lane. The greater the degree of exclusivity of bus lane and the greater the number of lanes available for buses to manoeuvre, the greater the bus lane capacity. Similarly, a report released by National Capital Region Transportation Planning Board, Washington (2011) divided bus lane types into exclusive lane, restricted lane and unrestricted lane. In which, exclusive lane is reserved solely for use by buses and other government vehicles such as emergency vehicles. Restricted lane is reserved for buses and high Occupancy vehicles. Unrestricted lane is a lane in which buses operate in mixed traffic with no special provisions to improve operations. Besides, the concept of “bus- only” street is also popular in some research studies. This is a street where access is prohibited to all but priority vehicles, which may include emergency vehicles, prioritized buses, etc. A short length of bus-only street allowing access to a particular facility is sometimes termed a bus gate (Priscilla, 2002). However, in Japan, the category of bus lanes is divided into three types, including ordinary lane type (in which buses travel in mixed traffic flow), exclusive bus lane type and bus priority-lane type. For the bus priority lane, once an oncoming bus comes in the priority-lane, passenger cars travelling in this lane have to change lane to give space for the oncoming bus (Koyama Kotsu, 2001; The MCB Butler Installation Safety, 2008). The bus priority-lane is a special bus lane and be concerned in this research.

1.3. BUS SIGNAL PRIORITY SYSTEM

A bus priority system aims at reducing the bus delay or total traffic delay at a signalized intersection. There are three strategies for a bus signal priority system including passive priority, active priority, adaptive control. The details of each strategy are reviewed in the following parts

- Passive priority: This strategy aims at improving bus operation by providing a signal timing plan based on the historical data of bus demand. Several common tasks in passive priority control are phase increase, phase splitting, cycle adjustment, vehicle metering, etc. The strategy does not need any detectors or external devices. The passive priority strategy is used in several tools for traffic management and control such as with SCOOT (Wood and Baker 1992), BALANCE (Toomey et al 1998), UTRANSYT, etc
- Active Priority: This strategy is more complex than the passive one. The active strategy will control traffic signal in a more flexible ways. It requires detectors to detect bus locations as well as advanced controllers to activate the priority calls. Three popular techniques used in this strategy are green extension, early green time and phase insertion. The illustration is shown in Figure 1.2
Adaptive control: This strategy is implemented based on a real-time evaluation of a selective performance criterion though continuous feedback between the priority request generator (i.e. bus or detector) and the priority request server (i.e. local controller or transit management center) (Kim, 2004). The adaptive signal control has been implemented at intersection level, street arterial level or street network level. Several systems developed are SPPORT (Yagar, et al. 1994, Conrad et al.1998; Dion et al. 2002); SCOOT (Robertson et al. 1991), UTOPIA (Mauru et al. 1990), PRODYN (Henry et al, 1994), SCATS (Cornwell et al, 1986), etc.

1.4. PROBLEM IDENTIFICATION

There are two specific terms driven in this research. The first one is related to bus lane and the second one is concerned with bus signal priority. In terms of bus lane, as presented in the introduction part, bus priority lane type is a popular bus lane type besides ordinary lane type and exclusive bus lane type in Japan. This bus lane type has already been deployed for years in the country (UTMS of Japan). Once an oncoming bus comes in the priority-lane, passenger cars travelling in this lane have to change lane to give space for the oncoming bus (Koyama Kotsu, 2001; The MCB Butler Installation Safety, 2008). It can be understood that the car drivers recognize the priority of the bus in lane usage and respond by changing lane to give space to the bus. Due to this flexibility of passenger cars in lane usage, bus priority-lanes can improve the bus level of service and lessen negative impacts on passenger cars simultaneously. The definitions of three popular bus lane types in Japan can be defined as follows:
For a main street with 2 lanes for each direction, there are possible bus lane types as follows:

- Roadside exclusive bus lane case: The outer lane is an exclusive bus lane. The inner lane is used mainly for other vehicle types (cars, big trucks, small trucks) and partly for buses which may want to overtake or turn right. An image at an exclusive bus lane in Japan is shown in Figure 1.3

![Figure 1.3 An exclusive bus lane](image)

- Bus priority lane case: buses, cars, small trucks and big trucks can use both lanes. However, because the outer lane is the priority lane, non-bus vehicles give up their lanes to buses which are reaching into the recognized distance $D$ of these non-bus vehicles on the priority lane. It means non-buses are allowed to use all lanes, provided that they do not obstruct the bus traveling on the priority lane. An image at a bus priority lane in Japan is shown in Figure 1.4

![Figure 1.4 A bus priority lane](image)

- Ordinary lane case: Buses and non-buses (cars, small trucks and big trucks) can use two lanes and freely change lanes if necessary. An image at an ordinary lane in Japan is shown in Figure 1.5

![Figure 1.5 An ordinary lane](image)

It is easy to recognize that, suffering from low speeds in the case of ordinary lane with mixed traffic flows, the travel time of bus is improved a lot when there are exclusive bus lanes in traffic system. However, it is really wasteful of space when the number of buses is usually much less than that of passenger cars in the case of exclusive case. In addition, the exclusive bus lane affects negatively on general traffic. The bus priority lane seems to relieve the negative effect and improve the bus service simultaneously. However, a comprehensive study on bus priority lane as well as comparison among the three bus lane types has not been
available. Moreover, a criterion relying traffic conditions to decide suitable bus lane types for an urban street has not been identified yet. In addition, the behavior of cars in the scenario of priority lane as well as the way to integrate into simulation models is an important point that should be investigated in this research.

In terms of bus signal priority, the advanced technology systems of the Japanese Urban Traffic Control system helps buses improve the service significantly. Special priority treatments can be provided to buses not only through the exclusive bus lane and the preemption but also through special warning system. The infrared beacon with two-way communication can predict bus arrival time exactly and plays important role in giving priority to buses at signalized intersections. Traditional signal timing techniques usually used in the system are green extension or early green. The illustration is as in Figure 1.6

![Figure 1.6 Public transportation priority systems](Image)

Bus arrival time prediction is an important step in developing bus signal priority models. An accurate prediction could produce a good control when a bus reaches to a signalized intersection. Therefore, improving the accuracy of bus arrival time prediction is an objective in this research. In addition, in a system with many degrees of freedom, the more the degree of freedom is, the more diversified the characteristics of that system are. Similarly, in a public transport system with the two-way communication technique as in Japan, this two-way communication technique can be utilized to improve the efficiency of public transport system. The introduction of bus speed guidance in some research studies may be a good idea to utilize. A compromise between the guidance task and the signal timing techniques should produce a better result in terms of total network delay. These targets should be identified in this research.
CHAPTER 2

LITERATURE REVIEWS

2.1. RELATED STUDIES ABOUT BUS LANE

There are many research studies on bus priority schemes in the past. These bus priority schemes such as reserved bus lanes, bus-only street, with-flow interior bus lane, exclusive median bus way and so on, have been implemented in many urban areas all over the world. The assignment of special lanes to bus or the provision of bus lane types to selected streets has strong effects on traffic operations. Based on studying exclusive bus lanes implemented in Dallas, Texas, USA., Cox (1975) concluded that the level of service of the vehicular traffic was not affected adversely by the assignment of special lanes to buses. Moreover, this assignment creates a reduction in travel time, a reduction in the number of stops and an increase in speed of buses. Besides, the implementation of bus lane improves the level of service of bus transit and attracts additional rider-ship. Then, based on selected streets in the central part of the city of Bangkok, Thailand, Tanaboriboon and Toonim (1983) analyzed the impact on bus movement and car traffic due to provision of with-flow bus lanes on selected streets and there were several conclusions concerning bus travel time saving. With this study, the author pointed out that bus travel time savings varied from 0.11 to 1.66 minutes. Not only for urban street, but for freeways, Huanyu et al. (2003) used the CORSIM simulation model to develop a decision model for determining whether a freeway preferential bus lane can be justified under prevailed conditions. This decision model for determining the most suitable freeway preferential treatment under a given set of local conditions considers the overall average person travel time and sensitivity to traffic compositions, number of lanes, free-flow speeds, occupancy rates under various preferential treatments (including no preferential conditions). The non-linear regression technique was applied to find the relationship about average speeds, the impact of bus volumes on average bus lane speeds, determination of carpool occupancy rate, etc. However, the simulated results were not validated as more field data. The model evaluation was only performed by comparing results from mixed-traffic speed model with those in the Highway Capacity Manual (HCM) and the Bureau of Public Roads (BPR) formula.

Recently, Lin Zhu et al (2010) evaluated the impacts of the planned exclusive bus lane on the western 3rd ring-road expressway in Beijing on traffic running conditions of the expressway by conducting a simulation approach using VISSIM. From designing 2 scenarios (curbside exclusive bus lane scenario and median exclusive bus lane scenario) based on the established simulation model, the authors found that for the mainline of the western 3rd ring-road expressway as well as the whole corridor network, the operational efficiencies of buses, general traffic and all mixed traffic are all improved with the deployment of the exclusive bus lane. The spatial-temporal speed distributions of general traffic have more noticeable characteristics with the deployment of the exclusive bus lanes. Furthermore, the paper also recognized that the median bus lane scenario slightly outperforms the curbside bus lane scenario for the western 3rd ring-road expressway network. Although the study results are of practically significance, Evaluations in the paper were still quite general. Also concerning
with exclusive bus lane, Takeshita et al. (2007) focused on an exclusive median bus lane system in Nagoya Japan. This “Key Route Bus System” was explored with dominant traffic characteristics about higher operation speed and the punctuality as well as mid- and long-term effects. Besides, due to shortages in-vehicle time in exclusive lanes, total travel time for bus passengers decreases. The paper conduct an ex-post evaluation for assessing its “Key Route Bus system” by a number of indicators from operation speed and punctuality, passenger demand to total road capacity in terms of the total number of passengers. From that, the paper regarded Bus Rapid Transit systems as good options of public transport as they provide better services with higher speed and meet higher capacity compared with the traditional buses. Besides, this system demonstrates evidently low capital and operation costs compared to the railways.

Concerning with bus priority lane, Kunihiro et al. (2007) tries to identify the effectiveness of a bus priority lane in Shizuoka City, Japan as a countermeasure for congestion. Based on data collected from before and after the implementation of BRT in Shizuoka, the paper found that there was a reduction in the number of vehicles using main road after introducing priority treatments. Besides, bus travel time including dwell times also reduced together with reduction of traffic congestion and improving travel time of general traffic. Although the author can bring out the effectiveness of priority treatments as a countermeasure for traffic congestion and for Modal Shifting of Transport options, this research is just based on empirical data. There are many factors inside that we obtain difficulty, and sometime unable to collect. Thus developing a better approach to comprehensively analyze is necessary.

Besides, the impacts of bus lanes on bus performance and general traffic have been received much attention. By considering the effect of an urban reserved bus lane on bus travel time for individual segments, Shalaby and Soberman (1994) reported that the bus lane has little impact on bus performance during off-peak periods or when traffic is low. Besides, due to the macroscopic simulator TRANSYT-7F, Amer S. Shalaby (1999) concluded several impacts of reserved bus lanes for the study case in downtown Toronto, Canada. Furthermore, the advantages of exclusive bus lane were surveyed when SEO, Young Uk et al. (2005) setting-up a methodology and criterion of exclusive bus lane based on finding a travel equilibrium point. This point is found by making the travel time between bus and automobile equal after operating it. Since then, they recognized that exclusive bus lane is useful only to equilibrium points with specific total traffic volume and bus volume. And not long ago, Venkatachalam Thamizh Arasan et al. (2008) focused on studying the impact of exclusive bus lanes on the flow of highly heterogeneous traffic on urban roads. The paper developed a simulation model of heterogeneous traffic flow for simulating heterogeneous traffic flow for specific purpose in the research. From that, the flow characteristics of heterogeneous traffic on selected stretches of urban arterials with specific reference to bus movement were investigated and the impacts of exclusive bus lanes introduced on urban arterials, for a wide range of traffic volume levels were studied by applying the validated simulation model. They proved that if an exclusive bus lane is provided under highly heterogeneous traffic conditions, the maximum permissible volume to capacity ratio that will ensure a level of service of C for the traffic stream comprising all the motor vehicles, except the buses, is about 0.53.

It is clear that most of the studies focused on exclusive bus lanes and others, the bus priority lane has been received less attention. The behavior of cars under bus priority lane effects as well as criteria of choosing bus lane types is not identified yet. This will be a big target in this research.
2.2. RELATED STUDY ABOUT BUS SIGNAL PRIORITY.

As mentioned before, bus signal priority control goes together with the accuracy of bus arrival time prediction. Related to the title, there are two groups reviewed in this part. One group is about arrival time prediction model and another is on bus signal priority control.

2.2.1. Research studies on travel time prediction

The accuracy of bus arrival time prediction plays an important role in the effectiveness of signal priority systems. There have been many methodologies for arrival time prediction. However, each methodology has its limitations. Indeed, Weerasooriya et al. (2008) simply assumed the bus arrival time as a constant. This simple assumption affects the efficiency of bus signal priority model. In fact, the bus arrival time is sensitive to the traffic volume and other factors. Shalaby et al. (2004) used AVL and APC dynamic data to develop a Kalman based bus travel time model capable of providing real-time information on bus arrival and departure times to passengers and to transit controllers for the application of proactive control strategies. Similarly, Chen et al. (2004) used real world APC data to develop a travel time prediction methodology based on an arterial neural network (ANN) model. Based on the Kalman Filtering Techniques, the proposed dynamic algorithm ANN models generally give a better estimate of travel times than the timetable. The methodology developed in this study can be used for providing real-time bus-arrival time prediction for each time point along the route. Based on detector data, signal controller data and saturation flow data, Bhaskar et al. (2007) presented a methodology to estimate average travel time on signalized urban networks using analytical procedure. The research divided into three different cases of data availability to evaluate the model performance. Although the model provides a reliable and good estimate for average travel time on a link between two consecutive signalized intersections, there was huge inconsistency in travel time estimation in some cases. Bus arrival time estimation was also done by using traffic signal database and shockwave theory in a research of Rahman et al. (2010). The authors developed a new approach to incorporate intersection delays in bus arrival time estimation. The developed approach can incorporate the intersection delay well in real time bus arrival time estimation. However, the pre-timed signal is not suitable for actuated control that is popular in modern societies. In addition, the macroscopic level does not reflect the real traffic nature in which the individual behaviors are specific. Probe vehicle data is also a useful resource used to estimate arrival travel time by converting bus trajectory to general traffic travel (Song et al., 2010). However, the data lost from probe vehicles as well as signal effects are main limitations needed to be overcome. To predict arrival time, the developments of linear regression models or adaptive algorithms (Chiou et al., 2003; Bo et al., 2010) have been investigated much in previous studies. However, the effects of signalized intersections, especially queue length, queue delay, etc. are important to the accuracy of the prediction model as well as the effectiveness of bus signal priority system.

2.2.2. Research studies on bus signal priority control

The concepts of priority and preemption are brought out clearly in this research. These concepts have been mentioned in some previous studies (Chang et al., 1996; Hsu et al., 2003; Wadjas et al., 2003; Chiou et al., 2003; Weerasooriya et al., 2008; Arasan et al., 2008; Eleni et al., 2011). Indeed, Chang et al. (1996) explored the advantage of integrating bus-preemption with adaptive signal control. Two integrated models with the absence and presence of automatic vehicle location (AVL) systems were introduced in the research. The experimental results proved the superiority of the proposed adaptive control model without preemption over the actuated control logic simulated by NETSIM, under all traffic conditions. Hsu et al.
(2003) developed a bus preemption signal control model that can deal with near-side bus stops and competition problems. The research built the model with four modules: green extension, red truncation, competition, and balance module and investigated under various traffic conditions and physical conditions. The research concluded several conditions for a food performance of the bus preemption model. Wadjas et al. (2003) developed and tested the concept of advanced detection and cycle length adaptation as a strategy for providing priority for transit vehicles. The control strategy identified substantial improvements to transit travel time as well as regularity with negligible impacts to private traffic and pedestrians. The proposed strategy is found to be more effective than simple preemption. The positive role of public transportation can be found more in the research of Chang et al. (1996), Tanaka et al. (1996), Sakakibara et al. (1999), Hsu et al. (2003), Wadjas et al. (2003), Shalaby et al. (2004) Hongchao et al. (2008), Arasan et al. (2008), HCM2010, etc. Although there have been many research studies about signal priority in the past, the priority with bus guidance task has not been received much. Indeed, the California PATH Center (Liu et al., 2003) has developed many models to improve bus service and minimize negative impacts on vehicles. The report presented ways to develop APIs for actuated signal, signal coordination and ramp control Recently, the models for bus signal priority have been developed by considering bus queuing delay at traffic signals when triggering TSP requests (Weerasooriya et al, 2008) or minimizing the intersection delays (Li, 2010; Eleni et al 2011). Li (2010) proposed an active TSP systems to granting priority to buses. The quantitative models with limited traffic detection inputs and constraints from state-of-practice signal control systems were evaluated properly. The research investigated the TSP impacts on pedestrian flows as well as the TSP coordination crossing multiple intersections. The developed model demonstrated significant benefits on bus movement while minimizing the impacts to other vehicular traffic and pedestrian traffic. Some research studies developed the models with not only a heuristic algorithm (He et al, 2011), a dynamic Programming Model (Wanjing et al 2011), analytical approaches (Hongchao et al 2008) but also practical approaches (Tanaka et al 1996; Wang et al 2010). The development is not also for a single request (Weerasooriya et al 2008) but also for multi requests (Lee et al 2005; Wanjing et al 2011) or for conflicting transit routes (Eleni et al 2011). It can be said that most of the research studies developed models for bus signal priority based on traffic volume, signal state or information related to buses. The research on bus guidance task by coordinating the bus speed and traffic state to grant priority bus has received less attention. In a research aiming at introducing the benefit of road side infrared beacons in a new public transportation system, an idea for two-communication application in improving the bus priority system has been proposed and conducted a trial operation test (Tanaka et al 1996). In this system, road side infrared beacons play an important role in two-way communication between bus drivers and the traffic control center. When the infrared beacon detects a bus, the bus information can be sent to the traffic control center and a recommend speed for the bus can be transmitted to the bus driver through In-vehicle Units in the bus. This study conducted an empirical test and concluded limitedly the benefits to bus. The effects on non-bus vehicles were not studied. Moreover, this is just a practical test, a detailed model for this system has not been considered. The recommended speed should depends on bus physical attributes, current traffic group signal state as well as the traffic demand on each approach of each intersection. These influences have not been investigated yet. Recently, Yang et al (2012) introduced the concept of bus guidance in a research for BRT network. In this research, the concept of transit speed guidance was used in the model to simulate signal priority systems in order to improve bus efficiency. However, the purpose of bus guidance in that research is just for easy prediction of bus arrival at a certain intersection. Its contribution to the efficiency of signal priority system was not studied enough.
2.3. RESEARCH OBJECTIVES

The main objectives of this dissertation are expressed as follows:

- For bus lane system, the research firstly aims at evaluating the effectiveness of the three types of bus lane, including exclusive bus lane, ordinary lane and especially bus priority lane in the improvement of traffic conditions. Based on the evaluation, the research secondly identifies criteria for choosing bus lane type in terms of delay reduction. The research thirdly investigates the behavior of passenger cars under bus effects in the case of bus priority lanes as well as presents ways to integrate the behavior into simulation models in PARAMICS.

- For bus signal priority system, the research aims at enhancing the efficiency of bus operation traveling through isolated signalized intersections and arterial roads with multi-intersections. As for isolated intersections, the proposal for bus arrival time prediction models as well as improvement in optimization algorithms of GA is the first target to update the efficiency of bus signal priority models. After that, investigation into intersection performance under different levels of bus priority is another target to understand comprehensively the effects of each bus priority scheme. As for arterial roads with multi-intersections, the research utilizes the two-way communication through Infrared beacons in Public Transportation system in improving the efficiency of bus service in arterial roads with multi-intersections. The improved model that relies on the coordination between bus speed guidance and signal timing techniques in this research is expected to have a good performance in terms of traffic delay reduction.
CHAPTER 3

METHODOLOGY

As mentioned in the title, there are two kinds of priority system being studied in this dissertation. The first one is bus lane system in which special treated lanes are designed for bus operation. The three popular bus lanes in Japan including exclusive bus lane, bus priority lane and ordinary lane are the objectives of this system. For the second system, developments of bus signal priority models are the main targets to improve the efficiency of bus system. The research studies not only for an isolated signalized intersection but also for arterial roads with multi-intersections. The general methodology of the research goes through following main parts:

- Proposal of improved models
- Data collection for model calibration and traffic simulation
- Calibration of the parameters of the proposed models
- Integration of the proposed models into simulation models
- Simulations in PARAMICS
- Model evaluation

The relations between these parts are as shown in Figure 3.1.

![Figure 3.1 General methodology](image-url)
3.1. PROPOSAL OF MODELS

3.1.1. Bus lane system

Car lane changing models are the target when investigating the bus lane system. In the scenarios of exclusive bus lane as well as ordinary lane, the effect of buses is assumed to be not significant to affect the lane changing behavior of cars in this research. For the scenario of bus priority lanes, the effect is obviously clear and a car lane changing model is necessary to be proposed to model the real behavior. The lane changing behavior of the proposed model is illustrated in this section. If a non-bus vehicle traveling in a priority lane recognizes oncoming buses coming in the same lane, the non-bus vehicle will find suitable lane changing conditions to change lane to give space to the buses. Otherwise, the non-bus vehicle will travel as default without any bus effect. The general structure of the car-lane changing model under bus priority lane effects is shown as in Figure 3.2

![Figure 3.2 The structure of the lane changing behavior](image)

Because the purpose of this chapter is to show the general methodologies used in the research, the suitable conditions as well as further developed models will analyzed in every detail in chapter 4.

3.1.2. Bus signal priority system

Concerning bus signal priority system, the objective functions for each signal timing technique are the main points that the research would like to mention. The objective functions are built based on two popular signal timing techniques including early green and green extension. To decide which signal timing technique as well as how much the share for each movement, the research solves the objective functions by using genetic algorithm (GA). According to HCM2010 (TRB 2010), the minimum green interval to ensure the walking time is expressed as follows:

\[
G_{\text{min,i}} = 3.2 + \frac{L_i}{v_p} + \left(0.81\frac{n_{p}}{w_c}\right)
\]
where,

\( L_i \): the width of the intersection at approach \( i \) (m)
\( v_p \): the average walking speed (m/s)
\( w_c \): the width of the crosswalk (m)
\( n_p \): the number of pedestrians (persons)

Optimizing the objective functions result in necessary information for signal control. The objective functions are built based on the boundary constraints of speed, signal cycles, offset, minimum green time for pedestrian, etc with the details for isolated intersections and for arterial roads as shown in the following parts.

### 3.1.2.1. For isolated intersection

There have been many research studies developing the model and trying to minimize the bus delays caused by signalized intersections. For comparison purposes, this part only aims at building a simple model and comparing the priority strategies with different priority levels. The traffic system is a signalized intersection that has an infrared beacon upstream on the main street. This beacon is to recognize coming buses for priority calls. The procedure is as follows.

![Figure 3.3 Studied signalized intersection.](image)

*Figure 3.3 Studied signalized intersection.*

![Figure 3.4 Algorithm to create DLL in PARAMICS for bus lane](image)

*Figure 3.4 Algorithm to create DLL in PARAMICS for bus lane*
As mentioned before, two techniques are used in this research. They are early green and green extension. For the early green technique, the delays include non-bus vehicle delays and bus delay as shown in Figure 3.5. The total traffic delay for the early green technique includes two parts: traffic delays and bus delays which as illustrated as follows:

\[
d_{\text{early}} = \sum_{i=1}^{8} \mu_{ij} \frac{\rho_{ij} r_{ij}^2}{2} + \frac{R}{T_q} \max(T_q - T_{bus}, 0)
\]

where

\[
\rho_{ij} = \frac{\lambda_{ij}}{\mu_{ij} - \lambda_{ij}}
\]

\(\lambda_{ij}\): the arrival rate at approach \(i\) of cycle \(j\) (veh/s)

\(\mu_{ij}\): the saturation rate at approach \(i\) of cycle \(j\) (veh/s)

\(r_{ij}\): the red time for approach \(i\) of cycle \(j\) (s)

\(T_{bus}\) is bus arrival time at signal (which reference to the beginning of the red duration for the bus phase). Buses are assumed to come on approach 1, the queue is dismissed at:

\[
T_q = \frac{\mu_{ij}}{\mu_{ij} - \lambda_{ij}} R_i
\]

For the green extension technique, the considered delays only include non-bus vehicle delays. The bus delay in this case is zero. Therefore, the total traffic delays is as follows:

\[
d_{\text{Ext}} = \sum_{i=1}^{8} \frac{\mu_{ij} r_{ij}^2}{2} \rho_{ij}
\]

For the sake of simplicity, the research compares the delays in the cases of early green \((d_{\text{early}})\) and green extension \((d_{\text{Ext}})\) to choose the better one.

![Figure 3.5 Delay of buses and general vehicles.](image)

*Source: Li, M (2010)*

The target of this part is to compare the intersection performance among bus signal priority strategies including the bus signal priority, bus preemption with exclusive bus lane, bus preemption without exclusive bus lane and the base case without any priority treatment. The preemption scenarios let buses have priority as soon as the network can. Therefore, the objective functions of preemption scenarios are not necessary is due to itself characteristics. The details of each scenario will be presented in the integration part of this chapter as well as in chapter 5.
3.1.2.2. For arterial with multi-intersections

a. The structure of the model

Usually, concerning bus signal priority in arterial roads, traditional research studies had trends to control the signal groups to optimize the green bandwidth. A compromise between signal status, green bandwidth and traffic demands is necessary to grant priority to bus and diminish negatives effects on non-bus vehicles simultaneously. Unlike traditional ways of bus priority strategy, the paper develops a model to simulate bus priority through arterials by both signal adjustments (do nothing, green extension or early green) and providing bus driver with recommended speed to traverse smoothly through the arterials. Being setup at the road side around 150m upstream from the first intersection, an infrared beacon can recognize the bus coming and help send bus information to the traffic control center. The current bus speed and bus physical attributes are important for the prediction module to predict the bus arrival time at the stop lines. Combining with traffic information and signal group status, an optimization program can be done to get the optimal recommended bus speeds and sets of signal timing at each intersection of the group. Based on the two-way communication between bus drivers and traffic control center, the information of recommended speeds is sent back to bus drivers through an In-vehicle unit. Bus drivers can control the bus speed following the speed guidance. At the same time, the control signal will be sent to each intersection in the group to control the signals (early green or green extension or do nothing). The structure is shown in Figure 3.6 and Figure 3.7.

**Figure 3.6** A hypothetical arterial road

**Figure 3.7** Algorithm to create a plugin in PARAMICS for BSP
b. Objective function
The research assumes that in the most extreme cases, the residual queue exists within one cycle. The delay includes the delay of non-bus vehicles and that of buses as shown in Figure 3.5. The total delay of a traffic system in three consecutive intersections will be considered in the objective function. The objective function is simplified as shown in the following formula:

\[
d = \sum_{k=1}^{K} \sum_{i=1}^{k} \left( \frac{\mu_{ki}}{2} \rho_{ki} (r_{ki} + r_{k2i} + \delta_{ki} \cdot \alpha_{ki} + \alpha_{ki})^2 - (r_{ki} + \alpha_{ki}) \mu_{ki} \min[\delta_{ki} \cdot (r_{ki} + \alpha_{ki})] \right) + w_b \sum_{k=1}^{K} \max(T_{ib} - T_{ik}, 0)
\]

where

\[
\delta_{ki} = \begin{cases} 
0 & \text{if } g_{ki} - (t_{ok} + T_k) \leq 0 \\
1 & \text{otherwise}
\end{cases}
\]

\[
\rho_{ki} = \frac{\mu_{ki}}{\mu_{ji} - \lambda_{ij}}
\]

\[v_k(t) \leq V_{max}\]

\[v_0(t): \text{the recommended speed at time } t \text{ at intersection } k \text{ (m/s)}\]

\[T_{kb}: \text{bus arrival time at signal of intersection } k \text{ (which reference to the beginning of the red duration for the bus phase)}\]

\[V_{max}: \text{the maximum speed of bus (m/s)}\]

\[K: \text{the number of studied intersections (intersections)}\]

\[\lambda_{kij}: \text{the arrival rate at approach of cycle } j \text{ at intersection } k \text{ (veh/s)}\]

\[\mu_{kij}: \text{the saturation rate at approach } i \text{ of cycle } j \text{ at intersection } k \text{ (veh/s)}\]

\[r_{kij}: \text{the red time for approach } i \text{ of cycle } j \text{ at intersection } k \text{ (veh/s)}\]

\[g_{kij}: \text{the green time for approach } i \text{ of cycle } j \text{ at intersection } k \text{ (s)}\]

\[a_{kij}: \text{the adjusted time for approach } i \text{ of cycle } j \text{ at intersection } k \text{ (s)}\]

\[w_b: \text{the bus weight}\]

The queue is dismissed at:

\[T_q = \frac{\mu_{ij}}{\mu_{ij} - \lambda_{ij}} - R_i\]

3.2. DATA COLLECTION
The research uses two ways to collect data. The first way is direct observation from the studied sites. The second one is the record of video and analysis in the transportation lab. The recorded videos are analyzed based on a computer software, namely SEV.exe, developed by the authors of the paper of Minh, C.C et al (2006). The details of analysis technique as well as collected data are presented as follows.

3.2.1. Analysis technique
After capturing the traffic flow from the study site, the video clip with 640x480 pixels resolution will be input to the software. According to Minh (2007), this software can measure multi-positions of a vehicle over time interval as low as one thirtieth of a second and can be repeated several times to verify preceding results or recollect missing data as well as to skim unnecessary data. The ability of measuring the trajectory of several vehicles simultaneously as well as user-friendly operation of the SEV is advantages to be employed to select
information from raw data in the videos and to carry out statistical analysis. The output file is an Excel compatible file, which has advantages in analyzing numbered data and operating necessary functions. The data collection and extraction using video recorders, media player, and SEV software can be as illustrated in Figure 3.8.

![Diagram of data collection and extraction using video techniques](image)

**Source:** Minh (2007)

**Figure 3.8** Diagram of data collection and extraction using video techniques

### 3.2.2. Collected data

For a traffic network, the collected data includes geometrical data, control data and Traffic data as presented in previous studies and reports. The geometric data consists of the number of lanes, width, length, grade, designed speed, the designated turn lanes, curb turn radius and horizontal curvature of street segments, etc. From aerial photos and field works, all these above information is collected. As for traffic data, the research records video tapes and analyzes the recorded videos in the urban transportation lab to extract information concerning with turn volumes, bus schedules, travel times, traffic counts. The data was extracted and processed with Microsoft Excel. The necessary data includes vehicle type, traffic proportion, traffic volumes, bus routes, vehicle travel time, etc. For control data, from field inspections, all information about traffic signals, priority rules are collected and input into the simulation models.

### 3.3. INTEGRATION INTO SIMULATION MODELS

Firstly, the research would like to confirm that the proposed model can be applied to simulate in any software. Indeed, although various simulation software is different from the way to use, how to call, etc., basically they have the same functionality of operation. In addition, the proposed models with estimated parameters in this research are independent from which simulation software. Secondly, the research would like to introduce PARAMICS as a tool to simulate. The integration into simulation models in PARAMICS has two levels in this research. The simple level is executed by using available tools in PARAMICS software. The complex one is implemented by developing dynamic linking library (DLL) in PARAMICS Programmer to connect to PARAMICS Modeler. The module Programmer of PARAMICS allows users to override the core of PARAMICS to change the behavior of vehicles. The programs for API is coded based on C++ and available functions in PARAMICS Programmer. The process of integration for the complex level is as in Figure 3.9

![Figure 3.9](image)
3.3.1. Bus lane system

The purpose of this part is to show the way of simulation of three popular lanes, including ordinary lane, exclusive bus lane and bus priority lane in PARAMICS. For exclusive bus lane and ordinary lane, it is easy to simulate in PARAMICS without any API development. The research uses available tools about vehicle restriction, public transport design (bus routes, vehicle type, bus stops, stop time, etc.) to complete the simulation. The ordinary and exclusive cases follow the core of PARAMICS with some constrained sets by the users. As for the case of ordinary lane, the movement of buses and that of other vehicles is considered as the same role in using lane and changing lane. Vehicles and bus joining traffic will follow the lane change model and car following model. As for the case of exclusive lane, vehicle and bus are also following the above models, but by setting lane restrictions for bus and other vehicles, there is a hard separation between the lane for bus and others. Buses and other vehicles cannot change lane through the separation.

For bus priority lanes, the default PARAMICS cannot simulate this kind of scenario. It is necessary to override the default core in PARAMICS by developing specific API for it. According to the manual of PARAMICS Programmer, it is possible to override the default lane changing model in PARAMICS by using the functions of Move_In and Move_Out and set_lanechange. These functions can be called at every step of simulations. The function for critical gap modification is also available for overriding critical lead gap and critical lag gap. The functions of vehicle position determination are utilized to determine the real gaps as well as the distance between buses and vehicles. The distances between the buses and such vehicles are determined as the following formula:

$$d_{bus(i) - j} = \sqrt{(x_{bus(i)} - x_{j})^2 + (y_{bus(i)} - y_{j})^2}$$

where

$(x_{bus(i)}; y_{bus(i)})$ : Co-ordinates of bus $i$

$(x_{j}; y_{j})$ : Co-ordinates of vehicle $j$ moving in front of bus $i$

By using available functions in PARAMICS Programmers, the research programs codes in C++ to create a dynamic linking library (DLL) with the algorithm as follows:
3.3.2. Bus signal priority system

In this section, the research would like to show ways to simulate a signal timing technique as well as how to override the car following model for bus guidance mechanisms proposed in bus signal priority controls. For the simulation of signal timing technique, the green extension, early green or doing nothing are the main objectives. For overriding the car following model, the possibility of increase of bus speed according to recommended speeds is the objective to developing an API in PARAMICS. The details are as follows.

### 3.3.2.1. Bus signal timing technique

In this research, the signal timing techniques for the scenario of preemption and bus priority are executed in different ways. For the scenarios of preemption, the research uses text files (*plans.txt* and *phases.txt*) to integrate into the simulation in PARAMICS. These files with text code determine clearly the private phase for buses in the scenario of preemption. For the scenario of bus priority, the research uses two important functions, a function for parameter acquisition and another for parameter modification. The function for parameter acquisition in PARAMICS Programmer can determine running phase, running moment, cycle time, expired time, stored green, current green, next green, maximum green, minimum green at every step of the simulation time. Meanwhile, the remaining function can modify or execute the signal
operation. It can change or fix a signal parameter, make the cycle of the signal variable or fixed, execute on current green or next green, modify the maximum green, minimum green, stored green or stored red. The procedure to execute the signal control is as shown in Figure 3.11. A priority call is on when a bus is detected by the infrared beacon. This priority call is off only when the bus passes through the last intersection of the intersection group and the compensation cycle is executed completely.

![Figure 3.11 Execution of signal control](image)

3.3.2.2. Modification of the car following model

As mentioned in the previous study (Tanaka et al., 1996), the two-way communication between bus drivers and traffic control center through the Infra-beacon and In-vehicle units help bus drivers know the information of recommended speeds. Bus drivers control the bus speed following the speed guidance. By using functions for overriding speeds in PARAMICS, the bus speed can be set as recommended speed output from optimization function once the bus is detected by the Infra-beacon. The flag assigning to buses for speed override is supposed to be released after the bus pass the last intersection in the group. By creating dynamic linking library (DLL) in PARAMICS, the research uses the algorithm to override bus speeds following the guidance mechanism as in Figure 3.12

![Figure 3.12 Algorithm for bus speed adjustment](image)
3.4. SIMULATION IN PARAMICS

3.4.1. The functionality of PARAMICS modules

Quadstone PARAMICS has many modules that are useful to analyze any traffic situation. There are five modules used in this research. They are PARAMICS modeler, PARAMICS Programmers, Estimator, Analyser and Processor. As introduced in PARAMICS manual (Quadstone, 2013), the functionality of each module is described as follows:

- **PARAMICS Modeller**: The research uses Modeller to build traffic networks. This is a module designed to operate at the simulation level and integrate with the core of PARAMICS. Using available tools in PARAMICS Modeler, the paper creates the traffic network. Besides Modeller tools, text editors (ASCII network files) are also be used to access and modify the network.

- **PARAMICS Programmer**: The research uses this module to develop two API (Application Programmer Interface) plugins. This module is considered as an important key that allows users to overcome the default nature of the simulation program. Through available functions in PARAMICS Programmer, the paper uses C++ to create two plugins for supporting to Modeler. These plugins are bus priority plugin and bus bay priority plugin. The bus-priority plugin is developed for the case of bus priority lane and “bus bay priority” plugin is applied to bus priorities at bus bays in the case of ordinary lane.

- **PARAMICS Processor**: The research uses this module to automate simulation and analysis processes. In PARAMICS, each seed number will generate a result. The results in this paper are obtained from combinations of many times of running (with different seed numbers) owing to PARAMICS Processor.

- **PARAMICS Analyser**: The research uses this module to analyze and report the model statistics. The Analyser can integrate with the core PARAMICS tools and this is a very strong and helpful module in analysis process. The statistic results are combined and analyzed to get final results. The general process is as follows:

![Figure 3.13 General process of executing traffic simulation in PARAMICS](image)

**Figure 3.13 General process of executing traffic simulation in PARAMICS**
3.4.2. Traffic network built in PARAMICS

Conveniences of PARAMICS software help us code the model easily. This is an important step to finish the simulations. Based on data from Internet, we can get the map of study sites and save as under image files. Using these files as tracked maps, the research can build any model with three basic types of data:

- Network geometry: This data includes the number of lanes, intersection positions, zone positions, link lengths, etc.
- Control data: This data includes traffic signs, traffic signal timing, priority control, turn conditions, etc.
- Demands: This data includes the attitude of the zone, the OD distribution, vehicle types, simulation periods, etc.

Following guidelines of using simulation software (Richard et al. (2002); Quadstone (2013)), the research builds models in PARAMICS with following steps:

- Import the aerial photo of the study site and size overlay image
- Set up coding templates including area type, link characteristics, standard link types, etc.
- Draw nodes and then links between nodes over the overlay image
- Assign link attributes including the number of lanes, free-flow speeds, etc.
- Designate attributes for intersection such as control type, control parameters, turn lane designations, stop bars, etc.
- Code source/sink zones or nodes
- Create profile, vehicle types, and origin-destination table for each period simulation.
- Finally, review all parameters

3.4.3. Calibration Process

There are many model parameters needed for calibration process. The research chooses influence factors to calibrate. Other less important factors are ignored due to its variety from community to community. The purpose for this process is to adjust slightly the basic behavioral models to account for the influence of the excluded factors to replicate local behaviors. The process will be divided into small steps. Highly correlated parameters are also categorized to deal with separately. The calibration process is as follows:

3.4.3.1. Control of fixed parameters.

The input code data in PARAMICS modeler is checked. This data concerning coded network data and other parts such as:

- Node positions to meet the accuracy of distances.
- Link positions and link attributes
- Vehicle characteristic parameters
- Intersection, bus bay attributes
- Demand data and traffic signal

3.4.3.2. Control of traffic operation parameters.

Running the model with fixed demand to check vehicle behavior, the research can verify the traffic network from link to link, node to node. The purpose is to minimize the gap between
the estimated flow rates from the model and that from the real field. It is necessary to modify link specific capacity adjustments, such as reaction factor, headway factor, free-flow speed for each link in PARAMICS. As some previous studies (Richard et al. 2002), the concept of the Mean Square Error (MSE), is the sum of the squared errors averaged over several model run repetitions is used to calibrate model parameters

\[
\text{Minimize } MSE = \frac{1}{R} \sum_{r} (M_{r} - F)^2
\]

where

- \( R \) = Number of repetitive model runs with different seeds
- \( M_{r} \) = Flow rate estimated from the model for repetition \( r \)
- \( F_{i} \) = Flow rate from the real field.

### 3.4.3.3. OD estimation

To construct a complete OD table, the step of connecting trip origins to their destinations by distributing the trip is necessary. There are many OD tables which can fix the traffic counts because the degrees of freedom of OD matrix is higher than the number of constrains concerning with traffic links. In gravity model, to get a single OD table, we will add an assumption that the number of trips between two points is directly proportional to the number of trips originating at one point and the number of trips destined to the other point. A “seed” OD matrix is initialized and be modified a little by little until getting the situation in which the link volumes after assigning OD table are equal to the traffic counts. In this research, PARAMICS Estimator is used to estimate the OD from traffic count, pattern OD, cordon values and turn flows. According to Quadstone PARAMICS (2013), PARAMICS Estimator is an OD matrix estimation package specifically designed to operate at the microscopic level and integrate with the core PARAMICS tools. By employing the concept of ‘continuous simulation’ to arrive at the generated OD matrix, the estimator can reach the best OD matrix based on the GEH Statistics. The GEH Statistics (Richard, 2002) is computed as follows:

\[
GEH = \sqrt{\frac{(S - O)^2}{0.5*(S + O)}}
\]

where

- \( GEH \) : The GEH Statistics
- \( O \) : Direct hourly count at a location (vph)
- \( S \) : Simulation hourly count at the corresponding location (vph)

For small traffic networks, the research uses traffic count and turn flow as input to PARAMICS estimator to estimate OD. For the large network of Nagaoka city, the input data for OD estimation process includes not only traffic count, turn flow, cordon but also pattern OD matrix. The research observes directly the values of traffic count, turn flow, and cordon at the studied site. For the OD pattern of Nagaoka city, the research uses the survey data in Population Census of Japan (2005). The process of OD estimation is as shown in Figure 3.14
The target of calibration is to get the best match possible between model performance estimates and field measurements of performance. To stop the calibration process with a certain error, the GEH statistic is used to guarantee acceptability targets. The GEH statistic is an empirical formula that incorporates both relative and absolute differences. Guidelines on its use in comparison of flows and calibration can be obtained from the United Kingdom Design Manual for Roads and Bridges (DMRB Vol. 12 Traffic Appraisal in Urban Areas). An indication of the ‘goodness of fit’ is given below:

- \( \text{GEH} < 5.0 \) - Flows can be considered a ‘good fit’
- \( 5 < \text{GEH} < 10 \) - Flows may require further investigation
- \( 10 < \text{GEH} \) - Flows cannot be considered a ‘good fit’

According to Wisconsin Department of Transportation based on guidelines developed in the United Kingdom, a GEH value of less than 5 for more than 85% of the locations is considered acceptable in United Kingdom practice. This Wisconsin DOT Model calibration criteria will be applied to stop the calibration process in this research.

### 3.5. MODEL EVALUATION

To evaluate the model performance, the research uses Mean Percentage Error (MPE) as a measure of goodness of fit. The definition is as follows:

\[
MPE = \frac{1}{N} \sum_{n=1}^{N} \left| \frac{O_n - S_n}{O_n} \right|
\]

where,

\( S_n \) : Simulation values at point \( n \)
$O_n$ : Observation values at point $n$
$N$ : The number of observation points
CHAPTER 4

BUS LANE SYSTEM

4.1. GENERAL INTRODUCTION

Deploying public transport system in general as well as bus system in particular is an indispensable trend to relieve traffic congestion and improve traffic quality. However, improving the performance of public transport will usually cause unfavorable conditions for non-bus operations. Therefore, city planners have to decide proper policies to take shape of a harmonious and sustainable traffic system. As presented in the introduction chapter, besides the ordinary bus lane type and exclusive bus lane type, another type of bus lane – bus priority lane – has already been deployed (Figure 4.1) for years in Japan. However, there have been very few studies on it. The special thing of this lane type is the complexity of non-buses in choosing lanes and changing lanes to avoid the arriving bus. This priority lane type concerns the degree of exclusivity of not only the bus, but also of the other vehicles. This type can improve the bus travel time significantly and minimize negative impacts on other vehicle types as well.

As mentioned in the chapter of literature review, it is easy to find out many definitions for bus lanes from literature reviews. Indeed, with-flow bus lanes, contra-flow bus lanes, bus ways are defined as link based measures to give priority to buses (Kevin et al, 2009), HCM, 2010), a report released by National Capital Region Transportation Planning Board, Washington (2011), etc. These bus lane types have been main objects in many research studies from the beginning. Typically, the assignment of special lanes to buses was studied with investigations on the changes in bus travel time and bus speed (Cox, 1975). Several papers tried to develop a decision model (Huanyu et al, 2003) for bus lanes, setup methodologies and criteria of exclusive bus lanes (SEO et al, 2005), or investigate the change in travel times when adding lanes to traffic networks (Joy et al, 1998; Venkatachalam, T. A. and Perumal, V., 2008). Effects on bus travels and general vehicle travels were considered not only for with-flow bus lanes (Shalaby, S. A. and Soberman, M. D., 1994) but also for exclusive bus lanes (Lin et al., 2010). These effects were studied not only on hypothetical
traffic networks (Huanyu et al., 2003), but also on real traffic networks (Amer, 1999; Hyung, 2003; Tanaboriboon, Y. and Toonim, S., 1983). Recently, Kunihiro et al., (2007) have examined the effectiveness of bus priority-lane in Shizuoka, Japan. The conclusion was merely based on empirical data analysis. However, because the approach compared two periods, before and after the implementation of BRT, it lacked a comprehensive investigation into concerned factors as well as a comparative analysis on the effects of each bus lane type. Meanwhile, Minh et al. (2007) also modeled bus lane priorities in a motorcycle environment using SATURN with the data collected in Hanoi, Vietnam. However, with this mesoscopic simulation, the individual vehicle behavior was not modeled. Therefore, it affected the accuracy of the results. It is clear from the review of literature that the choice of bus lane types and their effects on vehicle travel times have received less attention. How the vehicle travel times change in each case of bus lane type has not been analyzed and compared appropriately. In addition, the development of proper models for bus priority-lanes has not been received much attention commensurate with its advantages. Therefore, developing a car lane-changing model under bus priority-lane effects is necessary to get a comprehensive understanding about the benefits when bringing it into practice as well.

4.2. OBJECTIVES

The chapter has four targets needed to be finished. These objectives are:

- To evaluate the effectiveness of the three types of bus lane treatment, including exclusive bus lane, ordinary lane and especially bus priority lane in the improvement of traffic conditions; and,
- To assess the importance and the sensitivity of main road traffic volume, the average number of passengers on bus in choosing bus lane treatment.
- To develop a car lane-changing model under bus priority-lane effects in urban streets. Based on the proposed model, comparisons in critical gap characteristics are necessary to clarify the special lane-changing behaviour in the studied situation in particular as well as providing a more comprehensive view on the behaviour of changing lane in general.
- To integrate the proposed model into simulation model in PARAMICS to investigate the network performance under different bus lane types in Nagaoka city of Japan.

4.3. SIMULATION OF BUS LANE TYPES WITH SIMPLE ASSUMPTIONS

4.3.1. Introduction

As defined in the introduction part, exclusive bus lanes and bus priority lanes have themselves specific benefits. The travel time of buses is improved a lot when exclusive bus lanes are deployed as compared to ordinary lane with mixed traffic. However, it is really a waste of road space when the number of buses is usually much less than that of passenger cars in the case of exclusive lanes. Thus, non-bus travel time will be affected negatively in this case. To improve the situation, a traffic system with priority bus lanes is introduced. The questions are how good the traffic performance in each bus lane type is and what would be the threshold in deciding bus lane type for the specific situation. In this section, a simple assumption for car lane changing model under bus priority lane effects is proposed to simulate the scenario of bus priority lanes.

According to a Quadstone PARAMICS technical report (2004), the default lane changing model in PARAMICS follows gap acceptance rule based on the Dynamic Vehicle Unit
The gap acceptance policy plays an important role in the lane changing model. The gap acceptance policy is linked with the car-following model whose accepted gaps are based on the target headway. In order for a lane changing maneuver to take place, the lead and lag gaps (as shown in Figure 4.2) must satisfy the conditions:

\[ g_1 > d_{\Delta V_1} + h v_1 \quad \text{and} \quad g_2 > d_{\Delta V_2} + h v_2 \]

Where,

\[ d_{\Delta V_i} = t_{ri} + \frac{\Delta V_i}{D_i} \quad \text{and} \quad \Delta V_i = v_i - v_0 \]

\( v_N \) is the current speed of Dynamic Vehicle Unit N (DVUN)
\( D_N \) is the maximum deceleration of DVUN

The lane changing behavior depends not only on the above gaps, but also awareness factors (\( \alpha_{awareness} \)) to change lanes. Occasionally, drivers meet acceptable lead gaps, lag gaps, but they do not want to take a lane changing action. The probability for a vehicle changing lanes is:

\[ P_{changing \_lane \_i} = \alpha_{awareness} \cdot P(Lead \_gap \_accep \_tan \_ce), xP(Lag \_gap \_accep \_tan \_ce), = \alpha_{awareness} \cdot xP(G_i^{Lead \_i}(t) > G_i^{cri \_Lead}(t)) \cdot xP(G_i^{Lag \_i}(t) > G_i^{cri \_Lag}(t)) \]

With the above road segment, if \( \alpha_{awareness} \) and \( \beta_{awareness} \) are awareness factors to change from lane 1 to lane 2 and lane 2 to lane 1, respectively, the probability of increasing one vehicle (by lane change) on lane 1 would be:

\[ P_{Increase \_lane \_1} = 1 + (\beta_{awareness} - \alpha_{awareness}) \cdot xP(G_i^{Lead \_i}(t) > G_i^{cri \_Lead}(t)) \cdot xP(G_i^{Lag \_i}(t) > G_i^{cri \_Lag}(t)) \]

Comparing the two mentioned types, namely the priority and the ordinary, the awareness factors are quite different because of the recognition of priority lanes for buses. It is easy to see that the awareness factor for changing lane from lane 1 to lane 2 in the priority case is larger than that in the case of the ordinary lane. Meanwhile, its awareness factor for changing lane from lane 2 to lane 1 is smaller than that in the ordinary case. If assuming that the traffic situations such as lead gaps, lag gaps and the number of vehicles in the road segment are the same in the two above cases, it can be seen that:

\[ 1 + (\alpha_{\text{priority}} - \beta_{\text{priority}}) \cdot xP_{lead \_i} \cdot xP_{lag \_i} > 1 + (\alpha_{\text{ordinary}} - \beta_{\text{ordinary}}) \cdot xP_{lead \_i} \cdot xP_{lag \_i} \]

or \( P_{Increase \_Lane \_1 \_Priority} < P_{Increase \_Lane \_1 \_Ordinary} \) or \( Traffic \_density_{on \_Lane1 \_Priority} < Traffic \_density_{on \_Lane1 \_Ordinary} \)
On a road segment that is long enough for a bus not to change lanes, the bus travel time on that road segment is directly proportional to the traffic density on that bus lane. Therefore, bus travel time on lane 1 in the priority lane case is usually smaller than that in the case of the ordinary lane. The advantages in bus travel time when deploying bus priority lanes instead of ordinary lanes can be seen clearly. But how much the reduction would be and how it impacts on the non-bus movement, will be the subject of this study.

4.3.2. Simple assumptions for lane changing behavior

To simulate the bus priority lanes in PARAMICS, the research firstly assumes the behavior of cars under priority lane effects in the scenario of bus priority lane. Through rear-view mirrors, the visibility of the driver of leading vehicles to recognize any bus at the rear is in the range $D$ from 20m. to 60m. Therefore, vehicles within the distance of 20 m. – 60 m. ahead from the bus will have following responses:

- If a vehicle (non-bus) and the bus travel on the bus priority lane (the vehicle now travels on lane 1), the vehicle, if possible, changes its lane to lane 2, to give way for the coming bus (as shown in Figure 4.3).
- If the vehicle now travels on lane 2, this vehicle will not be allowed to change lanes to lane 1 (bus priority lane).

![Figure 4.3 Vehicle changes lane to give space for prioritized bus](image)

The above lane changes have two exceptions: one exception for the case of that vehicles want to turn left at the intersection, and another for the case of that the vehicles can not change lanes concerning with having no any acceptable gap for them to change lanes. This simple assumption is used to create a bus-priority plugin through Programer module with assistances of C++ program. The algorithm of this plugin is illustrated in chapter 3.

4.3.3. Studied site.

The study site is a main arterial which lies partly on the route No.351 and partly on the segment route No.36 leading to Nagaoka station. From field inspections, an around 500 m long segment of this arterial which is calculated from the station towards the direction to Oteohashi bridge has a large number of buses passing through and a high traffic volume in comparison with other areas in the city. As a gate entering Nagaoka station, this arterial plays an important role in increasing transport capacity and creating convenience for traffic participants. To collect a comprehensive data for this arterial, 10 cameras were placed as shown in the following figure to observe traffic during the period from 7.30AM to 9.30AM. Four cameras were set at 4 intersections to record traffic volume on the main street, the side streets and turn traffic volumes. The remaining cameras were used to video at bus stops. To get the accuracy of travel time calculation and the time bus coming, all cameras started at the
same time and they had the same local clocks. The traffic arterial and locations to locate video cameras to observe traffic are as follows:

![Figure 4.4 Camera’s locations for data collection](image)

**Figure 4.4** Camera’s locations for data collection

![Figure 4.5 Location of camera for data collection](image)

**Figure 4.5** Location of camera for data collection

The traffic arterials are displayed with the map and the interface in PARAMICS:

![Figure 4.6 The study site (left) and Network built in PARAMICS (right)](image)

**Figure 4.6** The study site (left) and Network built in PARAMICS (right)
4.3.3.1. Control data and traffic proportion

The details of this kind of data are shown as follows:

Except buses, the traffic proportions of cars, small trucks and big trucks at the studied site are expressed as follows:

![Figure 4.7 The studied traffic arterial (Time 7h30-9h30, May 13th 2010)](image)

![Figure 4.8 Traffic proportion.](image)
Based on the observed data, the research divides the main traffic volume and side traffic volumes into 3 periods: before peak hour, peak hour and after peak hour. During the peak hour, the main traffic volume on the direction to the station is around 534 veh/h and 365 veh/h on the opposite direction. The detailed traffic volumes are displayed in the part of comparison between simulated flows and observed flows at the end of the following calibration process.

4.3.3.2. Calibration Data

This kind of data concludes performance data such as travel time, speeds, delays, queues, etc. For simplicity, this research focuses on collecting vehicle speeds based on a developed software (Minh, C.C et al (2006)) and travel time from intersections to intersections. The data is collected simultaneously with the traffic counts. The observed data in this research cover the entire peak period (from 8h00 to 9h00), starting from the moment before peak hour (from 7h30), lasting until beyond the end of the peak hour, reaching to 9h30.

4.3.3.3. Bus routes

By allocate recorded video as shown in Figure 4.9, the research can obtain the bus routes as well as its figure. At the surveyed traffic corridor, there are 13 bus routes during the peak period from 7h30 to 9h30 (Collected day: May 13th 2010). The number of buses following its route is listed as Table 4.1 and Figure 4.9

<table>
<thead>
<tr>
<th>Bus routes</th>
<th>Quantity (buses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus route No.1</td>
<td>14</td>
</tr>
<tr>
<td>Bus route No.2</td>
<td>1</td>
</tr>
<tr>
<td>Bus route No.3</td>
<td>1</td>
</tr>
<tr>
<td>Bus route No.4</td>
<td>7</td>
</tr>
<tr>
<td>Bus route No.5</td>
<td>39</td>
</tr>
<tr>
<td>Bus route No.6</td>
<td>31</td>
</tr>
<tr>
<td>Bus route No.7</td>
<td>24</td>
</tr>
<tr>
<td>Bus route No.8</td>
<td>20</td>
</tr>
<tr>
<td>Bus route No.9</td>
<td>11</td>
</tr>
<tr>
<td>Bus route No.10</td>
<td>14</td>
</tr>
<tr>
<td>Bus route No.11</td>
<td>23</td>
</tr>
<tr>
<td>Bus route No.12</td>
<td>10</td>
</tr>
<tr>
<td>Bus route No.13</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 4.1 The number of buses on each bus route during 7:30-9:30
4.3.4. Model validation

4.3.4.1. Traffic flow validation

Based on the simulation results and observation data, the traffic flows in four intervals during the peak hour from 8:00AM to 9:00AM are plotted around the 45-degree line, as shown in the following figure:

**Figure 4.9** Bus routes at the study site from 7:30AM to 9:30AM
The coefficient of determination $R^2$ at each interval is very high, it means that the simulation results get the perfect explanation and the simulated traffic flow can be considered as the reproduction of the observed flow. With the same traffic volume, if the traffic patterns, traffic speeds are different, traffic characteristics would not the same. Therefore, not only traffic volume, but also the vehicle travel time will be considered as parameters for validation. The details of the results for the validation are explained in the following part.

4.3.4.2. Travel time validation

The way to calculate travel time in this research is based on the time that vehicles transfer from intersection to intersection. Based on vehicle number plates, vehicle types, vehicle color and the synchronism of local clocks at the intersection 1 and intersection 4, the general vehicle travel times, bus travel time when traveling from intersection 1 to intersection 4 (A1A2 segment shown as follows) is calculated and used to validate the base scenario. The intersection 1 and intersection 4 is shown in Figure 4.11.
Vehicle travel time calculated from the video tapes and vehicle travel time simulated from PARAMICS modeler are compared based on vehicle types (bus and non-bus), and time interval during the peak hour. The details are as follows:

The travel times of bus and other vehicles on the main street in the observation case and simulation case are approximately same. The mean percentage errors of travel times of bus and non-bus are less than 5% at each considered interval.

4.3.5. Comparative analysis.

After validating the base scenario for the ordinary lane, the research investigates two more cases, exclusive lane case and priority lane case based on the available traffic arterial road. These two cases utilize the geometry figures, the current traffic volumes, bus schedules, etc but change the policy for traffic activities. In the case of exclusive bus lane, the most left lane is used only for bus. The right lane is used mainly for cars, trucks, small trucks and buses which want to overtake or turn right. In the case of bus priority lane, buses and other vehicles (car, small truck, big truck) can use all lanes, but in this case, the most left lane is a bus priority lane. It means that, other vehicles (car, small truck, big truck) traveling in the bus priority lane will change lane to give space for bus coming on that lane. This lane change behavior happens only if the change lane conditions of critical gaps are satisfied.

The traffic treatments such as exclusive lane or priority lane are executed mainly on the main street. Therefore, choosing road segments covering the main street to compare the changes in traffic travel time when applying these treatments to the arterial is necessary. The research chooses the segment from the intersection 1 to the intersection 4 as the place to compare traffic characteristics. The total length of this segment is 495m, including 4 consecutive
intersections along the main street. The segment (A1A2) is displayed like the following figures:

![Figure 4.13 Road segment for traffic comparison among the cases](#)

With the same traffic conditions but differences in policy (ordinary lane case, priority lane case and exclusive lane case), the traffic performances during peak hour from 8:00 to 9:00 in 3 cases are different as shown in the following charts. The research compares bus travel time and general vehicle travel times for each simulation interval. The peak hour will divided into 4 intervals, from 8:00 to 8:15, from 8:15 to 8:30, from 8:30 to 8:45 and from 8:45 to 9:00. To show more clearly the advantages and disadvantages of each treatment, the changes in travel time among cases will be concretized and illustrated in the figures. On the studied direction, the bus travel time and non-bus travel time at each interval during the peak hour are displayed in Figure 4.14 and Figure 4.15.

From the figures, the bus travel times in the case of exclusive bus lane and bus priority lane are reduced significantly compared with bus travel time in the ordinary lane case. Meanwhile, non-bus travel time does not change so much when comparing the bus priority lane case and the ordinary lane case. The reductions in bus travel time in the bus priority lane case are 2.9%, 5.1%, 3.9% and 2.6% at each interval of the peak hour in comparison with the ordinary lane case. For the exclusive bus lane, reductions in bus travel time were 5.6%, 6.3%, 8.0% and 4.0%. On the average, the bus travel times in the bus priority lane case and exclusive bus lane case have been reduced by 3.63% and 5.98%, respectively during the peak hour. As for non-bus travel time, the increases were 1.0% (period from 8:00 to 8:15), 1.6% (period from 8:15 to 8:30), 2.3% (period from 8:30 to 8:45) and 2.2% (period from 8:45 to 9:00) for the bus priority lane case compared with the ordinary lane case. Meanwhile, non-bus travel times in the exclusive bus lane case increased significantly by 2.8%, 5.5%, 12.2% and 7.3% at each 15-minute interval of the peak hour period. Generally speaking, the non-bus travel times were not significantly different between the ordinary lane case and the case of bus priority lane. The non-bus travel times on the average increased by about 1.78% for the bus priority lane case and 6.95% for the exclusive bus lane case during the peak hour. Although the exclusive bus lane can reduce the bus travel time significantly, the non-bus travel time also increases greatly. With the bus priority lane treatment, bus travel time can be reduced considerably while there is a slight increase in non-bus travel time.
The non-bus vehicle travel times are different insignificantly between the ordinary lane case and the case of priority. Meanwhile, for the case of exclusive bus lane, the other vehicle travel times increase significantly. Averagely, the vehicle travel times increase around 0.18% for the priority case and 12.5% for the exclusive lane case during the peak hour from 8:00 to 9:00. In a word, for the direction to the station, the performances of 3 cases of bus lane in term of travel time can be seen clearly through this comparison. Although the exclusive bus lane can reduce a lot bus travel time, the car travel time also increase so much. With the bus priority lane treatment, bus travel time can be reduced so much along with the slight increase in vehicle travel times.

4.3.5.1. The decision on choosing bus lane type.

During the peak hour, there were 28 buses that passed segment A1A2 on the direction being studied. Based on the observation, the average number of passengers on each bus was 19.4 with the standard deviation of 3.2 for 28 buses and on each non-bus is 1.25 with the standard deviation of 0.4 for 110 passenger cars. Converting all bus travel times and non-bus travel times into passenger travel time, the time needed for one passenger going from intersection 1 to intersection 4 can be estimated with the results illustrated in Figure 4.16.
It is clear that compared with the exclusive bus lane and the ordinary lane case, the bus priority lane case had better performance in reducing passenger travel time. For this direction, the bus priority lane treatment can reduce travel time by 1.2 sec. (or 0.8%) per passenger in comparison with the current ordinary lane case. Meanwhile, the exclusive bus lane treatment made the passenger travel time increase by 1.3 sec. (equivalent to 0.8%). Although the exclusive bus lane can improve bus travel time significantly, its negative impacts on non-bus operation are significant in this case. Therefore, bus priority lane is the better policy which can improve bus operation and reduce negative impacts on non-bus simultaneously.

4.3.5.2. Sensitivity analysis.

Because of difficulties in counting exactly the number of passengers on all buses and on other vehicles as well, an analysis of choosing bus lane treatment varying on the number of passengers is put out in this research. Besides, deciding bus lane treatment based on the changes of main traffic volume is also an important manner needed to consider.

For general cases with unknown variables such as the number of passengers on bus or the main traffic volume, the differences in passenger travel time between the priority lane case and the ordinary lane as well as between the exclusive lane case and ordinary lane case for the direction to the station are formulated as follows:

\[
\Delta_{P_{ri}}(X_1, X_2) = T_{passenger_{Ordinary}}^{Priority} - T_{passenger_{Priority}}
\]
\[
\Delta_{Exc}(X_1, X_2) = T_{passenger_{Ordinary}} - T_{passenger_{Exclusive}}
\]

where,

\( \Delta_{P_{ri}}(X_1, X_2) \) : difference in passenger travel time between the ordinary case and the priority lane case (sec/passenger)

\( T_{passenger_{Priority}} \) : passenger travel time on A1A2 segment on the direction to the station in the priority lane case (sec/passenger)

\( T_{passenger_{Ordinary}} \) : passenger travel time on A1A2 segment on the direction to the station in the priority lane case (sec/passenger)

\( X_1 \) : traffic volume on the main street (vph)
$X_2$ : average number of passengers on buses (passengers)

$\Delta_{\text{Exc}}(X_1, X_2)$ : difference in passenger travel time between the ordinary case and the exclusive lane case (sec/passenger)

As being seen in these above equations, the bus priority lane or the exclusive bus lane case is considered a better case compared with the current ordinary lane case when the value of $\Delta_{\text{Pr}}(X_1, X_2)$, or $\Delta_{\text{Exc}}(X_1, X_2)$ is positive. The bigger the values of $\Delta_{\text{Pr}}(X_1, X_2)$, $\Delta_{\text{Exc}}(X_1, X_2)$, the better the cases of bus priority, exclusive lane respectively in comparison with the ordinary lane case. The research investigated the three cases of bus lane with varying levels of main street traffic volume. The considered values of main road traffic volume are 300 vph, 400 vph, 500 vph, 800 vph, 1,000 vph, 1,300 vph, 1,500 vph and 1,900 vph. At each value of main street traffic volume, the output travel times were obtained from PARAMICS after 10 times of running for each case of bus lane. The relationships are illustrated as in Figure 4.17

![Figure 4.17 Decisions on bus lane type](image)

From Figure 4.17, the violet lines and blue lines are contours of which values represent the differences in passenger travel time between the case of ordinary and bus priority lanes. Similarly, the yellow lines are also contours of which values represent the differences in passenger travel time between the ordinary case and the exclusive bus lane case. There are two main points that the research would like to bring out in this figure. The first one is the area distribution. It is easy to see that, the area with high number of passengers on bus and low main street traffic volume is the most suitable for exclusive bus lane treatment (the area with yellow lines). Meanwhile the area with the low number of passengers in the bus and high main street traffic volume is good for ordinary lane case (the area with violet lines). The middle area with blue hatch, between the area for exclusive bus lane and the area for the bus priority lane is proper for deploying bus priority lanes. If the bus priority lane were deployed in this area, the passenger travel time can be reduced by up to 1.8 sec. when traveling on the 500-meter main street segment. The second point the research wants to mention is the slope of the lines. Both the main street traffic volume and passenger numbers are very important factors in choosing bus lane types. However, the slopes in the case of the exclusive bus lane are steeper compared with those in the other cases. It means that the dependence on passenger
numbers in the exclusive bus lane case is very high, higher than that on the main street traffic volume. These slopes decrease gradually from the case of exclusive bus lane to priority bus lane and finally to the ordinary lane case when the main street traffic volume increases. At that moment, the dependence on the main street traffic volume becomes more important than that on the passenger numbers.

4.3.6. Conclusions and recommendations

This chapter summarizes the main points in this research as well as the contributions of this thesis. In addition, recommendations for further research are suggested.

4.3.6.1. Research summary

The research comparatively analyzed the impacts of the three popular types of bus lane in Japan by using PARAMICS as a tool to simulate the bus lane types. The results showed that although the exclusive bus lane type can improve bus service significantly, its negative impacts on other types of vehicles are also significant. If deployed at the study site, the exclusive bus lane would make the passenger travel time increase by 1.3 sec. on a 500-meter long urban street. Meanwhile, because of the flexibility in choosing lane in the priority bus lane case, developing bus priority lane at this study site can reduce 1.2 sec. for each passenger traveling the main street.

In addition, the research conducted a sensitivity analysis in choosing bus lane types when the main street traffic volume and the number of passengers in the bus vary. The analysis has shown that the exclusive bus lane is proper for conditions when the main street traffic volume is low and the number of passengers in buses is high. The improvement in terms of passenger travel time depends heavily on the passenger numbers. When the main street traffic volume increases, it has been found out that there are two special areas. One area that is defined by a range of main street traffic volume and passenger number is suitable for the priority bus lane case. The other area that is defined by a range of main street traffic volume and passenger number is suitable for the ordinary lane case. The dependence on the number of passengers in improving passenger travel time gradually switches to that on the main street traffic volume when the main traffic volume increases.

4.3.6.2. Recommendations

The part would like to analyze the advantages of bus priority lane in the aspect of city planning for bus operations. Calibrations of parameters as well as further analyses of the model are beyond the scope of this research. That should be dealt with by further studies. In addition, the final results for exclusive bus lane in this research are applied only for short periods. For long periods, because of being congested caused by bus lane operation, private vehicle users choose other routes or give up driving and take a bus to save travel time with respect to TDM policies. The area distribution in choosing bus lane type should be changed. Therefore, the bus lane policies would be appropriate for the long-distance travelers so that the private vehicle users shift their modes or change their routes.

- To provide city planners with sufficient information for making decisions of what bus lane policy to implement, a lengthy segment with a comprehensive investigation on factors such as bus schedule, tuning flow rate, effective distance between intersections and the awareness of drivers should be considered. In addition, not only in terms of travel time but also other aspects as specific geometrical conditions, convenience and safety are also necessary terms needed to be concerned and completed in future studies.
• Improving bus service and minimizing the negative impacts on other vehicles simultaneously are the essential targets of traffic policies. These targets can be obtained from the deployment of not only bus priority lanes, exclusive bus lanes but also bus signal priority system. Thus, focusing on studies about bus signal priority as well as combining the operations of bus priority lane and bus signal priority system is also a promising aspect for future works.
4.4. DEVELOPMENT OF A CAR LANE CHANGING MODEL UNDER BUS
PRIORiTY LANE EFFECTS

4.4.1. Introduction

The above section comparatively analyzed the three popular bus lane types in Japan with simple assumptions for car behavior under bus priority lane effects. This simple assumption affects the accuracy of the results to some extent. In this section, the research proposes a car lane changing model under bus priority lane effects. The development aims to get a comprehensive understanding about the benefits when bringing it into practice.

There have been many research studies about bus lanes and lane-changing models as well. However, a car lane-changing model under bus priority-lane effects has not been received much attention. Indeed, many previous papers proposed successfully lane-changing models for various vehicle types such as cars (Kazi, 1999), motorcycles (Minh et al., 2012) in different travel facilities such as urban street (Varun, 2007), freeway (Charisma, 2005). The lane-changing behaviour was studied just at merging locations (at ramps) or weaving sections with a typical lane-changing process including lane selection model, gap acceptance model and execution model (Charisma et al., 2007). In other words, most of the lane-changing models were built under the effects of different Origin-Destination (OD) pairs or different cost perceptions. Meanwhile, the lane-changing behaviour in the case of having bus priority-lanes is quite different from that in previous studies. The effects of oncoming buses in priority-lanes cause the lane-changing manoeuvre of passenger cars unexpectedly as well as take shape new features of the lane-changing behaviour.

4.4.2. Research assumptions

To build the model, there are some assumptions used in this research.

- The proposed model is applied to traffic cases in Japan with the most left lane being considered the bus priority-lane. The effects of oncoming buses are supposed to influence mostly on non-turning-left cars that are currently travelling in the priority-lane. Under bus priority-lane effects, an affected passenger car will change into adjacent lane to give the priority-lane to the oncoming buses. Passenger cars which are going to turn left or currently travelling in the other lanes are supposed to be not affected by the coming buses. The lane-changing behaviour of these cars as well as the behaviour of changing lane that is not caused by the bus effects is beyond the scope of this research.
- The looking-back threshold of a vehicle’s driver is defined as the longest distance between that vehicle and the nearest behind bus in the priority-lane. This distance is considered at the moment that the vehicle starts to turn on the winker before changing the lane. The looking-back threshold is assumed to follow the normal distribution. A car is considered under the bus effects when the distance back to the behind bus \( d \) (as shown in Figure 4.20) is shorter than the looking-back threshold of that car’s driver.

4.4.3. Model development

The lane-changing philosophy of a passenger car under bus priority-lane effects is proposed in this part. Firstly, based on the looking-back threshold, a car recognises oncoming buses in the priority-lane (step 1). If the current lane is the priority-lane, the car will find its satisfying lead gap and lag gap (step 2) and then make a decision of changes (step 3). If all the above
conditions are satisfied, a manoeuvre from the priority-lane to its adjacent lane will occur to give space for the coming bus. However, as a real behaviour at the studied sites, the above lane-changing philosophy is not applied to left-turning cars which have no choice to change lane because of safety and lane-usage’s regulations. The details of the structure are shown as in Figure 4.18.

![Diagram](image)

**Figure 4.18** The structure of a car lane-changing process

### 4.4.3.1. Looking-back threshold determination (step 1)

This step is suggested to determine the looking-back threshold of a vehicle’s driver. This value is assumed to be different for different drivers and follow the normal distribution. While driving, approximately 90 percent of the information drivers use is visual (Roger *et al*., 2004). According to the Universal Traffic Management Society of Japan (UTMS), information displayed on warning display board helps passenger cars recognise oncoming buses. However, in reality, vehicle’s drivers have to recognise oncoming buses through the rear-view mirrors on their cars. The probability for a car \( n \) at time \( t \) to recognise oncoming buses is defined as follows:

\[
P(r_{i,n}) = \begin{cases} 
1 & \text{If } d \text{ is less than looking-back threshold} \\
0 & \text{Otherwise}
\end{cases}
\]

The looking-back threshold is determined based on the recorded videos and field observation (detailed in Figure 4.21, Figure 4.22). With Kolmogorov-Smirnov Test (test statistic \( Z=1.017 \); Most Extreme difference \( D=0.069 \); and \( P\)-value=0.252>0.05), the threshold distribution can be considered a normal distribution as shown in Figure 4.19.
4.4.3.2. Gap acceptance model (step 2)

Like many previous papers about lane-changing models (Charisma et al., 2007; Kazi, I. A., 1999; Minh et al., 2012), this study also uses the concepts of lead gap and lag gap in the gap acceptance model. The gaps between the subject vehicle and the lead vehicle, the lag vehicle in the adjacent lane are defined as the lead gap and the lag gap, respectively. The displays are illustrated in Figure 4.20.

\[
\ln(G_{n,\text{lead}}^{cr}(t)) = \beta_{cr,\text{lead}} X_{n,\text{cr,lead}}^{cr}(t) + \varepsilon_{n,\text{lead}}^{cr}(t)
\]
\[
\ln(G_{n,\text{log}}^{cr}(t)) = \beta_{cr,\text{log}} X_{n,\text{cr,log}}^{cr}(t) + \varepsilon_{n,\text{log}}^{cr}(t)
\]

where

- \(G_{n,\text{lead}}^{cr}(t)\) and \(G_{n,\text{log}}^{cr}(t)\) are critical lead, lag gaps, respectively for vehicle \(n\) at time \(t\) (m);
- \(X_{n,\text{cr,lead}}^{cr}(t)\) and \(X_{n,\text{cr,log}}^{cr}(t)\) are the vectors of the explanatory variables of the lead gap and lag gap, respectively;
- \(\beta_{cr,\text{lead}}\) and \(\beta_{cr,\text{log}}\) are the vectors of the unknown parameters of the lead gap and lag gap, respectively;
- \(\varepsilon_{n,\text{lead}}^{cr}(t)\) and \(\varepsilon_{n,\text{log}}^{cr}(t)\) are the random terms associated with the lead gap and lag gap, respectively, and assumed to follow the normal distribution.

![Figure 4.19 Looking-back threshold distribution](image)

**Figure 4.19 Looking-back threshold distribution**

![Figure 4.20 Lead gap and lag gap at the studied site](image)

**Figure 4.20 Lead gap and lag gap at the studied site**

The minimum acceptable space gaps are defined as critical gaps. These gaps are used to evaluate the current gaps and assumed to follow the lognormal distribution.
\[ \varepsilon_n^{\text{lead}}(t) \sim N(0, (\sigma_n^{\text{lead}})^2) \]
\[ \varepsilon_n^{\text{lag}}(t) \sim N(0, (\sigma_n^{\text{lag}})^2) \]

where 
\[(\sigma_n^{\text{lead}})^2 \text{ and } (\sigma_n^{\text{lag}})^2 \text{ are the variances of the error terms in gap acceptance models.}\]

The lead gap and lag gap will be compared with the critical lead gap and critical lag gap, respectively. If the available gaps are larger than the corresponding critical gaps, these available gaps are acceptable and the passenger cars have chance of changing lane. Otherwise, the passenger cars will stay in the priority-lane and wait for next chances. The probability of the gap acceptance for a car \( n \) at time \( t \) is given by:

\[
P(\text{Acc} \mid r)_{i,n} = \Pr(\text{Lead\_gap} \geq \text{Crit\_lead})_{i,n} \cdot \Pr(\text{Lag\_gap} \geq \text{Crit\_lag})_{i,n} = \\
= \Phi \left( \frac{\ln(G_{n, lead,i}^{\text{lead}, i}(t)) - G_{n, lead,i}^{\text{cr}, lead,i}(t)}{\sigma_{\text{lead}}} \right) \cdot \Phi \left( \frac{\ln(G_{n, lag,i}^{\text{lag}, i}(t)) - G_{n, lag,i}^{\text{cr}, lag,i}(t)}{\sigma_{\text{lag}}} \right)
\]

where \( \Phi(.) \), \( \Pr(.) \) are cumulative function of a standard normal random variable and the probability function, respectively.

### 4.4.3.3. Execution model (step 3)

Even when a passenger car can find acceptable gaps for changing lanes, this car does not change lanes in some cases due to some reasons. The reasons may include the current speed states, the driver’s awareness about advantageous traffic situations at that moment (such as no traffic queue ahead, or just turning-on green signal), or even because of the poor awareness of drivers, etc. The decision of lane-changing execution can be modelled as a binary Logit Model with the probability function defined by

\[
P_\nu(j_i \mid \nu_{n}) = \begin{cases} 
1 & \text{if lead gap and lag gap are satisfied} \\
1 + \exp(-(\beta X + \alpha \nu_{n})) & , \text{Otherwise}
\end{cases}
\]

where:

\( j \) is the lane-changing action, and \( X \) are explanatory variables. Driver specific random term \( \nu_{n} \) that is constant for a given driver is assumed to follow the normal distribution. The final lane-changing action of passenger cars to give space to oncoming buses in the priority-lane is observed.

The probability of such an action consists of three parts: the looking-back threshold probability, the probability of gap acceptance and the probability of execution decision. The joint probability of this combination for a car \( n \) at time \( t \) is defined by

\[
P(J)_{t,n} = P(r_{i,n}) \cdot P(\text{Acc} \mid r)_{t,n} \cdot P_\nu(j_i \mid \nu_{n})
\]

Assuming the independence of the lane-changing observations of different passenger cars, likelihood function is expressed as follows:

\[
L = \prod_{n=1}^{N} P(J)_{t,n}
\]

where \( N \) is the number of observations.
In summary, the structure of the car lane-changing model proposed in the paper is different from that of previous studies. In this study, the step of looking-back threshold plays a key role for the following lane-changing process to happen. Meanwhile, in the car lane-changing models of previous studies, lane selection model plays an important step. Because of bus effects, the passenger cars travelling in the bus priority-lane perceive the priority of bus in lane usages. They have only one choice that is moving out of the priority-lane to escape the situation. However, the driver’s perception finally decides the completion of the lane changes.

4.4.4. Data collection

Bus priority-lanes have been deployed in Niigata prefecture, Japan for years. The bus priority-lanes on route No.7 connecting Niigata station to the office areas in the northern help improve the transportation system. Data was collected in normal conditions about time, weathers at several points on this route. The recorded cameras are set at the studied site as shown in Figure 4.21.

The total recorded time was 40 hours, including peak hours and off-peak hours. The research used two ways to collect data simultaneously, namely direct observation and recorded video. For direct observation, observers would take note the moment as well as special signals at which lane-changing winkers are on, or the moment that buses come, etc. For video record, the researchers used cameras mounted on high positions to observe lane-changing manoeuvre along urban streets. In the transportation lab, a video based software (Minh, 2007; Minh et al., 2012) was used to analyse traffic data needed for model calibration and validation. The data collected includes lead gaps, lag gaps, speeds, the distance back to oncoming buses at which the passenger car turning on the winker before changing lane out of the priority-lane, etc.

According to Minh (2007), a Coordinate Transformation Technique was introduced to transform screen coordinates to roadway coordinates. This technique was utilized the principles of projective geometry that is derived from one of two fundamental operations in
photogrammetry projection. The fundamental principle of the general concept of projection is the theory of cross ratio. After estimating related coefficients in the simultaneous equations of a so-called base points, the coordinate between screen and roadway is matched. Therefore, all screen and roadway coordinates were determined. The information of lead distances, lag distances, vehicle speeds are easy to get by tracking point on the screen and output to excel file. For the accuracy of the data, only “candidate” cars were chosen to measure the speeds and distances. Figure 4.22 shows the interface of SEV software used to collect data at the studied site. The real distances between base points are directly measured at the site to input real coordination to the SEV software. The interface is as follows:

![Figure 4.22 A snapshot of using SEV to collect data](image)

4.4.5. Results and analysis

The model is calibrated by maximum likelihood estimation using Newton Raphson method in the statistical estimation software GAUSS. The parameters of lag critical gap, lead critical gap and binary decision as well as their test values can be estimated by programming in the statistical software. The $\rho^2$ index tests are conducted to evaluate the model performance. The result shows that, the test statistic is $-2(L(\beta)-L(0))=63.40$, which is used to test the null hypothesis, in which all of the parameters are zero. The critical value of the chi-square distribution with 7 degrees of freedom at the 1% level of significance is 18.48. Therefore, the null hypothesis can be rejected at 0.01 level of significance. For the null hypothesis test $-2(L(\beta)-L(0))=25.93$, in which all the parameters other than the alternative-specific constant are zero, the critical value is 9.21, indicating that the null hypothesis can be rejected at 0.01 level of significance. The estimated results are illustrated in Table 4.2.
Table 4.2 Estimated parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Estimation</th>
<th>t-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lag Critical Gap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>1.587</td>
<td>10.92</td>
</tr>
<tr>
<td>max($\Delta V_{lag,0}$) (m/sec)</td>
<td>0.079</td>
<td>3.32</td>
</tr>
<tr>
<td>$\sigma_{lag}$</td>
<td>0.251</td>
<td>1.99</td>
</tr>
<tr>
<td>Lead Critical Gap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-0.187</td>
<td>-0.17</td>
</tr>
<tr>
<td>$\sigma_{lead}$</td>
<td>1.359</td>
<td>1.60</td>
</tr>
<tr>
<td>Execution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>3.158</td>
<td>4.37</td>
</tr>
<tr>
<td>$V_{s,adv}$, (m/sec)</td>
<td>-0.202</td>
<td>-3.91</td>
</tr>
</tbody>
</table>

Number of cases = 216
L(0) = -148.33, L($\beta$) = -116.63, $\rho^2$=0.214
L(c) = -129.60, $\rho^2$=0.100

where

$max(\Delta V_{lag,0}) = max(V_{lag} - V_{subject,0})$

$V_{subject}, V_{lag}$ are speeds of subject vehicle $n$ and the corresponding lag vehicle $n$, respectively.

Like many previous models about lane changes, the positive sign of maximum relative lag speed variable in the lag critical gap function is as expected. Indeed, a large lag gap is required when the speed of lag vehicles is considerably larger than that of the subject vehicle. Despite the low t-values in the lead critical gap results, the lead gaps are necessary for a safe lane change. Unlike most of the traditional results about lead critical gaps, the lead critical gap is independent from the relative lead speed in this study. It reflects that the lane-changing behaviour in the studied situation is compulsory. As soon as a passenger car recognises oncoming buses, it would rather pay attention to the speed of the lag vehicle than concern that of the lead vehicle in finding acceptable gaps. Regardless of how small the lead vehicle’s speed is, the passenger car can find a minimum possible lead gap. In addition, the negative sign of the subject speed variable in the function of execution model means that the passenger cars trend to decide changing lane with low travel speeds. This is reasonable for safety purposes. The simulation results show that the proposed model could produce properly the number of lane changes at the studied location with the Hit-ratio of as 55.6%.

4.4.6. Critical gap comparison

In this section, the research would like to show a comparison between critical gaps in the proposed model and that of previous studies. As shown in Figure 4.23, the behaviour of a passenger $i$ changes lane under priority-lane effects in this paper may differ from that in previous studies. In most of the previous studies on car-lane-changing behaviour, the behaviour was considered at merging or weaving locations. The motive of the lane changes is to change the trip direction. There was no any concern with the effect of priority-lane like being investigated in this study. Therefore, the behaviour on critical gap recognitions under priority-lane effects is not the same to that under the conditions of no priority-lane effects. The research conducts the comparison for critical lead gap and critical lag gap in every detail as following parts.
4.4.6.1. Critical lead gap

Compared with the lane-changing behaviour at traditional merging locations (ramps, weaving sections, etc.) in normal lane cases of some previous studies (Kazi I.A., 1999; Charisma F.C., 2005), the critical gaps in this study have several specific characteristics. Indeed, the relationship between critical lead gap and relative lead speed is shown as in Figure 4.24.

\[
\text{Min}(\Delta V_{\text{lead},0}) = \min(V_{n,\text{lead}} - V_{n,\text{subject}}, 0)
\]

where \( V_{n,\text{subject}} \) and \( V_{n,\text{lead}} \) are speeds of subject vehicle \( n \) and the corresponding lead vehicle \( n \), respectively.

Traditionally, the critical lead gaps at merging locations in most of the previous studies have strong relationships with relative lead speed differences (stars and triangles marked curves). The smaller the minimum relative lead speed is, the larger the critical lead gaps are needed. However, the critical lead gap in the priority-lane case (circles marked line) is a constant with respect to the relative difference in lead speeds. It reflects the compulsory lane-changing manoeuvre when prioritized buses come. How different the speeds between the subject vehicle and the lead vehicle are, the subject vehicles can find a minimum critical gap in the cases of priority effects. Except smaller values in terms of average critical gap, the critical lead gap in the studied case looks similar to that of in the compulsory model (squares marked line) developed by Kazi I.A. (1999). But, the motivations of finding gap are under different locations (ramps, weaving sections versus urban segments) and different lane-changing purposes (OD trips or perceived costs versus bus effects). The smaller values of critical lead gaps in this study tell somewhat the passivity of passenger cars when buses come.
4.4.6.2. Critical lag gap

Similarly, with respect to relative lag speed, the curve of critical lag gap in the studied case is generally smaller than that of other studies as shown in Figure 4.25.

![Figure 4.25 Critical lag gap comparison](image)

The critical lag gap in the priority-lane effects slightly depends on the relative lag speed between the subject car and the lag car in the adjacent lane. Meanwhile, the curves in the other cases show a strong relationship between critical gaps and relative lag speed, especially the case study at ramps in the research of Kazi, I. A. (1999). The less dependence on the relative lag speed in this study is somewhat caused by the existence of buses in the priority-lane. After recognizing an oncoming bus in priority-lane, car’s drivers perceive the priority of the bus and try to find suitable gaps to change lane. The critical gaps in this situation are not as usual even with a big relative lag speed difference. This reflects the lane changes in this situation is a compulsory lane changes. However, because of the compulsoriness in changing lane, the safety level should be an important point to consider. The consideration is for not only city planers on deploying bus priority-lanes but also for car’s drivers on adjustment the speeds before changing lanes.

4.4.7. Conclusion and recommendation

The part proposes a car lane-changing model under bus priority-lane effects in urban streets. Unlike any previous car lane-changing model, this model consists of three steps: looking-back threshold determination, gap acceptance model and execution model. These three steps are represented for the philosophy of a lane-changing manoeuvre of passenger cars under the influence of oncoming buses. Once a passenger car recognises oncoming buses travelling in the priority-lane, this passenger car will evaluate the acceptable lead and lag gaps. If the acceptance model is satisfied, the car will revise the execution decision and decide that whether the lane-changing manoeuvre should be completely executed.

To calibrate the model and analyse the special lane-changing behaviour under bus priority-lane effects as well, the research conducts two periods of calculation. The first period concerns with using actual data to calibrate the model parameters by applying the method of Maximum Likelihood estimation. The estimation results with satisfying statistic tests are as expected. The positive sign of maximum relative lag speed variable in the lag critical gap function is reasonable. It means that a large lag gap is required when the speed of lag vehicles is considerably larger than that of the subject vehicle. The lead critical gap is independent from the relative lead speed in this study. It reflects that the lane-changing behaviour under
bus priority-lane effects is compulsory. As soon as a passenger car recognises oncoming buses, it would rather pay attention to the speed of the lag vehicle than concern that of the lead vehicle in finding acceptable gaps. The second period is to compare the differences in perception behaviour of lane-changing cars under priority-lane effects and under no such effects. This comparison was conducted in terms of critical lead gap and critical lag gap. The results show that the lane-changing behaviour under bus lane effects has specific characteristics with smaller critical gaps when compared with that of the cases of no bus lane effects. The less sensitive relationship between critical gaps and its corresponding relative speed is the consequence of the existence of buses in priority-lane. The interference makes car drivers understand the priority of the buses in lane usages and change lane to give space to the buses. Because of the priority recognition in this situation, the research would like to send a message on warnings of traffic accident to car drivers and city planners. Although the lane-changing behaviour could help the bus service more convenient, it may obstruct the traffic in the other lanes by interference or accidents. Therefore, a safe lane change requires a full control of the car’s speed as well as careful observation. City planners should consider more about the maximum permitted speed or other safety requirements before deploying bus priority-lanes in urban streets.

The data about lane-changing manoeuvre, lane-changing gaps as well as traffic characteristics were collected by setting videos at high positions to record the traffic stream along the street. The longitudinal observation field of the recorded videos was not large enough, around 200m long, causing the loss of data outside the observation field, making difficulties in upgrading the model. Moreover, the lane changes that are assumed to be not caused by the effects of bus priority-lanes in this paper have not been investigated much. A further research study with advanced methods of data collection should consider more detailed the behaviour of car drivers when buses come. In addition, the priority effect on trucks or turning left cars was also not considered in this research. It should be considered more in further studies.

Looking-back threshold determination is an important part in the proposed model to recognise oncoming buses. However, the development of the looking-back model in this research remains several weak points. The looking-back threshold depends on not only driver characteristics but also the vehicle types, surrounding geometry, etc. Thus, this model should be received more comprehensive investigation. Moreover, the aspect of state dependency among sub-models over time as well as other influential factors such as the distances between oncoming buses and subject vehicles, the effects of the distance from the subject vehicles to intersections, lane flow density, geometry feature, etc also need more concern in future works.
4.5. INTEGRATION OF THE PROPOSED MODEL INTO SIMULATION MODELS

4.5.1. Introduction

The purpose of this section is to integrate the proposed car lane changing model in the previous section into simulation model to investigate the network performance in Nagaoka city of Japan under different bus lane types. The details are presented as in following parts.

4.5.2. The proposed model and integration

The proposed lane changing behavior in this section is as follows. Through the looking-back threshold, if a non-bus vehicle traveling in a priority lane recognizes oncoming buses coming in the same lane, the non-bus vehicle will follow the proposed gap acceptance model. Otherwise, the default lane-changing model in PARAMICS is used. The structure of the car-lane changing model used to simulate the scenario of bus priority lane in PARAMICS is as shown in Figure 4.26.

![Figure 4.26 The structure of the lane changing behavior](image)

The model is calibrated by maximum likelihood estimation using Newton Raphson method in the statistical estimation software GAUSS. The parameters of lag critical gap, lead critical gap and binary decision as well as their test values can be estimated by programming in the statistical software. The estimation parameters as well as t-values of each term in the proposed model are presented as follows:

\[
G_{\text{cr, lag}}(t) = \exp[0.587 + 0.079 \max(\Delta V_{\text{lag}}, 0) + \epsilon_{\text{lag}}(t)], \quad \sigma_{\text{lag}} = 0.251
\]

\[
G_{\text{cr, lead}}(t) = \exp[-0.187 + \epsilon_{\text{lead}}(t)], \quad \sigma_{\text{lead}} = 1.359
\]
\[ P_{c}(j_{i} | v_{n}) = \begin{cases} \frac{1}{1 + \exp(-(3.158 - 0.202V_{n}^{s})^{(t=4.37)} (t=-3.91))} & , \text{if lead gap and lag gap are satisfied} \\ 0 & , \text{Otherwise} \end{cases} \]

where, 
\[ V_{n}^{s}, V_{n}^{lag} \] are speeds of subject vehicle \( n \) and the corresponding lag vehicle \( n \), respectively.

\[ G_{n}^{cr,lead}(t), G_{n}^{cr,lag}(t) \] are critical lead, lag gaps, respectively for vehicle \( n \) at time \( t \) (m);

\[ \max(\Delta V_{n}^{lag},0) = \max(V_{n}^{lag} - V_{n}^{s},0) \]

\[ \varepsilon_{n}^{lead}(t), \varepsilon_{n}^{lag}(t) \] are the random terms associated with the lead gap and lag gap, respectively, and assumed to follow the normal distribution.

\[ \varepsilon_{n}^{lead}(t) \sim N(0,(\sigma_{lead})^{2}) \]

\[ \varepsilon_{n}^{lag}(t) \sim N(0,(\sigma_{lag})^{2}) \]

With the acceptable test values as well as reasonable signs of the parameters, the model could reproduce the lane changing behavior under the bus priority lane effects. The integration of the proposed model into simulation models in PARAMICS (Quadstone, 2006) was mentioned in Chapter 3. A developed DLL file is connected to Modeler to override the critical gaps as well as default lane changing model in PARAMICS.

4.5.3. Comparison between the proposed model and the assumed model

In this part, the research comparatively evaluates the effects of the car lane changing models on the results of the criteria for bus lane types or area distribution. The research conducts two terms of comparison of the difference. One term is related to travel time and the other one is concerned with area distribution. The details of the comparison are as follows.

a. The comparison in terms of travel time

The effects of the models on the travel times of buses and non-bus vehicles should studied separately. However, the research investigates the difference in terms of all vehicle travel time (including buses and non-bus vehicles) along the main street preliminarily for the purpose of simplicity. The difference in vehicle travel time between the cases of the simple car lane-changing model application and the proposed car lane-changing model application is illustrated by using the difference in percentage defined as the following formula:

\[ P = \frac{|T_{S} - T_{P}|}{T_{S}} \times 100\% \]

where

\( P \): The difference in percentage (%)

\( T_{S} \) : Vehicle travel time in the case with the simple lane changing model (s)

\( T_{P} \) : Vehicle travel time in the case with the proposed lane changing model (s)
Based on the traffic situation at the studied site, the research investigates the difference under various traffic flow conditions by changing the main traffic flow. The difference is shown in Figure 4.27.

**Figure 4.27 Comparison in terms of vehicle travel time**

*Figure 4.27* shows that the maximum difference in vehicle travel time between cases of the simple car lane-changing model and the proposed car lane-changing model is 6.84%. At the two extremes of traffic volume (very high or very low), the difference is trivial. At the two extreme differences, the research conducts study scenarios to investigate comparatively the effect under the applications of the proposed models.

b. **The comparison in terms of area distribution**

It is necessary to redraw another figure representing the area distribution for bus lane type in which the proposed model is applied. However, it takes a lot of time to complete the entire figure. For simplicity, the research conducts the two scenarios at the lowest difference and the highest difference as shown in *Figure 4.28* to investigate the area distribution for bus lane type. The comparison is as follows:

**Figure 4.28 Comparison in terms of area distribution**

Based on *Figure 4.28*, the research has two conclusions. The first conclusion is that there is difference in determination of the boundary value of suitable areas for bus lane types. This difference occurs at the border between ordinary lane and priority lane, priority lane and
exclusive lane. The second conclusion is that the tendency of choosing bus lane type in cases of applying the proposed model and the simple model is the same. When the main traffic volume increases, the tendency for choosing ordinary lane is determined. However, the number of passengers in buses decides strongly to choose the exclusive bus lane. The bus priority lane is a compromise between ordinary lane and exclusive bus lane.

4.5.4. A case study

In local cities in Japan, bus is the only public transportation mode that plays an important role in carrying passengers to big stations for trains, high-speed rails, etc. This kind of mode is less expensive, easier to navigate and more frequent than other public transport modes. And yet, the performance of the bus service in Nagaoka city is not very effective, which has worsened many environmental problems and severe urban problems such as congestion, accidents on the roads, etc. The number of public transportation users has decreased year by year and even some unprofitable bus routes had been abolished in this area (Sano et al., 2007). The reliability of bus is the main reason to these problems. As shown in Figure 4.29, bus delay increased gradually after 7AM. In which, 70% of the buses arrived later than the timetable and 40% of them arrived later by more than 8 min as shown in Figure 4.29.

![Figure 4.29 Bus punctuality in Nagaoka city (Source: Sano et al.(2007))](image)

Improving bus service is a very important step to improve the life quality. It can bring benefits not only to bus users but also to bus operators. In addition, the improvement is also one way to alleviate traffic congestion, increase punctuality and reduce traffic accident. If there is no bus delay, the benefit to bus users can be predicted as about 20% of the total bus operation costs and the benefit to the bus operator is about 10% of the total costs as well for the case study in Nagaoka City (Sano et al., 2007). Being aware of the benefit, the local authority has deployed various measures such as improving bus shelters as well as service style, implementing special policies to bus users, or applying bus lanes, bus signal priority, etc (UTMS of Japan). However, the deployment has been at a modest level, which has resulted in low efficiency. Therefore, improving bus service is necessary to attract more bus users in Nagaoka city. Obtaining the amount of 50-60% of the running time that a bus typically spends in motion (NCRTPB, 2002), bus lanes should be preliminary choices to upgrade the bus service. However, the evaluation of bus lane types for Nagaoka traffic network has been not identified yet. This section conducts the evaluation based on the proposed model in the previous part. The studied site in Nagaoka city covers an area of around 80km², including 1563 nodes, 4146 links and 65 zones. There are 13 city bus routes in
the city. During the morning rush hours, the research collects traffic flows at 56 locations on weekdays under normal weather conditions in Nagaoka city of Japan. The collection points and the network built in PARAMICS are shown as in Figure 4.30.

![Network Validation Diagram](image)

**Figure 4.30** The studied traffic network (left) and the network in PARAMICS (right)

### 4.5.5. Network validation

There are many indicators to validate the simulation model such as travel time, flow, speed, queue length, etc. Typically, two indicators among three ones (travel time, flow and speed) are chosen for the validation. In this research, traffic flow and travel time are major indicators. For traffic flow validation, the research compares the observed flow and simulated flow at 56 collected points. The distribution around the 45-degree line is shown in Figure 4.31.

![Traffic Flow Validation](image)

**Figure 4.31** Traffic flow validation

Connecting the west part and the east part of Nagaoka city, five bridges including Chosei Bridge, Oteo Bridge, Nagaoka Bridge, Zao bridge and Koshiji bridge play an important role in the regulation of smooth traffic in this city. The research would like to validate the traffic flow at these important locations. As shown in Figure 4.32, the traffic count in 10 minute interval in the simulation model is approximately same to that in the observation case. The Mean Percentage Error (MPE) values are less than 0.2 at these locations. The details are shown in the following figure:
For travel time validation, the researchers choose three typical main road segments through the connecting bridges to validate the travel time. As seen in Figure 4.30, the locations of Chosei bridge, Oteo Bridge and Nagaoka bridge are close. Any change of traffic situation should affect strongly the others. Three road segments through these routes were chosen to validate. The travel time validations for the three segments are as in Figure 4.33.

Note:
- Traffic count unit: vehicles per 10min
- MPE values shown in the figure are the average MPE values

Figure 4.32 Traffic count validation at the connecting bridges

Figure 4.33 Travel time validation
4.5.6. Network performance analysis

Located in the central part of Niigata prefecture, Nagaoka city has a large network of bus routes with Nagaoka Station as a hub. The station serves approximately 1500 buses, 11,600 railway passengers and 25,000 bus users everyday. There are five bridges, including Chosei Bridge, Naogaoka Bridge, Oteo Bridge, Zao Bridge and Koshiji Bridge, which connect the west part with the east part of the city. According to the survey, the main route through Oteo Bridge to the station serves the large number of buses operating in the city. Indeed, there are more than 85% of the total bus routes in Nagaoka city which wholly or partly use the main connection route through Oteo Bridge to the station. Therefore, a segment through Oteo Bridge to Nagaoka station is the most possible segment to have bus priority lanes or exclusive bus lanes. This proposed treatment segment in the research has the initial point at the T junction connected with the route No. 8 and the end point at Nagaoka station.

The research conducts two simulation scenarios after validating the current traffic network. These scenarios utilize the geometry figures, the current traffic volumes, bus schedules, etc. but change the policy for traffic activities. The first scenario is to simulate the traffic network when the treatment segment has the most left lane as a bus priority lane. The evaluation of the bus priority lane is then comparatively studied more when the research conducts the second simulation scenario in which the treatment segment is treated to have the most left lane as an exclusive bus lane. The results show that the bus priority lane makes the bus travel time on the treatment segment reduce by 8.2% compared with that in the scenario of the current ordinary lane. However, this figure is smaller than the decrease of 28.3% of the bus travel time once the exclusive bus lane is deployed. The improvement of bus travel time on the treatment segment depends on the traffic volume. As shown in Figure 4.34, the efficiency is significant with high values of traffic volume on the segment. The maximum reductions of bus travel time in this research are 63.1% and 34.8% for the exclusive bus lane and the bus priority lane, respectively. The detailed comparison is as shown in Figure 4.34.

The bus priority lane may benefit some bus routes and bring disadvantages to several ones as well. The benefit to a bus route depends on the geographical characteristics of the bus route, the bus frequency, etc. Among the considered 13 bus routes in Nagaoka city, routes No.3, No.5, No.6, No.9, No.10 and No.12 are negatively affected by the lane deployments. However, compared with the scenario of the exclusive bus lane, the negative effects are relieved once the bus priority lane is applied. The bus travel time on these routes increases averagely by 2.68% and 7.49% in the scenarios of the bus priority lane and the exclusive bus lane, respectively. The remaining bus routes receive the benefits in terms of bus travel time with different amounts. On average, the bus travel-time reductions for the remaining bus routes are 2.91% and 4.57% for the scenario of the bus priority lane and the exclusive bus lane, respectively. The effects on the bus routes are illustrated as shown in Figure 4.35.
Once a priority treatment is deployed on the treatment segment, there is influence on the traffic network, especially at the bridges connecting the west and the east part. The treatment makes the flow at Oteo bridge reduce significantly. Compared with the current ordinary lane, the reduction in the scenario of the bus priority lane is smaller (19.92%) than that in the scenario of the exclusive bus lane (22.23%). Meanwhile, the traffic flow increases at the remaining bridges. Indeed, in the exclusive scenario, the traffic flow increases by up to 5.88%, 4.74%, 7.32% and 0.75% at Chosei bridge, Nagaoka bridge, Zao bridge and Koshiji bridge, respectively. Similarly, in the scenario of the bus priority lane, the traffic flow at the remaining bridges increases by 6.56%, 6.81%, 1.32%, 1.00% for Chosei bridge, Nagaoka bridge, Zao bridge and Koshiji bridge, respectively. Because Chosei bridge and Nagaoka bridge are close to Oteo bridge, the influence on the two bridges is significantly high. Whether the scenario is the exclusive bus lane or the bus priority lane, the increase in traffic flow at these bridges is from 4.74% to 6.81% compared with the current ordinary lane. At Zao bridge, the scenario of the exclusive bus lane increases the traffic flow considerably (7.32%). However, the increase is slightly greater (1.32%) with the scenario of the bus priority lane. Koshiji bridge is rather far from the treatment segment compared with the others, the effect on traffic flow at this bridge is insignificant in both the two scenarios.

\[ P(+) = 2.68\% \quad E(+) = 7.49\% \]
\[ P(-) = 2.91\% \quad E(-) = 4.57\% \]

**Figure 4.35** Effects on the bus routes

**Figure 4.36** Observed and simulated traffic flows at the bridges

Note: P and E are represented the change percentage of the flow rate in the scenarios of priority lane and exclusive lane with respect to that in the ordinary scenario.
Because of the lane deployments at Oteo bridge, non-bus vehicles switch their routes through Oteo bridge to the other bridges when traveling from the west part to the east part. Most of the switching vehicles change to use Nagaoka bridge with the share range from 42.4% to 66.7% in the scenarios of the priority treatments. This is reasonable due to the convenience of traveling through this bridge.

In terms of overall system performance, the paper uses three key indicators to evaluate. They are Vehicle-distances Traveled (VDT), Vehicle-hours Traveled (VHT), and Mean System Speed (Richard, 2002). Compared with the current scenario of the ordinary lane, the VDT values in the scenarios of the bus priority lane and the exclusive bus lane are trivial, approximately 0.28%, 0.51%, respectively. For the amounts of traveling time expended on the system, the scenario of the bus priority lane reduces the VHT by 0.45%, a little smaller than that in the scenario of the exclusive bus lane (0.76%). The decreases in VHT indicate improved system performances of the scenarios of the bus priority lane and the exclusive bus lane. For the Mean System Speed of the network, it decreases insignificantly. Indeed, the reductions are 0.17%, 0.25% in the scenario of the bus priority lane and the exclusive bus lane, respectively.

4.5.7. Conclusions

This part aims at evaluating the effect of bus priority lanes in comparison with that of exclusive bus lanes based on the current ordinary lane in Nagaoka traffic network. To do that, the research integrates the proposed car lane-changing model under bus priority-lane effects into simulation models to simulate the scenario of the bus priority lane. The effect of the bus priority lane is then comparatively evaluated together with that of the exclusive bus lane based on the current ordinary lane. The results show that the bus priority lane can reduce the bus travel time on the treatment segment by 8.2% compared with the current ordinary lane without any lane treatment. This reduction is smaller than that in the scenario of the exclusive bus lane, which is 28.3%. In terms of entire bus route, the bus priority lane and the exclusive bus lane may benefit some bus routes and bring disadvantages to several ones as well. The benefited bus routes can save the travel time by 2.91% and 4.57% in the scenarios of the bus priority lane and the exclusive bus lane, respectively. In terms of traffic flow, the priority lane reduces traffic flow on the treatment segment by 19.92%, smaller than that in the scenario of the exclusive bus lane (22.23%). In addition, most of the switching vehicles change to travel through Nagaoka bridge with the share range from 42.4% to 66.7% among the candidate bridges. Although strongly influencing traffic flow and travel time at the connecting bridges, the deployments affect slightly the vehicle-hours traveled as well as the system speed. In summary, the bus priority lane can improve considerably the bus service. The improvement is especially significant for the bus routes that use much the treatment segment. The number of passengers on buses using the treatment segment contributes to the efficiency of the bus lane deployments in terms of passenger delay savings. Therefore, switching the rider-ship from private cars to public buses to increase the number of riding passengers on these routes is a long important target in this area. However, because the deployments of the bus lanes worsen the congestion at the other connecting bridges. The negative effects become considerably serious if the deployment is for the exclusive bus lane instead of the bus priority lane. Thus, the bus priority lanes should be considered a transitional treatment before the deployment of the exclusive bus lane.

The research has several shortcomings that need to be improved in next studies. The first shortcoming is about the car lane changing model applied in this research. The accuracy of the proposed model is important to the result of the evaluation. In this model, looking-back
threshold determination is an important part in the proposed model to recognize oncoming buses. However, the looking-back threshold is simple in this research. It should depend on not only driver characteristics but also the vehicle types, surrounding geometry, etc. In addition, the gap acceptance model had some weak points. Other related factors such as lane flow density, geometry feature, etc. also are required more concern in future works. The second shortcoming is related to the sufficiency of observed data for model evaluation. This research simplifies the validation step with two typical validated indicators including traffic flow and travel time among many indicators such as traffic flow, travel time, speed, delay, stops, density, etc. It should be investigated more to get a better validation. Moreover, although a large number of buses can benefit from the bus priority lane, it is not meaning if the number of passengers on the benefited buses is low. Therefore, the number of passengers on buses and cars is important information to evaluate accurately the effects of the bus priority lane on the traffic network. It should be a target in future studies.
CHAPTER 5

BUS SIGNAL PRIORITY SYSTEM

5.1. GENERAL INTRODUCTION

Concerning bus signal priority system, there are two important factors. The first important factor is the accuracy of bus arrival prediction to know exactly the moment that buses come. The second one is the utilization of signal timing technique. For arrival time prediction, the accuracy of bus arrival time prediction plays an important role in the effectiveness of signal priority systems. There have been various methodologies such as Kalman Filtering (Shalaby et al., 2004), linear model (Chiou et al., 2003), neural network model (Chen et al., 2004), etc. used to predict arrival time. However, each methodology has its limitations. Indeed, the assumption that bus arrival time is a constant (Weerasooriya, et al., 2008) was considered the simplest way. In fact, the bus arrival time is sensitive to the traffic volume. A Kalman filter based model using Automatic Vehicle Location (AVL) and Automatic Passenger Counting (APC) dynamic data (Shalaby et al., 2004, Chen et al., 2004) to predict bus travel time in downtown Toronto outperformed other conventional models in terms of accuracy. Yet, the results depend mainly on the role of emerging technologies. Based on detector data, signal controller data and saturation flow data, a methodology to estimate average travel time on signalized urban networks using analytical procedure (Bhaskar et al., 2007) was introduced. There was huge inconsistency in travel time estimation in some cases. Bus arrival time estimation was also done by using traffic signal database and shockwave theory (Rahman et al., 2010). But, it does not reflect the real traffic nature in which the individual behaviors are specific. Probe vehicle data is also a useful resource used to estimate arrival travel time by converting bus trajectory to general traffic travel time (Song et al., 2010). However, the data lost from probe vehicles as well as signal effects are main limitations needed to be overcome. To predict arrival time, the developments of linear regression models or adaptive algorithms (Chiou et al., 2003, Bo et al., 2010) have been investigated much in previous studies. However, the effects of signalized intersections, especially queue length, queue delay, etc. are important to the accuracy of the prediction model as well as the effectiveness of bus signal priority system. In this research, Image Processing sensor (Higashikubo et al., 1996) was used to measure directly useful traffic flow information such as speed, queue length, queue delay lane by lane, etc. According to Universal Traffic Management Society of Japan (UTMS), with the ITV camera installed above the approach lane at signalized intersections, the image processing sensor can process the received images through the algorithm in control unit. The sensor can collect more precise and more detailed traffic information. Spatial area measured by image processing sensor is shown as in Figure 5.1.

Related to the utilization of signal timing techniques, the California PATH Center (Liu et al., 2003) has developed many models to improve bus service and minimize negative impacts on general vehicles at isolated signalized intersections, coordination arterial roads, ramp metering, etc. Recently, the models for bus signal priority have been developed by considering bus queuing delay at traffic signals when triggering TSP requests (Weerasooriya et al., 2008) or minimizing the intersection delays (Li, 2010, Eleni et al. 2011). The models
were developed with not only a heuristic algorithm (He et al., 2011), a dynamic Programming Model (Wanjing et al., 2011), analytical approaches (Hongchao et al., 2008) but also practical approaches (Tanaka et al., 1996, Wang et al., 2010). The development is not also for a single request (Weerasooriya et al., 2008) but also for multi requests (Lee et al., 2005, Wanjing et al., 2011) or for conflicting transit routes (Eleni et al., 2011).

It can be said that, there are many ways to improve bus service in urban areas, from considerations of bus lanes, bus stops, bus stations to developments of traffic signal priority at intersections, such as queue jumping systems, bus signal priority strategies, bus preemption strategies, etc. Deploying and improving public transport system in general as well as bus system in particular is an indispensable trend to relieve traffic congestion and improve traffic quality. However, improving the performance of public transport usually causes unfavorable conditions for non-bus operations, especially at signalized intersections. In this chapter, there are three points which are studied. The first point is the investigation of effect of bus priority strategies on the intersection’s performance. How much the effects of priority strategies are, depends on the priority level granted to bus at studied intersections. The research compares the effects for four scenarios with different bus priority levels based on a proposed model for bus arrival time prediction at isolated signalized intersections. The second point is the improvement of genetic algorithm (GA) for adaptive bus signal priority control. This target aims to overcome the shortcomings of traditional method that is not suitable for real control application (Guangwei et al., 2007) due to the huge calculation time. The last point is the improvement for arterial with multi-intersections. Although there have been many research studies about signal priority as presented in the literature review, the priority with bus guidance task has not been received much. Utilizing all factors to improve bus service and minimize the traffic delay is another target in this research. Besides traffic volume, signal state, the research would like to analyze in more details the effects of bus guidance task on the network performance.

5.2. OBJECTIVES

There are three main objectives in this chapter. These objectives are clarified as follows:

- The first objective is to propose a bus arrival time prediction model to predict bus arrival time when applying image processing sensor at intersections. Taking full advantage of the accuracy of the proposed model, the research then conducts a comparative analysis of the effects on intersection performances when the priority level of buses increases. To do that, four scenarios with different bus priority levels are considered, including a base case with no priority or preemption treatments, bus signal priority strategy (BSPS), bus preemption with exclusive lanes and bus preemption without exclusive lanes. Based on the results of the comparative analysis, the authors would like to investigate the advantages as well as disadvantages of using the bus priority strategies at signalized intersections.

- The second objective is the improvement of Genetic Algorithm (GA) in improving the calculation speed for adaptive bus signal priority control. This improvement can save the calculation time for optimization task and it is suitable for any real application.

- The last objective is the development of an improved bus signal priority model in arterial roads with many intersections. This model with bus speed guidance can involve the coordination of bus speed guidance and traffic delay minimization to better a bus signal priority system in arterial roads. Based on that, a sensitivity of the model performance as well as the comparison with previous model is conducted.
5.3. IMAGE PROCESSING SENSOR AND INFRARED BEACON

This section takes an overview of the functionalities of image processing sensor and infrared beacon in traffic engineering. The overview is mostly based on the data base of Universal Traffic Management Society of Japan (UTMS). The details are as follows:

5.3.1. Image Processing sensor

Unlike traditional Ultrasonic Vehicle Detector, Image Processing sensor can collect more precise traffic flow information, directly measure a spatial area to collect information of queue and delay length. The Image Sensor processes an image received from the ITV camera installed aside and above the approach lane at the traffic signal intersection. With an image Processing sensor, vehicle speed, vehicle type, as well as number of passed vehicles on more than one lane at the same time can be measured. Due to the direct measurement, the collection is more precise and more detail the information of queue and delay length. A spatial area measured by processing sensor is as illustrated in Figure 5.1.

![Figure 5.1 Spatial area measured by processing sensor.](source)

Image Processing sensor can measure directly the queue length in each lane with high accuracy as shown in Figure 5.2.

![Figure 5.2 Queue length measured by image Processing sensor.](source)
5.3.2. Infrared beacon

According to UTMS, Infrared beacons with its low installation cost can perform two-way communication with traveling vehicles based on highly directional infrared communication technology. Because of its good capability in detecting vehicles, Infrared beacons can provide more accurate traffic information. According to technical report produced by UTMS, the communication zone of an Infrared Beacon can be illustrated in Figure 5.3

![Communication Zone](source: UTMS of Japan)

**Figure 5.3** The communication zone of an Infrared beacon

5.4. STUDY ON ISOLATED SIGNALIZED INTERSECTIONS

5.4.1. Introduction

In this section, the research proposes a model for bus arrival time prediction. The bus arrival time prediction model is developed based on Image processing sensor. The research then investigates the effects of priority level on the intersection performance. Four scenarios with different bus priority levels including a base case with no priority or preemption treatments, bus signal priority with signal timing techniques, bus preemption with exclusive bus lanes and bus preemption without exclusive bus lanes are studied in this research. As mentioned in the chapter of literature review, although the concepts of priority and preemption are brought out clearly in this research. These concepts have been mentioned in some previous studies (Chang et al., 1996, Hsu et al., 2003, Wadjas et al., 2003, Chiou et al., 2003, etc). According to Oxford dictionary online, preemption is the fact or condition of taking action in order to prevent an anticipated event from happening. Meanwhile, priority is the fact or condition of being regarded or treated as more important than others. Therefore, preemption can be understood as priority with the highest priority level to priority bus or emergency vehicles. Preemption signal strategies make buses or emergency vehicles such as fire trucks, ambulances, police cars etc. pass the intersections without delay. At some signalized intersections with queue jumping lanes or exclusive bus lanes, preemption signal strategies play an important role in the effective performance of the intersections. In a likely-similar way, priority signal strategies try to minimize delays when granting priority to bus at signalized intersections. Because of the delay-minimization task, the bus delay caused by the
signalized intersection may be significantly high. The bus travel through intersections with signal priority strategies is generally not as smooth as that with preemption signal strategies. However, how much the effects are have still been received less attention.

In summary, the research proposes a bus arrival prediction model to apply to the scenarios of bus priority levels. Because the priority techniques and preemption strategies in the studied scenarios have different priority levels, the effects on intersection performance are quite different. Although there have been many priority schemes deployed at signalized intersections, a comprehensive comparison of schemes with different priority levels has received less attention. This target is investigated in this part.

5.4.2. Bus arrival time prediction model

5.4.2.1. Formulation

Ultrasonic vehicle detectors set on each approach detect traffic flow every time detector interval (Sakakibara et al. 1999). Traditionally, the flow patterns during each green periods of the detection interval are supposed to be parallel to one another. The predicted value of current detector count is calculated based on previous detector intervals. Bus arrival time prediction is executed at the moment that the bus is detected by infrared beacon. This is the travel time of bus on the road section from the infrared beacon to the stop line. By considering the signal state as well as the real traffic data collected by Image Processing Sensor at the detection moment, the research suggests a model for bus arrival time prediction.

One new point in this technique is that traffic information is considered lane by lane. If a bus is detected in lane i, the traffic information in that lane such as the queue length, the number of vehicles in lane, lane flow, etc. is concerned. The lay-out of a studied intersection is shown as in Figure 5.4.

![Figure 5.4 Studied signalized intersection.](image)

Applying Global Positioning System (GPS) to measurements of moving-object’s positions through GPS receivers, traffic engineers can track exactly moving vehicle’s positions in a given coordinate under normal conditions. The real time tracking information is stored in a database and can be useful for many GPS applications. As one kind of the applications from GPS tracking database, bus speed can be known (Rahman et al., 2010). Depending on the bus speed, distance $D$ and traffic signal states at the detection moment, the bus arrival time model is divided into four sub-models. The details are shown in Figure 5.5 and following parts.
If the signal is green at that moment, the stretch of road moved by bus during the remaining green time ($G_i - e_i$) is compared with the distance from the infrared beacon to the stop line ($D$). If this distance is shorter than the stretch of road, model 1 is used. Otherwise model 2 is used. The formulas of model 1 and model 2 as well as that of model 3 and model 4 are illustrated in every detail as follows:

- **Model 1**

$$ T_b(t) = \frac{D}{V_b} $$

- **Model 2**

$$ T_b(t) = G_{i,i} - e_i(t) + R_{i,i} + \frac{[D - (G_{i,i} - e_i(t))V_b]N}{D \cdot q_s} $$

where,

- $T_b(t)$: Predicted bus arrival time at time $t$ (s)
- $D$: the distance from the beacon to the stop line (m)
- $V_b$: detected bus speed (m/s)
- $G_{i,i}$: Green time of movement 1, cycle $i$ (s)
- $R_{i,i}$: Red time duration of movement 1, cycle $i$ (s)
- $e_i(t)$: Elapse time at time $t$ of cycle $i$ (s)
- $N$: the total number of vehicles in front of the considered bus in the same lane (veh)
- $q_s$: saturation flow rate (veh/s)

In cases that the signal is red at that moment, the current queue length ($d$) that is directly output from the Image Processing Sensor (Higashikubo et al., 1996) is compared with the distance from the beacon to the stop line ($D$). If the queue length ($d$) is larger than the distance ($D$), the bus is already in queue at the detection moment. The bus arrival time is calculated based on model 3. Otherwise, model 4 is used to predict.
\textbf{Model 3}

\[ T_{bu}(t) = R_{ij} - e_i(t) + \frac{N}{q_s} \]

\textbf{Model 4}

\[ \varepsilon = (R_{ij} - e_i(t))W_b - [D - d - (N - N_q)H_s] \]

If \( \varepsilon > 0 \), the predicted arrival time is as follows:

\[ T_b(t) = R_{ij} - e_i(t) + \frac{N}{q_s} \]

Otherwise

\[ x_1 = \frac{DN_q - [R_{ij} - e_i(t)]W_bN_q - V_b d \cdot q_s}{V_b q_s - N_q} \]

\[ x_2 = \frac{DN - [R_{ij} - e_i(t)]W_bN - V_b d^* q_s}{V_b q_s - N} \]

where

\[ d^* = d + (N - N_q)H_s \]

\[ d_b = (R_{ij} - e_i(t))W_b \]

if \( (x_1 < 0) \), the predicted arrival time is as follows:

\[ T_b(t) = R_{ij} - e_i(t) + \frac{D - d_b - |x_1|}{V_b} + \frac{|x_1|}{L \cdot q_s} \]

or

if \( (x_2 > 0) \), the predicted arrival time is as follows:

\[ T_b(t) = R_{ij} - e_i(t) + \frac{D - d_b}{V_b} \]

Otherwise, the predicted arrival time is as follows:

\[ T_b(t) = R_{ij} - e_i(t) + \frac{D - d_b}{V_b} + |x_1| \begin{pmatrix} 0.5 \\ q_sL \\ V_b \end{pmatrix} \]

where

\( d \): the considered queue length (m)

\( H_s \): the saturation space headway (m)

\( N_q \): the number of vehicles in queue in front of the considered bus in the same lane (veh)

In summary, the bus arrival time prediction model is part of a whole process in the algorithm for bus signal priority strategy. Firstly, the bus is detected by the infrared beacon. The information will be sent to the control center. Based on the database of current signal states and image processing sensor, the bus arrival time is predicted by prediction module. The predicted bus arrival time and traffic information detected by ultrasonic detectors on each approach are used to minimize the delay and decide the signal timing technique. The procedure is programmed in C++ to create dynamic linking libraries (DLL) in PARAMICS with the algorithm as in Figure 5.5.

\subsection*{5.4.2.2. Results and analyses}

The bus arrival time module was programmed in C++ in PARAMICS (Lee et al, 2001, Quadstone, 2013) to extract bus travel time information. The predicted bus arrival times were
compared with the real arrival time. The predicted arrival time and real arrival time distribute closely on the 45 degree line as shown in Figure 5.6 and Figure 5.7.

![Figure 5.6 Bus arrival time prediction validation.](image)

![Figure 5.7 Predicted error distribution.](image)

![Figure 5.8 Absolute errors of bus arrival time prediction.](image)

The root mean square error (RMSE) shown in Figure 5.6 is smaller than that of previous studies (Song et al, 2010, Bo et al, 2010). For the predicted error distribution as shown in Figure 5.7, the probability of getting exact predictions is high. The research also tests the accuracy of the proposed model when the traffic flow rate changes. Considering the above four lane arterial, the absolute errors are as shown in Figure 5.8.
The proposed model can predict bus arrival time with rather small errors. If the traffic flow rate is less than 1100 (vph), the error is less than 10 (s). With the increase of flow rates, the upper boundary of error is enlarged, up to 80(s). The number of tested samples which have absolute errors of being larger than 20s is low (sparse density) in cases of high flow rate. Meanwhile, the number of points whose absolute errors are less than 20s obtains up to by 88.2%. The high absolute error values damage the prediction model’s performance. However, there is no transit vehicle priority with signals operating level of service (LOS) E or F as per highway capacity manual (HCM) definition of LOS (Li, 2010).

5.4.3. Bus signal priority strategy comparisons

5.4.3.1. Four scenarios of bus signal priority strategy

Four scenarios with different priority levels including a base case with no priority or preemption treatments, signal priority strategies, bus preemption with exclusive lanes and bus preemption without exclusive lanes are compared in this research. The details for each scenario are as follows:

a. Setting up the base case

As shown in Figure 5.9, the base case was conducted at a real intersection in Nagaoka city, Niigata prefecture with the traffic information illustrated in Table 5.1.

<table>
<thead>
<tr>
<th>Traffic signal at the study intersection (8AM-9AM).</th>
</tr>
</thead>
<tbody>
<tr>
<td>G = 82s</td>
</tr>
<tr>
<td>Y = 4s</td>
</tr>
<tr>
<td>R = 2s</td>
</tr>
<tr>
<td>Q1=535(vph)</td>
</tr>
<tr>
<td>Bus interval: 5min</td>
</tr>
</tbody>
</table>

The main arterial of the intersection has four lanes. There are right-turn lanes on each approach. The side street has two lanes and no right-turn lane. The collected data including vehicle types, traffic flow rate, travel time, etc. were recorded by cameras and analyzed in transportation lab. After validating the base case, three traffic scenarios including bus signal priority scenario and the scenarios of bus preemption with and without exclusive lanes are developed. The most different thing between bus signal priority system and preemption scenarios is that, BSPS adjusts the normal signal operation to better accommodate buses, meanwhile the preemption scenarios give a special control phase to buses by terminating the normal signal operation.
b. Bus signal priority system

As mentioned above, when a bus comes, the signal controller will receive the bus information through detector systems. The signal controller will determine the moment, amount of time, and the type of signal timing techniques needed to grant priority to bus. The signal timing techniques considered in this research includes green extension and early green. The decision of granting priority to bus depends on the result of the optimization functions.

c. Bus preemption with exclusive lane

There is a difference in signal timing techniques between bus signal priority and bus preemption scenarios. For the bus signal priority strategy, the techniques of early green or green extension are used in the control cycle. These techniques resulted from the considerations of total intersection delays. After finishing doing the signal techniques, the signal phases are returned as the normal phases. For the signal preemption strategies, there is a private phase for bus travel. The magnitude of green phase for the bus private phase depends on the predicted arrival time of the proposed arrival time module. As soon as the bus is detected, the private phase for bus is on, meanwhile other phases are inactive. The arrival time prediction plays an important role in the preemption strategies. It decides the delays of non-bus vehicles due to preemption situations.

In the scenario of exclusive bus lanes, buses have a private most left lane to move. Other non-bus vehicles must not use this lane. However, this principle is exceptive for non-bus vehicles that are turning left at the intersection. As a part of real cases, the turning left non-bus vehicles are allowed to use a short section of exclusive bus lane (around 10m upstream from the stop line) to turn. This principle is assumed to affect insignificantly in this research, especially for arterials with small side street’s volumes.

![Exhibit Figure 5.10 Preemption cases.](image)

d. Bus preemption with with-flow lane

As shown in **Figure 5.10**, the research proposes two scenarios of preemptions. The first one is bus preemption with exclusive lanes and the second one is bus preemption without exclusive lanes. For the scenario of no exclusive lanes, buses have to travel together with non-bus vehicles. Therefore, the bus travels will be affected by non-bus vehicle’s travels.

It can be seen that, when a bus reaches to the signalized intersection, the queue length delay in the scenarios of signal priority or preemption without exclusive lanes causes the delay of bus to traverse the intersection. Meanwhile, the scenario of preemption with exclusive lanes can overcome the situation. It operates as a “queue jumping lane” to avoid the bus delays.
caused by long queues. In this scenario, bus can travel continuously through signalized intersections without any obstruction.

5.4.3.2. Results and analyses

a. Validation of the base case

After validating the reasonableness of operating parameters such as traffic signals, lane operations, etc. the research conducts a comparison between the simulation result and observation data to validate the base case. For the flow rate validation, the comparison is shown in Figure 5.11.

![Figure 5.11 Flow rate validation.](image)

As can be seen in Figure 5.11, the simulation values and the observation data are closely distributed along the 45-degree line with a mean percentage error of 11.1%. Besides traffic flow rate, the vehicle travel times are also validated. For the travel time validation, a comparison between the simulated result and observed travel time for every 15 min interval is conducted for vehicles traveling through the intersection in two directions of a 300m-long segment on the main street.

![Figure 5.12 Vehicle travel time validation.](image)

As shown in Figure 5.12, the research concludes that the observation data and simulation value are approximately same with a Mean Percentage error of 0.09. This base case is used to build the three bus priority strategies including bus signal priority and two scenarios of bus preemption to comparatively analyze how difference the effects are.
b. Comparative analysis

The research suggested categorizing the four scenarios into four levels of bus priority. The base case with no priority or preemption treatments is considered no priority (level is zero). In this scenario, buses and non-bus vehicles are treated equally in terms of traveling. For a little higher rank in bus priority level, bus signal priority scenario can grant priority to bus. However, as presented above, the final decision depends on the total delay at the intersections. Buses sometimes incur a delay caused by the intersection. Similarly, the preemption scenario without exclusive lanes can help bus reduce the delays with the preemption phase for bus. However, the queue effects are also significant to the bus travel. Finally, the preemption scenario with exclusive bus lane can be considered the scenario with the highest bus priority level. Bus can traverse the intersection on exclusive lanes without any delay. The above explanation is illustrated in detail in the following part of trajectory analysis.

By extracting vehicle positions at every simulation time step, the research plots the distance-time relationships of any vehicle in PARAMICS. Usually, the vehicle trajectory changes with the changes of traffic situations or simulation scenarios. However, in the four studied scenarios, the order as well as the shapes of the bus trajectories is generally unique when compared with one another. The straight bus trajectory in the bus preemption scenarios as well as the shorter queue waiting time in the bus signal priority scenario compared with that in the normal base case tells its advantages. Considering typical bus trajectories in the four studied scenarios at the same simulation period, the arrangements are shown in Figure 5.14

The blue line represents the bus trajectory in the base case. The bus has to wait in queue until the long queue (d_2) dissipates. Meanwhile, the shorter queue delay (d_1) in the bus signal priority scenario (pink line) helps the bus traverse the intersection faster. The yellow line represents bus trajectory in the scenario of preemption without exclusive lanes. The bus speeds in this scenario trends to slow down slightly because of the queue effects. The straight green line represents the bus trajectory in the scenario of preemption with exclusive lane. In this scenario, bus can travel smoothly through the intersection. Besides, the times at which the bus traverses the intersection in each scenario (time points 1, 2, 3, 4 as shown in Figure 5.14) can say how much the saving time is when bus priority strategies are applied to the normal base case. The higher the bus level priority is, the more left-hand this time point is.

Apart from trajectory analysis, the effects of the exclusive lane as well as the effects on vehicles in the main and side streets are necessary to be studied. Let the studied intersection be a center, the research calculates the vehicle travel time on 300m-long route segments of the main and side streets. The percentage in travel time changes is calculated as the formula:

\[
\text{Percentage}_{i,j} = \frac{S_{i,j} - N_i}{N_i} \times 100\%
\]

where,

- \(\text{Percentage}_{i,j}\) : the percentage of travel time changes when comparing the travel time on route segment \(i\) of case \(j\) with that on route segment \(i\) of the base case. (\%)
- \(i=\{\text{Main street route, side street route}\}\)
- \(j=\{\text{Bus signal Priority case, Bus preemption with exclusive lanes, and Bus preemption without exclusive lanes}\}\)
- \(S_{i,j}\) : the simulation value on route \(i\) of case \(j\) (s)
- \(N_i\) : the simulation value on route \(i\) of the normal base case (s).
Based on the travel times in the base case, the percentage of travel time changes in each priority strategy is analyzed. This percentage of travel time changes is calculated for buses and non-bus vehicles traveling in the main and side streets when bus or non-bus vehicles are reaching the signalized intersection. After conducting nearly 50 simulation-running with different random seeds for each scenario, the results are calculated and analyzed. The curves of travel time changes in percentage when the priority level increases are drawn with acceptable test values. The comparison is shown in Figure 5.13.

**Figure 5.13 Changes in travel time.**

This figure shows two main points. The first one is the sign of the change percentage. As shown in Figure 5.13, when the priority level increases, the change percentage of bus (blue curve) is negative, but that of non-bus vehicles in the main street (pink curve) and side street (yellow curve) are positive. This means that on studied route segments, the travel time of bus decreases when the bus priority level increases. Conversely, the travel times of non-bus vehicles in the main and side streets increase with the increase of bus priority level. The second point is the magnitude and tendency of the change percentage. The higher the bus priority is, the more positive effects on bus travel time are, the more negative effects on non-bus travel time are. Indeed, as for the bus travel time, bus priority strategies can reduce bus travel time considerably, by up to 10.7%, 18.2% and 23.6% for bus signal priority, bus preemption without and with exclusive lane, respectively. However, the priority strategies cause the increase in non-bus vehicle’s travel times, especially non-bus vehicles traveling in the main street (pink curve). Compared with the current base case, the bus preemption with exclusive lane causes the most negative impacts on non-bus’s travel. The increase is up to around 28.9% in comparison with the car travel time in the current base case.

**Figure 5.14 Bus trajectory comparisons.**
One factor that concerns directly to the travel time changes is turn delay at the intersection. In this research, the turn delay is recorded from the entry stop line of the entry link to the entry stop lines of the exiting link and is the difference between the actual travel time and free flow travel time. Considering all approaches at the studied intersection, turn delays for bus and non-bus vehicles are as shown in Figure 5.15.

For the bus turn delays, when bus priority level increases, the bus turn delays reduce (the blue curve). It is suitable for the purpose of granting priority to bus. The bus turn delays are almost zero when the preemption scenarios are applied. Contrary to the bus turn delay, the non-bus vehicle turn delay increases too much when the bus priority level increases (the red curve). In deed, the current bus signal priority model can reduce the bus turn delays by 53.5% in the bus signal priority scenario; meanwhile the non-bus turn delay increases by 47.1% for this study site. The bus preemption causes the non-bus turn delays to increase significantly, by up to 74.7% and 94.2% for the preemption without and with exclusive lanes, respectively.

According to equilibrium relationships, if the number of persons using buses increases, the number of non-bus vehicles should be decreased. Thus, the number of passengers in bus (bus occupancy) is an important factor to evaluate the intersection performance in particular and traffic systems in general. To evaluate the importance of bus occupancy, the total passenger delays for all approach should be considered. Based on actual observations, the average number of persons in non-bus vehicles is 1.2 with the standard deviation of 0.4 for 110 vehicles. Assuming the bus occupancies are 15 passengers or 35 passengers, the passenger turn delays at the intersection for passengers in non-bus vehicles and all passengers are shown in Figure 5.16.

As shown in Figure 5.16, the increase of priority levels makes the turn delay of passengers in non-bus vehicles increase (blue curve). If the number of passengers on bus (bus occupancy) is high, the total passenger-turn delay at the intersection is also high (pink curve and yellow curve) and quite different from the turn delay of passengers in non-bus vehicles in the base case. The total passenger-turn delay curves (pink and yellow curves) trends toward the turn delays of passengers in non-bus vehicles (blue curve) when the bus priority level increases. With high priority levels, the role of passengers using bus in increasing turn-delay is insignificant. The turn-delay caused by only passengers in non-bus vehicles is as shown in the figure. Because of the equilibrium relationship between the number of passengers using
buses and that of using general vehicles, the higher the bus priority is, the more important the role of bus occupancy in the delay reductions at intersections is. A good bus level of service makes passengers see theirs benefit and switch from non-bus vehicles to buses. In other words, a high bus priority level with high bus occupancies should be a target of any transportation system.

\[ \text{Figure 5.16 The role of bus occupancy.} \]

5.4.4. Genetic algorithm for adaptive bus signal priority control

5.4.4.1. An overview on optimization approach

Genetic algorithms are global optimizers that have been used successfully for many research studies (David et al., 1993, Der-Hong et al., 2001, Jitendra et al., 2004). Compared with other traditional optimization techniques such as random search, gradient methods, iterated search, simulated annealing, etc., the genetic algorithm can overcome the shortcomings that the other methods incur. In addition, these traditional optimization techniques lack both speed and robustness needed for real-time adaptive traffic signal control (Guangwei et al., 2007). Therefore, genetic algorithms should be the suitable way for complicated signal control optimizations.

Indeed, traditional optimization techniques remain important limitations. Specifically, the random search optimization technique is considered as a very unintelligent strategy because of the random selection in the search space (David et al., 1993). Some other optimization techniques using the guide of direction of search called gradient methods can improve the computation convergence speed well. However, these methods usually fail because of the discontinuity that causes the impossibility of the function-derivative computation. By combining random search and gradient search, the iterated search technique is also considered a good way of optimization problems. Although this combination can improve the speed significantly, no overall picture of the “shape” domain is obtained because each random trial is carried out in isolation. Similarly, a modified version of hill climbing method called simulated annealing technique was developed to be a good way for optimization. But, this method only deals with one candidate solution at a time and therefore does not build up an overall picture of the search space (David et al., 1993).

In bus signal priority control, minimizing negative effects on traffic to find proper sets of parameters has been objectives of many research studies (Li, 2010, Wanjing et al., 2011).
The scope of the optimizations covered not only isolated signalized intersections, arterial roads with multi-intersections but also large traffic networks with co-ordinations among signalized intersections. The larger the scope is, the more complicated the optimization problems are. Especially, the complexity becomes problematic when a lot of related factors such as signal state, pedestrian factor, traffic factor are concerned in adaptive bus signal priority control. Therefore, to optimize such a multi-dimension problem, GAs have been chosen as the proper way (Ayad et al., 2009, Halim et al., 2004, Heydar et al., 2009, Leena et al., 2009). But, most of these papers focused on developing methods to apply GAs as a way to optimize only. The slow convergence speed of conventional GAs has not received much attention. The huge computation time of conventional GAs is a obstacle to any real-time application. Several advances in the field of evolutionary computation have been suggested to overcome the obstacle, namely Parallel GA, Hybrid GA, etc. These advanced GAs try to structure the populations into the number of subpopulations running parallel on processors (Guangwei et al., 2007), or to use heuristics of specific problems to improve the convergence speed (Liviu, 2011). But, these advances required huge resource of calculation facilities or designed for specific cases only. In the scope of adaptive bus signal priority control, this paper would like to present a heuristic approach to improve the convergence speed of the conventional GA. This heuristic approach is based on the compensation rule between consecutive cycle lengths assumed in adaptive signal control. The improved GA would contribute partly to a comprehensive view of how to faster the GA convergence speed when applied to the optimization problems of bus signal priority control systems.

### 5.4.4.2. Adaptive bus signal priority control

Since the purpose of this paper is to propose an improved genetic algorithm (GA) for adaptive networks, the paper investigates an adaptive bus priority control system for a signalized intersection only. The investigations into multi-signalized intersections, grid networks or other related factors are beyond the scope of this paper. Based on previous research studies about adaptive bus signal priority control in actuated system (Li, 2010), this section would like to take an overview of the relationships as well as some constraints at a simple signalized intersection whose signal follows the National Electrical Manufacturers Association (NEMA) standard (Regina, 2008). The definitions for the left-hand drive in Japan are as follows:

**Table 5.2 Definitions of phases, rings and barrier**

<table>
<thead>
<tr>
<th></th>
<th>Main phase</th>
<th>Cross phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring A</td>
<td>1 2 4 3</td>
<td></td>
</tr>
<tr>
<td>Ring B</td>
<td>6 5 7 8</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.17 Standard NEMA phases, rings and barrier**
There are several constraints for fixed cycle length intersections under NEMA operations. These constraints are necessary and boundary conditions of objective functions in optimization problems. They include cycle length constraints, minimum green time constraints, barrier constraints, red-green relationships, etc (Li, 2010). Several typical constraints are briefly expressed in this section. For example, the fixed cycle length constraint for the lead-lead phase sequence is expressed as follows:

\[ L_1 \cdot L_2 \left( C - \sum_{i=1}^{8} g_{ji} \right) = 0 \]

where

- \( C \): cycle length (s)
- \( g_{ji} \): the green duration of movement \( i \), cycle \( j \) (s), \( j=1,2 \).

\[ L_i = \begin{cases} 1, & \text{if movement } i \text{ is lead} \\ 0, & \text{if movement } i \text{ is lag} \end{cases}, \quad i=1, 3, 5, 7 \]

Similarly, the minimum green interval to ensure the walking time is calculated based on walking speed, effective crosswalk, number of pedestrians and the road width as shown in the previous equation in Chapter 3. Or concerning barrier and rings, the constraints are built based on the upper ring and bellow ring relationship. The upper ring and the below one at the same side of the barrier should have the same duration. The relationships are as follows:

\[ \begin{align*}
\sum_{j=1}^{4} g_{j1} + g_{j2} &= g_{j5} + g_{j6} \\
\sum_{j=1}^{4} g_{j3} + g_{j4} &= g_{j7} + g_{j8}
\end{align*} \]

Relating to bus signal priority control, there have been many research studies about it as presented in the chapter of literature review. However, this paper ends in proposing an improved genetic algorithm to increase the convergence speed as well as analyzing the effects of the improved GA only. The research would not analyze deeply the model nor try to develop new models to improve the bus service.

The optimization model used in this research is assumed to include the movement splits in two consecutive signal cycles. The first cycle is the cycle in which the bus is predicted to come. This cycle is the controlled cycle in which the movement splits are divided following the optimal results of the optimization problem. The second cycle is the compensation cycle in which the movement splits are re-compromised to compensate for the lost time in the controlled cycle. The amount of movement splits in the compensation cycle are output from the optimization results, too. The illustration is shown in Figure 5.18.

**Figure 5.18** Considered consecutive signal cycles

In Japan, two signal timing techniques, including green extension and early green are popularly used (Geetha et al, 2008). Depending on the optimal results of the optimization task, these two techniques are applied to adaptively control the traffic signal once the bus approaches to the intersection. The optimization task is proposed to minimize the total delay
in the two consecutive cycles in this research. With arrival rate $\lambda_{ji}$, saturation flow $\mu_i$, the traffic delay and bus delay are calculated based on relationship as shown in Figure 5.19.

![Figure 5.19 Early green time technique](source: Li, M (2010))

Assuming that there is no residual queue in each signal cycle, the total delay is calculated based on the bus delay and general traffic delay as mentioned in previous studies (Li, 2010) as follows:

$$d = \sum_{i=1}^{s} \left[ \frac{\mu_i}{2} \rho (r_{i1} + r_{i2})^2 - r_{i2} \mu_i \min(g_{i1}, \rho_i r_{i1}) \right] + \phi \cdot w_b \frac{R_i}{T_q} \max(T_q - T_b, 0)$$

where

$$\rho = \frac{\lambda_{ji}}{\mu_i - \lambda_{ji}}$$

$\lambda_{ji}$: is the arrival rate on approach $i$ of cycle $j$ (veh/s)

$\mu_i$: is the saturation rate on approach $i$ (veh/s)

$r_{ji}$: is the red time for approach $i$ of cycle $j$ (s)

$T_b$: is bus arrival time at signal (which reference to the beginning of the red duration for the bus phase).

$w_b$: is the bus weight which is assumed to be 20 in this research.

$\phi$: is a binary indicator to choose early green or green extension techniques. The indicator is as follows:

$$\phi = \begin{cases} 1, & \text{if early green is applied} \\ 0, & \text{otherwise} \end{cases}$$

Buses are assumed to come sparsely on approach 2 of the main street (as shown in Figure 5.17), the queue is dismissed at:

$$T_q = \frac{\mu_i}{\mu_i - \lambda_{ji}} R_i$$

In summary, once buses are detected by the road-side infrared beacon, the optimization algorithm determines the movement splits in the bus arrival cycle and in the compensation one. The optimization task is trying to minimize the total delay caused by granting priority to the bus. To get the results, the optimization task uses the improved genetic algorithm to find optimal sets of parameter which are sent to the traffic control center to modify the traffic signal to adapt to the current priority situation.
5.4.4.3. Evolution algorithm

To overcome the low convergence speed of the conventional GA, the paper introduces a new process of GA type determination. Considering a simple adaptive bus signal priority control based on the actuated system, the research tries to develop a GA to minimize the total control delay. As many actuated control systems in Japan, once a bus is detected by the infrared beacon setup upstream from the intersection (Ryohei et al., 1996), the signal control center will determine the optimal solution of signal timing to grant to the bus. The determination step shown in Figure 5.20 is proposed to use GAs in this research and should be a function of traffic state, bus occupancy, signal state, etc. Depending on the evaluation of the current traffic situation, the improved GA or conventional GA should be chosen for the optimization. The structure of the process is illustrated in Figure 5.20.

![Figure 5.20 The process of GA type determination](image)

The conventional GA shown in Figure 5.20 is introduced with its mechanism inspired by evolutionary biology such as inheritance, mutation, selection and crossover (David et al., 1993). This robust global optimizer has been applied successfully for many research in the field of transportation (Der-Hong et al., 2001; Guangwei et al., 2007; Jitendra et al., 2004). Because of being premised on the evolutionary ideas of natural selection and genetic, this algorithm tries to eliminate the bad traits from the population through genetic process. From parameters (known as genes) needed for the estimation, the GA process joins them together to form a string of value (refered to as a chromosome). Each gene represents a specific trait of the organism. Using selection and applying genetic operators such as mutation and crossover, the GA creates new populations of solution from the initial population. Namely, the selection operator chooses the chromosomes randomly in the population for offspring reproduction. The crossover operator exchanges subsequences of two chromosomes to create offsprings (Melanie, 1995). The probability of crossover occurring is assumed to be 0.8 in this research. The process of crossover operator is illustrated as shown in Figure 5.21.

![Figure 5.21 Crossover operator](image)
After finishing the crossover operator, the mutation operator then randomly flips some bits in a chromosome in order to ensure genetic diversity within the population. The mutation probability proposed in this paper is 0.15. The illustrated figures of the mutation operator are as follows:

![Mutation Operator](image)

**Figure 5.22 Mutation operator**

The conventional GA process including population generation, fitness evaluation, individual selection, mutation, crossover is executed until reaching the stop conditions. Once the stop conditions are satisfied, the best solution of parameter sets is used to control the traffic signal. The process of optimization is illustrated as in the following figure.

![Conventional GA for Optimization](image)

**Figure 5.23 Conventional GA for optimization**

As mentioned above, the conventional GA requires huge time to converge the optimal solution. Therefore, the paper would like to present an evolution algorithm to improve the convergence speed when optimizing delay in bus signal priority control. According to previous studies, the most important aspects of any genetic algorithm implementation are the fitness evaluation function and the reproduction scheme that must be mutually compatible (Liviu et al., 2011). The reproduction of new population is carefully concerned in this research. Because the general purpose of the optimization in adaptive control system is to compromise the movement splits to get the total minimum delay, the balance rule should be kept in terms of time delay. Once the first cycle is shrunk or extended, the second cycle will have a tendency to compensate the first cycle for time loss caused by the priority granted to bus. Let $C_s$, $C_e$ be the constrained spaces of signal shrink and signal extension respectively, the population spaces of the first cycle ($P_i$) and the second one ($P_{i+1}$) in the conventional GA and the improved GA are illustrated as follows:

For the conventional GA: $P_i = <S,E>$, $P_{i+1} = <S,E>$

For the improved GA: $P_i + P_{i+1} = <S,E>$

where

- $S$: Population space for signal shrink $S = \{ s_u \mid u \in C_s \}$
- $E$: Population space for signal extension $E = \{ e_v \mid v \in C_e \}$
Relying on that relationship, the research tries to improve the convergence speed of the conventional GA by properly upgrading the reproduction of new populations to continue the genetic process. This tendency makes the new generated population narrow and distributed around the possible optimal points if the traffic evaluation step is good enough. Once the new population spaces contain optimal points as shown in Figure 5.24, the search engine of the improved GA to generate a number of citizens in such the narrowed population is therefore more effective than that of the conventional one. The illustration of this improvement is illustrated as in Figure 5.24.

Considering a case study at a simple signalized intersection, all information of the adaptive bus signal priority control such as the objective function, constraints, etc are coded in C++ language. Using the same characteristic parameters of genetic algorithms such as crossover probability, mutation probability, etc. for the computation processes of the conventional GA and the improved GA, the paper would like to present the advantages of the proposal. In terms of the the improved GA is presented and comparatively analyzed as shown in following sections.

5.4.4.4. A simple numerical test

The research computation time and the number of iterations for convergence, the performance of conducts a numerical test with the real traffic information of an intersection in Nagaoka, Niigata, Japan. The main street and cross street of this intersection have four lanes. There are right-turn lanes on each approach. For simplicity, the research assumed the constant arrival rates as well as constant saturation flows. By analyzing recorded videos at the studied intersection, the average flow rates on each movement as well as real signal information (8:00-9:00 AM, May 13rd, 2010) are simplified into two phases as shown in the following table and figure.

<table>
<thead>
<tr>
<th>Flow rates for each movements (vps)</th>
<th>Conventional GA</th>
<th>Improved GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_1=0.011$</td>
<td>$\lambda_2=0.103$</td>
<td>$\lambda_3=0.023$</td>
</tr>
<tr>
<td>$\lambda_4=0.154$</td>
<td>$\lambda_5=0.038$</td>
<td>$\lambda_6=0.070$</td>
</tr>
<tr>
<td>$\lambda_7=0.020$</td>
<td>$\lambda_8=0.143$</td>
<td>$\mu=1.250$</td>
</tr>
</tbody>
</table>

Figure 5.24 Population space improvement
5.4.4.5. Result and analyses

Assuming the bus arrival time on local clock $T_B$ of 25s, the optimization processes are graphed for two scenarios tested in this paper. The first scenario uses the conventional GA to find the optimal set of parameters and the second one is applied with the improved GA. With the studied traffic situation, the results show that after around 10-20 iterations, the nearly stable solutions are achieved. As shown in Figure 5.26, the changes of the optimized delays over the number of iterations can be compared clearly. The figure shows that the convergence rate of the improved GA is faster than that of the conventional GA. The details are shown in the following figure:

It is clearly illustrated in Figure 5.26 that, the improved GA has a faster convergence speed. The improved GA converges after 6 iterations. Meanwhile the figure is up to 10 in the conventional GA case. In addition, because the computation time to achieve the optimal result is an important factor, the paper would like to compare the amount of time needed for each iteration in the two cases.

As a fact of using GA to solve any optimization problem, there are many random numbers used in the optimization process. This technique tries to “select the best, discard the rest”. Of two popular engines of this technique, optimization and search problem, the engine of search problem uses much random numbers to mimic the natural selection. As shown in the following figure of the genetic algorithm, the search process including operations, crossover and mutation, to create populations are steps needed to be concerned. The random function $\text{rand}()$ is used by utilizing the library function of C++ language. As shown in the above
The procedure of the algorithm starts with the initial population. This initial population is chosen randomly from population space defined with constraints in this research. The algorithm will evaluate how fit of these selected candidates and select the best individual among them. Also from candidates, the algorithm will operate mutation and crossover to create new population to evaluate the fitness of each individual. The operations of mutation and crossover that search candidates for the best selection run randomly. If lucky, the process can search a good candidate to become the best selection just after a very few number of iterations. Otherwise, this process needs more time to find the required solutions. The result of the model performance under different random seeds is compared with the conventional GA as in Figure 5.27

**Figure 5.27 The results with different random seeds**

Under different random numbers, the fluctuation areas of the result in the proposed model and the conventional one are illustrated in Figure 5.28. The area produced by the proposed model is smaller than that by the conventional model. The fluctuation is very significant at the first several steps (Dev. = 446.27s) but becomes small after 20 iterations (Dev. = 0.22s).

**Figure 5.28 The fluctuation areas**

Based on these investigations, the research concludes that the random numbers that reflect the nature of selection process affect heavily the convergence rate of the algorithm at the first several iterations. However, the search engine operating all search space can find the best
offspring among selected parents after five iterations under the precept that “select the best, discard the rest”

Assuming that the stop condition is the number of iterations with its figure of 200 iterations, the paper conducts the computations in a computer whose configurations are 0.99GB of RAM, Core 2 CPU, T7200 @2.00GHz. Converted from stair charts output by the programs, the computation times are compared as follows:

![Computation Time Comparison](image)

**Figure 5.29** The computation time comparison

With the accuracy analysis of millisecond, the computation time in the case of improved GA is usually smaller than that in the conventional GA as shown in **Figure 5.29**. After 200 iterations, it takes $T_1=31$ milliseconds for the conventional GA to converge to a nearly optimal delay of 1798.38s. Meanwhile, the improved GA lost 16 milliseconds only to get a better nearly optimal delay of 1797.99s. It can be said that, the improved GA is better than the conventional one in terms of computation time. Compared with the conventional GA, the improved algorithm can reduce the computation time by up to 48.39% after 200 iterations. On an average, each iteration can save 75 microseconds if the improved GA is applied. The saving time benefits the smoothness of any simulation animation. It is especially necessary for real time control which requires small computation time.

As mentioned above, the idea to improve GAs for adaptive bus signal priority control is based on the compensation rule between the consecutive cycles. This rule is sometimes ruined by the different levels of the total delays in the first cycle and in the second one. According to **Figure 5.20**, to choose which GAs, improved GA or conventional GA, is the proper algorithm at a certain traffic situation, the step of traffic evaluation is extremely important. This step should be depended on many factors. However, for the purpose of GA algorithm improvement, the research simply assumes that only saturation degrees on the main street and cross street are related fators. The saturation degree (HCM, 2010) for movement $i$ is defined as follows:

$$\chi_i = \frac{\lambda_i}{\mu_i}$$

where,

$\lambda_i$: Arrival flow rate for movement $i$ (veh/s)
$\mu_i$: Saturation flow rate for movement $i$ (veh/s)
The performance of the improved GA is compared with that of the conventional GA by introducing the concept of convergence rate improvement. The convergence rate improvement is defined as the average ratio of the reduced delays benefited by applying the improved GA to the initial delays optimized by using the conventional GA.

\[
R = \frac{\sum_{i=1}^{N} \left( \frac{C_i - I_i}{C_i} \right) \cdot 100\%}{N}
\]

where

- \( R \): The convergence rate improvement (%)
- \( C_i \): The optimal delay at iteration \( i \) optimized by the conventional GA (s)
- \( I_i \): The optimal delay at iteration \( i \) optimized by the improved GA (s)
- \( N \): The number of considered iterations

Based on the convergence rates of the two GAs, the research identifies that most of them converge to stable points after 10-20 iterations. However, for valid comparisons, the paper investigates 200 iterations for each type of GA. The demand based efficiency of the improved GA is shown as in the following figure.

![Figure 5.30 The demand based efficiency](image)

The figure shows the performance of the proposed genetic algorithm when traffic saturation degrees change. As shown clearly in the figure, the improved GA are successful at most of the points where the saturation degree on the cross street is higher than that on the main street (bus approach). These success points present that the improved GA can perform a better convergence speed compared with the conventional GA. The convergence rate improvement can reach to 36.2\% in situations of high saturation degrees on cross street and small ones on the main street. On the contrary, when the saturation degree on the main street is higher than that on the cross street, the damage of compensation rule caused by the big difference in traffic demand occurs. The failure makes the slower convergence rate in the improved GA when compared with the conventional one. Therefore, the conventional GA is suggested to use for this area as proposed in Figure 5.30.
5.4.5. Conclusions

5.4.5.1. Comparative analysis at isolated intersections

The part aims at two targets. Firstly, the research proposes a model for bus arrival time prediction based on data from image processing sensor and signal database. The model can predict the bus arrival time at the studied traffic situation with a Mean Percentage Error of 4.44%. The predicted arrival time plays an important role in the accuracy of any bus signal priority model. This arrival time prediction model is applied to bus priority strategies with different bus priority levels: bus signal priority scenario, bus preemption without exclusive bus lanes, and bus preemption with exclusive bus lanes.

Secondly, the research conducts a comparative analysis of bus priority strategies with four priority levels as mentioned above. The result shows that with the increase of bus priority level, the bus travel time decreases significantly. However, it affects negatively on the travel of non-bus vehicles. Indeed, bus travel time on the studied segment reduces considerably, by up to 10.7%, 18.2% and 23.6% for bus signal priority, bus preemption without and with exclusive lane, respectively. However, the increase in non-bus vehicle travel time is significant, by up to 28.9% in comparison with non-bus travel time in the current base case. In terms of turn delays at the intersection, the bus priority level can reduce the bus turn delay well, by up to 100%. But, a considerable increase up to 94.2% of non-bus vehicle turn delay causes negatively effects on non-bus vehicle travels. Besides, the more the bus priority levels is, the more important the role of bus occupancy in the delay reduction at intersections is.

The bus arrival time prediction model in this research has some limitations. The model has ignored the lane changing behaviors in the road section from the infrared beacon to the stop-line. That caused large errors in the prediction results. Moreover, the speeds of all other vehicles within the studied segment are important to the accuracy of the model. An improved model to overcome these shortcomings should be studied in next studies.

For the purpose of comparisons, the bus signal priority model is simplified in this research. The minimized functions should be concerned with more variables at a more complicated level to deal with the diversified nature of traffic. A careful consideration on improving bus signal priority model is necessary for future works. In addition, the co-ordinations in adaptive networks with multi-phases, multi-requests are more realistic and more important aspects. Thus, the signals for not only isolated signalized intersections, but also arterial roads or grid networks with multi-requests or conflicting bus routes are promising research objectives needed to be studied.

In Nagaoka where the key public transportation mode is bus, the applications of the bus signal priority strategies to improve bus service are extremely necessary. Depending on local area characteristics such as population, road geometry, bus frequency, traffic demand, pedestrian, etc, the city planners should choose the proper strategy. Because preemption scenarios cause unexpected queue lengths for general vehicles, it is necessary to comprehensively consider factors before the deployments. To balance user’s benefit among different transportation modes in dense population areas, a BSP system that can both improve bus service and minimize negative impacts on general traffic simultaneously as well should be introduced.
5.4.5.2. The GA improvement

This part aims at three targets. The first target is to propose an improved genetic algorithm (GA) for optimization in adaptive bus-signal priority control at signalized intersections. Based on the compensation rule between signal cycles in adaptive control, the paper suggests an improved GA that can increase the convergence rate to reach the optimal solutions. The convergence speed of the proposed GA is then compared with that of the conventional GA. The faster convergence speed reduces the computation time, which is very important to signal control in complicated networks. Secondly, the paper would like to present a way to apply the algorithm to a simple adaptive bus-signal priority control system as well as compare the amount of time saved when applying the improved algorithm. The result shows that after 200 iterations, the improved GA can save the computation time by 48.39%. This time saving is important to the smooth running of any simulation model as well as real time control systems. Then the research thirdly investigates the efficiency of the proposed algorithm under various values of traffic saturation degree. The results show the improvement of the proposed GA when compared with the conventional GA. The improvement can be up to 36.2% in the positive extreme cases. This improvement becomes significant when the saturation degree on the cross street is higher than that on the main street.

For the purpose of algorithm evaluations, the numerical test is rather simple in this paper. To recognize clearly the benefits of the improved GA, the bus-signal priority control should be considered at a larger network scale or at a more complicated level. In addition, the traffic evaluation step to choose which genetic algorithms is critical to the success of the proposal. However, it was assumed simply in this research with the saturation degrees as related factors. A more comprehensive survey should be dealt with other factors such as bus occupancy, number of stops, queue length, etc. These shortcomings are expected to be concerned in the studies to follow.

Although the improved GA can reduce the computation time significantly, the effect of the improved GA is still modest. The application is suitable in the cases where the saturation degree on cross street is higher than that on the main street only. Moreover, the main limitation of the improved GA is that the algorithm is bound in adaptive signal control, where the compensation rule between signal cycles is the important factor for the algorithm. For negative extreme cases in which the compensation rule does not occur, the convergence rate of the proposed GA improves insignificantly when compared with that of the conventional GA. Therefore, a further improvement of the genetic algorithm for bus-signal priority control to get a better convergence rate should be a target of future studies.
5.5. STUDY ON ARTERIAL ROADS WITH MULTI-INTERSECTIONS

5.5.1. Introduction

In Japan, more than half of prefectures have already deployed bus priority systems. The current priority system which includes bus lanes, warnings to vehicles which are illegally running in the bus lane, and traffic signal preemption can improve convenience for users, encourage the use of public transportation as well as ensure on-time bus operation, bus safety (UTMS). However, there is a pessimistic reality that the fluctuation of bus punctuality is very high, the number of private cars increase, and some bus routes are abolished because of poor passenger demands (Sano et al., 2007). Although the bus signal priority system can improve bus service well, its negative effects on general traffic are significant, causing traffic congestion as well as potential rider-ship switch. In a research aiming to introduce the benefit of road side infrared beacon in setting up a new public transportation, an idea for two-communication application in improving the bus system priority has been proposed and conducted trial test (Tanaka et al., 1996) as illustrated in Figure 5.31.

![Figure 5.31 A new public transport system](source: Tanaka et al. (1996))

In this system, road side infrared beacons play important role in two-way communication between bus driver and traffic control center. When the infrared beacon detects a bus, the bus information can be sent to the traffic control center and a recommend speed for bus can be transmitted to bus driver through in-vehicle unit set in bus as well. The study conducted an
empirical test and concluded limitedly the benefits to bus. The effects on non-bus vehicles were not studied. Besides, this is just a practical test, a detailed model for this system has not been considered. Moreover, the recommend speed should depend on bus physical attributes, current traffic group signal status as well as the traffic demand on each approach of each intersection. These influences have not been investigated yet. Recently, a similar research was conducted for BRT network (Yang et al., 2012). The concept of transit speed guidance was used in the model to simulate signal priority systems in order to improve bus efficiency. However, the purpose of bus guidance in that research is just for easy prediction of bus arrival at a certain intersection. Its contribution to the efficiency of signal priority system was not studied enough.

Although there have been man research about signal priority in the past, the priority with bus guidance task has not been received much. In summary, utilizing all factors to improve bus service and minimize the traffic delay is the target of this research. Besides traffic volume, signal state, the research would like to analyze in more details the effects of bus guidance task on the network performance.

5.5.2. Model development

5.5.2.1. Bus arrival time prediction

Considering a six-lane arterial with three consecutive signalized intersections, the research proposes that a road side exclusive bus lane and an Infrared beacon are installed as shown in Figure 5.32

Bus arrival time prediction is executed at the moment that the bus is detected by infrared beacon. This is the travel time of bus on the road section from the infrared beacon to the stop lines of each intersection in the intersection group. Because of the exclusive lane for bus, bus is assumed to increase speed freely within its physical attribute limit. With the priority treatments at intersection $k$, the bus can traverse smoothly this intersection without any delay. Therefore, the bus arrival times at the stop lines of intersection $k$ is calculated as a function of the distances and recommended speed. Assuming bus follows a uniform and accelerated motion, the stretch of road that the bus traveled:
The changes in bus acceleration can be divided into two terms: one term with the maximum acceleration and another with no acceleration increase. That is suitable to real situations in which bus will increase speed with maximum its acceleration till the maximum speed. When the maximum speed is reach, the bus cannot increase its speed. Therefore, it will travel at the maximum speed. The illustrations can be seen in Figure 5.33

![Figure 5.33 Space and velocity relationship](image)

For intersection \( k \), the bus arrival time is calculated based on following formula:

\[
t = \frac{-v_0 + \sqrt{v_0^2 + 2a_{max}d_k}}{a_{max}} + \frac{\max(d_k - s, 0)}{v_{re}} + \zeta_k
\]

where,
- \( a_{max} \): the maximum bus acceleration (m/s²)
- \( d_k \): the distance between the infrared beacon and the stop line of intersection \( k \) (m).
- \( v_0 \): the bus speed at the detect moment (m/s).
- \( v_k \): the recommended bus speed to traverse intersection \( k \) (m/s).
- \( \zeta_k \): The stop time related to the red signal at intersection \( k \) (s).

A vehicle cannot change the speed as fast as possible because of its physical attribute limitation. The recommended speeds should be reasonable in terms of the vehicle dynamics. In this research, the limit characteristics are modeled with the constraint of maximum acceleration and maximum deceleration. Considering on a link with its length of \( d_{ij} \), the relationship between the speed at the head of the link \( (v_i) \) and the recommended speed \( (v_{i+1}) \) at the end of the link is as follows:

\[
\frac{v_{i+1} - v_i}{d_{ij} + \frac{v_{i+1} - v_i}{a_{max}}} \leq a_{max}
\]

### 5.5.2.2. An improved model

As introduced in the introduction section, the idea for improving the model comes from the coordination between the adjustment of bus speed and the modification of traffic signal status based on traffic situations. Assuming that a bus will travel through studied group of intersections including three intersections \( k-1, k, k+1 \) as illustrated in Figure 5.34. A value of bus speed \( i \) can produce an optimal set of signal timing parameters after solving the optimization function. Among possible bus speeds, the model can find the optimal speed value that can minimize the total network delay.
The objective function was presented in chapter of methodology. The research uses GA as an algorithm to find the optimal result. The research conducts two approaches to investigate the performance of the model. They are analytical approach with numerical analyses and simulation approach with a real case study. The details are as follows.

5.5.3. Analytical approach

5.5.3.1. Assumed input parameters
Before applying the model to simulation to a real case in Niigata, the research firstly conducts an analytical approach to test the performance of the model under hypothetical input data. The approach uses numeric relationships among parameters such as stretch of road, speed, traffic signal, etc. to establish the investigation. With the optimization tools available in Excel and Matlab, the authors easily get the result as shown in the result part. The assumed input parameters for this approach is displayed as in Table 5.4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Assumed values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to the beacon, d1</td>
<td>400.00</td>
<td>m</td>
</tr>
<tr>
<td>Intersection span, (a, b)</td>
<td>400.00</td>
<td>m</td>
</tr>
<tr>
<td>Acceleration, amax</td>
<td>1.50</td>
<td>m/s/s</td>
</tr>
<tr>
<td>Maximum Speed, Vmax</td>
<td>14.0</td>
<td>m/s</td>
</tr>
<tr>
<td>Detected bus speed, V0</td>
<td>1.00</td>
<td>m/s</td>
</tr>
<tr>
<td>Bus weight, wb</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Lost time,</td>
<td>2.00</td>
<td>s</td>
</tr>
<tr>
<td>Saturation rate, μ</td>
<td>1.25</td>
<td>veh/s</td>
</tr>
<tr>
<td>Offset intersection 1</td>
<td>0.00</td>
<td>s</td>
</tr>
<tr>
<td>Offset intersection 2</td>
<td>4.00</td>
<td>s</td>
</tr>
<tr>
<td>Offset intersection 3</td>
<td>8.00</td>
<td>s</td>
</tr>
<tr>
<td>Cycle length, Ci</td>
<td>140.00</td>
<td>s</td>
</tr>
<tr>
<td>Split</td>
<td>70:30</td>
<td>%</td>
</tr>
</tbody>
</table>

The advantage of this approach is the convenience for manipulation as well as the easiness for recognizing the performance of the proposal model. However, because the behavior of each vehicle is usually complicated and cannot be modeled correctly with the analytical approach, a simulation applied to a real case study should be conducted to understand more about the performance of the model.

5.5.3.2. Results and analysis
To demonstrate the model performance in comparison with that of other models, the research defines the concept of the network delay improvement and improvement percentage, which are defined as follows:
\[ I = D_p - D_i \]
\[ IP = \frac{D_p - D_i}{D_i} \times 100\% \]

Where,

- \( I \): Network delay improvement (s)
- \( D_p \): Optimal network delay by the proposed model (s)
- \( D_i \): Optimal network delay by model \( i \) (s)
- \( IP \): Delay improvement percentage (%)

In this research, the research compares the proposed model and the conventional adaptive model based on the base scenario without any bus priority treatment. Firstly, compared with the based case, the proposed model reduces drastically the network delay. The side street flows play an important role in the efficiency of the model. With low values of side street flow, the proposed model is not so effective. However, the model becomes significantly efficient in scenarios of low main street flow and high side street flow as in Figure 5.35.

![Figure 5.35 Compared with the base scenario](image)

Compared with the conventional adaptive model that minimizes the total delay to allocate signal timing appropriately, the proposed model reduces the network delay slightly as shown in Figure 5.36. The proposed model is much better than the conventional one when the main traffic flow is high and the side street flow is low. The details are shown in Figure 5.36.

![Figure 5.36 Compared with the conventional adaptive model](image)
In terms of bus travel time, the research calculates the bus travel time on a 960m long road segment, containing the three studied signalized intersections. Because the coordination in bus signal priority technique of the proposed model, bus travel time in the proposed model is the smallest among the three scenario. The reduction is up to 44% in the proposed model. Meanwhile, it is 38.2% in the conventional adaptive model when compared with the base scenario. This is reasonable because in the proposed model, buses can move more smoothly than in the conventional one. Therefore, the lost time concerning bus stops is significant reduced in the proposed model.

In summary, the analytical can show the model performance preliminarily. This approach has its own limitations related to the declaration of the lane capacity, the identification of interaction factors, etc. Therefore, a micro-simulation model should be applied to survey more the efficiency of the proposed model.

5.5.4. Simulation approach

5.5.4.1. Study site

The research surveys the real traffic situation at a site in Niigata to apply the proposed model in PARAMICS. This is a real arterial with three lanes per direction. Data was collected in normal conditions about time, weathers. The research uses four cameras to collect data at the studied site. The recorded cameras are arranged as illustrated in Figure 5.37

![Camera’s positions: Studied street](image)

![Camera’s positions: Studied street](image)

**Figure 5.37** The studied street (above) and PARAMICS (below)
The researchers used four cameras to collect data in the studied urban street. Two of them were mounted at high positions to observe vehicle maneuvers, lane flow distributions as well as turning flows at intersections. The other two cameras were set at the two cordons of the main street to collect the main traffic volume, the travel times of bus and passenger cars. The collection was carried out on normal days under the normal weather conditions. A video based software (Minh, 2007) was used to analyze traffic data needed for model calibration and validation.

5.5.4.2. Modification of the car following model

As mentioned in previous studies, the two-way communication between bus drivers and traffic control center through Infra-beacon and In-vehicle units help bus drivers know the information of recommended speeds. Bus drivers control the bus speed following the speed guidance. By using functions for overriding speeds in PARAMICS, the bus speed can be set as recommended speed output from optimization function once the bus is detected by the Infra-beacon. The flag assigning to buses for speed override is supposed to be released after the bus pass the last intersection in the group. By creating dynamic linking library (DLL) in PARAMICS, the algorithm for bus operation under the mechanism of the speed guidance is as in Figure 3.12

5.5.4.3. Simulated scenarios

After validating the base scenario, two scenarios are applied to this arterial. The first one is the scenario in which the proposed model is applied. This scenario tries to find the best solution by compromising the bus speed and traffic delays through the speed guidance mechanism. The second scenario is to apply the conventional adaptive bus signal priority model. The detected moment by infrared beacon is used to predict the bus arrival time at each intersection. The network delay optimization function will determine how much the amount of time for bus as well as which strategy (green extension, do nothing, early green) needed.

5.5.4.4. Results and analyses

a. Validation of the base scenario

The flow rates were compared between the simulation values and observation ones for every 5 min interval. The simulation values and corresponding observation ones are generally approximate. The mean percentage error is rather small as shown in Figure 5.38.

![Figure 5.38 Traffic flow validation](image)
b. Bus speeds under recommended speed guidance in PARAMICS

The algorithm for modification of the car following model under speed guidance mechanism is integrated with the algorithm for bus signal priority execution (as shown in Figure 3.12) in C++ language to create dynamic linking library (DLL) in PARAMICS. Extracting the vehicle’s positions at every simulation time, the trajectories of buses can be drawn. After being detected by the infrared beacon, the bus will change the speed according to the speed guidance mechanism. Because the infrared beacon is setup at the bus stop, the detected bus speed at the infrared beacon is usually small. After loading passengers at the bus stop, buses will increase the speed as shown in Figure 5.39. In the cases of recommendation, the bus speed increases with the maximum acceleration until getting the recommended speed. However, for the normal case without any speed guidance, buses increase speed with lower acceleration. This is reasonable because of the relaxation of driving in the normal case. The speed guidance mechanism makes bus drivers more serious and more careful in driving. The variation of bus speed can be tracked based on PARAMICS simulations as follows.

\[\text{Figure 5.39 Bus speed under speed guidance mechanism.}\]

c. Simulation results

After validating the base scenario, the research simulates two other scenarios for the purpose of comparison. The first scenario is applied with the proposed model. The second scenario is conducted with the conventional adaptive model. Considering the bus interval of 10 minutes, the research compares the values of link delay average in each simulation scenario. The result shows that the proposed model is much better than the conventional one in terms of delay reduction. The detail of the comparison is as shown in Figure 5.40

\[\text{Figure 5.40 Comparison of the average link delay}\]
As illustrated in Figure 5.40, compared with the conventional adaptive model, the proposed model reduces the link delay considerably, with the figures of 1.6%, 0.26%, 2.36%, 5.22%, 2.58%, and 7.12% respectively for each 5 minute interval of the simulation time. In summary, the link delay can be reduced when applying the proposed model instead of the conventional adaptive models. The reduction value is around 3.19% on average during the simulation time.

5.5.5. Conclusions

The section aims at two targets. The first target is the development of a bus signal priority model for arterial roads. This model involves the coordination between bus speed guidance and signal timing techniques to give priority to buses in arterial roads. The coordination allocates the proper recommended bus speed as well as minimizes the traffic delays simultaneously. The second objective is the sensitivity of the model performance in comparison with other different models. In this paper, there are two approaches used to evaluate the performance of the proposed model. They are analytical approach using Excel, Matlab and simulation approach utilizing PARAMICS. The authors compare the proposed model with the conventional adaptive model that was developed to grant priority to buses by minimizing the total delay only. The analytical approach and the simulation approach show that the proposed model is more efficient than the conventional one in terms of delay reduction. This model can be integrated into simulation models to investigate the performance more realistically.

There are many factors influencing the model performance. Firstly, the physical attributes of bus such as acceleration, deceleration, maximum speed, etc. are important factors affecting the efficiency of the model. A higher value of maximum speed should provide with more freedom for variable constraints. That leads to different results. Therefore, an investigation into bus attribute’s effects should be carefully considered. Secondly, the role of bus occupancy is another important factor. The higher the bus occupancy is, the more weight to the main street is. This creates the compromise of delay between the main street and the side street. In addition, the proposed delay formula is simple in this research. In fact, traveling along the arterial has its delay due to the shockwave of queue caused by red lights of the intersections. A more survey should be done to build an accurate formula as well as investigate the effects of intersection spans, bus occupancy, the number of intersections in the group, etc. Thirdly, due to the assumption of signal operation in three consecutive cycles, the model can be applied only to one-direction bus routes whose bus frequency is low. A further study that can deal with cases of bus bunch, bus platoon, conflicted bus routes, etc is suitable to real traffic networks. Besides, the aspect of safety should be considered in this research when the bus speeds up the travel following the speed guidance. This long-sighted shortcoming should be a target of future studies.
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

6.1.1. Bus lane system

The research firstly investigates the operation of three popular bus lane types in Japan with simple assumptions on lane changing behavior. An arterial with four consecutive intersections near Nagaoka station is surveyed for this purpose. The base simulations confirm the significant advantage of exclusive bus lane in terms of bus travel time improvement. However, its negative impacts on other types of vehicles are also considerable. Meanwhile, because of the flexibility in choosing lane in the scenario of priority bus lane, developing bus priority lane at this study site can improve the bus travel time and relieve the negative impact simultaneously. The sensitivity analysis determines suitable areas for each bus lane type based on information of the main street traffic volume and the number of passengers in the bus. The result has shown that the exclusive bus lane is proper for conditions when the main street traffic volume is low and the number of passengers in buses is high. When the traffic volume of the main street increases, there is an area defined by a range of main street traffic volume and passenger number that are suitable for the priority bus lane case and an area defined by a range of the main street traffic volume and passenger number that are suitable for the ordinary lane case. The dependence on the number of passengers in improving passenger travel time gradually switches to that on the main street traffic volume once the main traffic volume increase.

Secondly, the research investigates the behavior of cars in the scenario of bus priority lane by proposing a car lane-changing model under bus priority-lane effects in urban streets. Unlike any previous car lane-changing model, this model consists of three steps: looking-back threshold determination, gap acceptance model and execution model. The estimation results with satisfying statistic tests are as expected. The positive sign of maximum relative lag speed variable in the lag critical gap function is reasonable. It means that a large lag gap is required when the speed of lag vehicles is considerably larger than that of the subject vehicle. The lead critical gap is independent from the relative lead speed in this study. It reflects that the lane-changing behaviour under bus priority-lane effects is compulsory. As soon as a passenger car recognises oncoming buses, it would rather pay attention to the speed of the lag vehicle than concern that of the lead vehicle in finding acceptable gaps. Based on the estimation result of the proposed model, the research then compares the differences in perception behaviour of lane-changing cars under priority-lane effects and under no such effects. This comparison is conducted in terms of critical lead gap and critical lag gap. The results show that the lane-changing behaviour under bus lane effects has specific characteristics with smaller critical gaps when compared with that of the cases of no bus lane effects. The less sensitive relationship between critical gaps and its corresponding relative
speed is the consequence of the existence of buses in priority-lane. The interference makes car drivers understand the priority of the buses in lane usages and change lane to give space to the buses.

Thirdly, the research integrates the proposed model into simulation models again and evaluates the effect of bus priority lane in comparison with that of exclusive bus lane based on the current ordinary lane in Nagaoka traffic network. The results show that the bus priority lane can reduce the bus travel time on the treatment segment by 8.2% compared with the current ordinary lane without any lane treatment. This reduction is smaller than that in the scenario the exclusive bus lane with its figure of 28.3%. It can be said that the bus priority lane can improve considerably the bus service. The improvement is especially significant for the bus routes that use much the treatment segment. The number of passengers in buses using the treatment segment contributes to the efficiency of the bus lane deployments in terms of passenger delay savings. Therefore, switching the rider-ship from private cars to buses to increase the number of riding passengers on these routes is a long important target in this area. Because the deployments of the bus lanes worsen the congestion at the other connecting bridges, the negative effects become considerably strong if the deployment is for the exclusive bus lane instead of the bus priority lane. Thus, bus priority lanes should be considered as a transitional treatment before the deployment of exclusive bus lanes.

6.1.2. Bus signal priority system

For isolated signalized intersections, the research firstly proposes a bus arrival time prediction model based on data from image processing sensor and signal database. The model can predict the bus arrival time at the studied traffic situation with a Mean Percentage Error of 4.44%. The proposed prediction model is then applied to investigate four priority strategies at a signalized intersection, including bus signal priority scenario, bus preemption without exclusive bus lanes, and bus preemption with exclusive bus lanes. The comparative analysis of different priority levels show that with the increase in bus priority level, the bus travel time decreases significantly. However, it affects negatively on the travel of non-bus vehicles. In addition, the increase in non-bus vehicle travel time is considerable, by up to 28.9% in comparison with non-bus travel time in the current base case. In terms of turn delay at the intersection, the bus priority level can reduce the bus turn delay well, by up to 100%. But, a considerable increase up to 94.2% of non-bus vehicle turn delay causes negatively effects on non-bus vehicle travels. The more the bus priority levels is, the more important the role of bus occupancy in the delay reduction at intersections is. Also for isolated signalized intersections, the research proposes an improved genetic algorithm (GA) for optimization in adaptive bus-signal priority control. The improved algorithm can increase the convergence rate to reach the optimal solutions based on the compensation rule between signal cycles in adaptive control. Compared with the traditional GA, the improved GA can save the computation time by 48.39%. This time saving is important to the smooth running of any simulation model as well as real time control systems. In terms of the algorithm efficiency, the sensitivity analysis shows the improvement of the proposed GA when compared with the conventional GA. The improvement can be up to 36.2% in positive extreme cases. This improvement becomes significant when the saturation degree on the cross street is higher than that on the main street.

For arterial roads with multi-intersections, the research proposes a model to improve the efficiency of bus service. To do it, the research firstly proposes a model for the prediction of bus arrival time in arterial roads. Based on the proposed prediction model, the research develops a model for bus signal priority controls. This model involves the coordination
between bus speed guidance and signal timing techniques to give priority to buses in arterial roads. The coordination allocates proper recommended bus speeds as well as minimizes the traffic delays simultaneously. Secondly, the research conducts two approaches to investigate the model performance, which includes analytical approach and simulation approach. The result shows that the proposed model is more efficient than the conventional one in terms of delay reduction. This model can be integrated into simulation models to investigate the performance more realistically.

6.2. RECOMMENDATIONS

6.2.1. Bus lane system

For the part of comparative analysis, the suitable areas for bus lane types should be applied only for short periods. For long periods, because of being congested caused by bus lane operation, private vehicle users choose other routes or give up driving and take a bus to save travel time with respect to TDM policies. The area distribution in choosing bus lane type may be changed. The bus lane policies would be appropriate for the long-distance travelers so that the private vehicle users shift their modes or change their routes. Therefore, to provide city planners with sufficient information for making decisions of what bus lane policy to implement, a lengthy segment with a comprehensive investigation on factors such as bus schedule, tuning flow rate, effective distances between intersections and the awareness of drivers should be considered. In addition, not only terms of travel time but also other aspects such as specific geometrical conditions, convenience and safety are also necessary terms needed to be concerned and completed in future studies.

For the development of a car lane-changing model, advanced methods of data collection instead of the simple way in the research should consider more detailed the behaviour of car drivers when buses come. Looking-back threshold determination is an important part in the proposed model to recognise oncoming buses. However, the development of the looking-back model in this research remains several weak points. The looking-back threshold depends not only on driver characteristics but also on vehicle types, surrounding geometry, etc. Thus, this model should be received more comprehensive investigation. Moreover, the aspect of state dependency among sub-models over time as well as other influent factors such as the distances between oncoming buses and subject vehicles, the effects of the distance from subject vehicles to intersections, lane flow density, geometry feature, etc also need more concern in future works.

For the network evaluation part, the sufficiency of observed data for the model evaluation is important to valid the evaluation. This research simplifies the validation step with two typical validated indicators including traffic flow and travel time among many indicators such as traffic flow, travel time, speed, delay, stops, density, etc. It should be investigated more to get a better validation. Moreover, although a large number of buses can benefit from the bus priority lane, it is not meaning if the number of passengers in the benefited buses is low. Therefore, the number of passengers in buses and cars is important information to evaluate accurately the effects of the bus priority lane in traffic networks. It should be a target in future studies.
6.2.2. Bus signal priority system

First of all, the bus arrival time prediction model for the case of isolated intersections in this research has some limitations. The model has ignored the lane changing behaviors in the road section from the infrared beacon to the stop-line. That caused large errors in the prediction results. Moreover, the speeds of all other vehicles within the studied segment are important to the accuracy of the model. An improved model to overcome these shortcomings should be studied in next studies. Moreover, for the purpose of comparisons, the bus signal priority model is simplified in this research. The minimized functions should be concerned with more variables at a more complicated level to deal with the diversified nature of traffic. Therefore, a careful consideration on improving bus signal priority model is necessary for future works. In addition, the co-ordinations in adaptive networks with multi-phases, multi-requests are more realistic and more important aspects. Thus, the signals not only for isolated signalized intersections, but also arterial roads or grid networks with multi-requests or conflicting bus routes are promising research objectives needed to be studied.

For the GA improvement in adaptive signal control, the numerical test is rather simple for the sake of algorithm evaluation. To recognize clearly the benefits of the improved GA, the bus-signal priority control should be considered at a larger network scale or at a more complicated level. In addition, the traffic evaluation step to choose which genetic algorithms is critical to the success of the proposal. However, it was assumed simply in this research with the saturation degrees as related factors. Therefore, a further improvement of the genetic algorithm for bus-signal priority control to get a better convergence rate should be a target of future studies.

For the arterial with multi-intersections, future research should improve not only the simple formula of the objective function but the physical attributes of bus such as acceleration, deceleration, maximum speed, etc. that affect the efficiency of the model. A higher value of maximum speed should provide with more freedom for variable constraints. That leads to different results. Therefore, an investigation into the role of bus’s attribute should be carefully considered afterwards. In addition, the role of bus occupancy is also another important factor. The higher the bus occupancy is, the more weight to the main street is. This creates the compromise of delay between the main street and the side street. Besides, due to the assumption of signal operation in three consecutive cycles, the model can only be applied to one-direction bus routes whose bus frequency is low. A further study that can deal with cases of bus bunch, bus platoon, conflicted bus routes, etc is suitable to real traffic networks. Finally, the aspect of safety should be considered in this research when the bus speeds up the travel following the speed guidance. This long-sighted shortcoming should be a target of future studies.
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106


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