Reliability Assessment and Improvements along a Bus Corridor

by

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ABSTRACT

Service reliability is an important indicator of transit performance, and has been the subject of much attention in both the research and practice for decades. Reliability of bus service depends on variations in service characteristics such as travel time, schedule adherence, headway, and wait time. As a fundamental property of bus service, reliability determines services' cost and attractiveness to existing and potential passengers. It is important to the transit agency for resource planning and operation. In this study, two frameworks are developed to assess and improve bus route service reliability.

The reliability of a bus route is assessed by measuring variations in service characteristics, and this can be achieved through: 1) selection of performance measures, 2) evaluation of selected measures, and 3) calculation of selected measures. 16 performance measures are selected after conducting a comprehensive literature review, 12 of which are for the assessment of reliability, and 8 for service efficiency. The 16 measures are evaluated with respect to interested party (agency, operator & passenger), service type (high & low frequency service), and analysis level (stop, corridor, route & network). The assessment framework is applied to Route 1 in the City of Edmonton. Historical Route 1 performance data is collected from the Automatic Passenger Counter (APC) database of Edmonton Transit System (ETS). The overall results of estimated measures indicated that a set of performance measures can reflect reliability from every aspect. It was observed that some measures show that Route 1 is reliable, while some indicate unreliability of Route 1. It is also observed that performance of Route 1 during peak periods is worse than off-peak periods.

A reliability improvement process through bus route scheduling is also introduced. A schedule-based holding strategy was tested, where early buses with slack time are hold at the timing point until scheduled departure time. In this strategy, slack time is determined from a stochastic optimization model, where the objective is to minimize schedule deviation as well as variation in schedule deviation. Slack time is incorporated into the scheduled departure time. Thus, early buses are required to depart at scheduled departure time. Besides schedule-based holding strategy, transit signal priority (TSP) is also used to improve reliability. In this study, the schedule-based holding strategy is also applied to a bus corridor that has TSP. The application of new schedules that incorporate the holding strategy on bus Route 1 along a corridor with active TSP, in simulation, appears to improve the reliability and efficiency of the bus service.

Dedicated

To

My

Family

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Automatic Passenger Counter	APC
Automatic Vehicle Location	AVL
Advance Signal Controller	ASC
City of Edmonton	CoE
Coefficient of Variation	CoV
Edmonton Transit System	ETS
Green Extension	GE
Quality of Service	QOS
Red Truncation	RT
Transit Capacity and Quality of Service Manual	TCQSM
Transit Signal Priority	TSP

CHAPTER 1. INTRODUCTION

The objective of this chapter is to demonstrate the importance, motivation and objectives of this thesis. The research background and motivation provides a broad sense of the current research on bus service reliability and the reasons of selecting this research are described. Two primary objectives of this thesis are indicated in the research objective part of this chapter. Finally, the layout of this thesis is briefly described.

1.1 Research Background and Motivation

Service reliability is an important indicator of bus operational performance, and has been the subject of much attention in both the research and practice. The performance of a transit system holds interest for three major groups, including the transit agency, the operator, and passenger. An agency is the body responsible for administration and management of transit activities and services; and operator is the employee engaged in transit service operation. In addition, according to Transit Capacity and Quality of Service Manual (TCQSM), reliability is an important service attribute for passengers, influencing ridership (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). The 2005 Edmonton Household Travel Survey indicates that the share of travel by transit is 9 percent (City of Edmonton 2009). Based on the TCQSM, transit ridership can be improved by making transit services more reliable.

Much research has been done on transit service reliability, and can be stratified into two types: assessment and improvement. The assessment of bus service reliability is normally conducted by measuring the variation in service characteristics. Service characteristics include travel time, schedule adherence, headway and passenger waiting time. A significant number of performance measures exist in the literature. A set of performance measures is required, to assess service reliability from the perspective of the interested body (agency, operator & passenger), application level (stop, corridor, entire route, route direction, and network), and service type (high or low frequency). A multi-criteria selection and evaluation is required to build a set of measures that best reflect the performance of bus service. Based on literature review, there are very few studies that analyze reliability from different perspectives, except Currie, Douglas and Kearns (2011) and Ma, Ferreira and Mesbah (2013). These two studies developed a set of measures through a comprehensive evaluation process. After identifying suitable measures, the calculation process can be conducted with data from Automatic Data Collection (ADC) systems. ADC system includes Automatic Passenger Counter (APC), Automatic Vehicle Location (AVL), Automatic Fare Collection (AFC) and others. These systems can collect transit related data in an efficient and cost effective way. From the literature review, these transit data are used for analyzing and modeling bus service reliability (Abkowitz and Engelstein 1983, Uniman 2009, Mandelzys and Hellinga 2010). After calculation of measures, it is helpful to measure service measures against performance rating scales. TCQSM developed two scales to quantify quality of service for on-time performance and coefficient of variation (CoV) of headway. Camus, Longo and Macorini (2005) used weighted delay index as a reliability measure, which can be compared with a scale to express level of service. It can be stated that very few performance measures have scale for assessing quality of service.

Since buses are not travelling in a grade separated environment, it is natural to observe variation in service. This variation can be absorbed by a holding strategy. Schedule-based holding strategy is a process of providing services slack time at specific bus stop(s). A bus stop where holding is conducted is defined as the timing point. Under this strategy, early buses will be hold at the timing point, while late buses will depart after serving passengers. Earliness and lateness of a bus are determined by comparing the observed departure time with the scheduled departure time. This strategy was first introduced by Turnquist (1981). The methodology was adjusted in subsequent studies, although the objective (to absorb variation into the schedule) remained the same. Since the strategy only holds early buses, the frequency of late buses will affect the reliability of bus service. Frequent observation of late buses indicates the necessity of increasing scheduled travel time. This idea is adopted by Yan, et al. (2012) in their study. Besides the idea of lateness and earliness, they also considered the response of the operator towards the schedule deviation. Usually, operators react to the late arrival by increasing the bus speed along subsequent section under prevailing conditions (speed limit, congestion level, etc.). Yan, et al. (2012) developed a stochastic optimization algorithm for developing a robust schedule for a bus route.

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The implementation of a schedule-based holding strategy along a corridor with active TSP can help to improve system's reliability as well as efficiency. TSP is a method to improve the efficiency and reliability of buses, where priority is given to buses approaching signalized intersections with TSP. Active TSP is the most commonly used TSP strategy in North American cities (Smith, Hemily and Ivanovic 2005). Altun and Furth (2009) used the advantage of TSP during scheduling of bus route. In their method, the route running time schedules are determined with a conditional TSP. Based on previous research showing that TSP improve reliability, this study examines the effects of implementing a schedule-based holding strategy along a corridor with TSP.,

1.2 Research Objectives

The main objective of this thesis is to explore bus service reliability. This exploration process includes assessment and improvement of reliability of bus service. Two major tasks are performed in this study, and these are given below:

1. Develop a comprehensive performance assessment framework to evaluate reliability and efficiency of an urban bus route service, with the help of Automatic Passenger Counter (APC) data.
2. Propose a schedule-based holding strategy for an urban bus route with and without active Transit Signal Priority (TSP).

1.3 Thesis Structure

This chapter introduces the research background, motivation and objectives of this thesis. Chapter 2 includes the review of the studies on transit service reliability in terms of assessment and improvement. Chapter 3 discusses the framework of assessing performance of bus route service. Chapter 4 presents the optimization model of building schedules for a bus route, and the assessment of performance of bus service by using a VISSIM simulation model. Finally, Chapter 5 provides the conclusion and recommendation of this study, and the future research direction.

CHAPTER 2. LITERATURE REVIEW

This literature review discusses bus service reliability measures, and approaches to improving service reliability. Besides reliability, efficiency measures from different studies are also discussed briefly. Variation in service characteristics can be improved by using different holding strategies such as schedule-based holding strategy. Modeling approach of this strategy is discussed under this chapter. Transit Signal Priority (TSP) is also used to improve reliability of bus service. A brief discussion about the studies related to TSP is also presented at the end of this chapter.

2.1 Reliability

A bus transit system is a combination of four subsystems: the bus as a vehicle, the timetable, the operator, and finally the system manager. The reliability of bus service depends on the operational properties of a bus and timetable. Travel time is considered as the operational property of a bus, while schedule adherence and headway are the operational properties of a timetable. Variation in these operational properties influences reliability of bus service. All of these operational properties are related to each other. For instance, if the travel time of a bus varies then the variation in schedule and headway will be observed. Schedule adherence includes the arrival and departure times of a single bus at a stop, while headway refers to the arrival or departure times of two consecutive buses at a stop. Headway variation is more suitable for assessing reliability of high frequency service, while variation in schedule adherence is often used to address the reliability of low frequency service (Furth and Muller 2009). Variation in schedule adherence and headway can results variation in passengers' wait time, which can be used to present the reliability of bus service. Thus, in this study, the variations in travel time, schedule adherence, headway and wait time are considered in order to measure the reliability of a bus route.

2.1.1 Impacts of unreliability

Service reliability is assessed in various ways such as the effect of reliability on agency and passengers, causes of unreliability, measurement of reliability, and different strategies to improve reliability. Bus service reliability has a considerable effect on both the agency and passengers

(Wirasinghe and Liu 1995, Cham 2003, Uniman 2009). Wiransinghe and Liu (1995) mentioned that unreliable service results in extra wait time to boarding passengers, earliness or lateness in terms of reaching the destination, and additional cost to the agency due to paying more overtime to operators. Unreliable service degrades user's perception of the service in comparison to other modes of transportation, and pushes the agency to implement additional service in order to minimize the disruption (Cham 2003, Uniman 2009). Therefore, reliable bus service helps operators manage resources and enhance passengers' satisfaction.

2.1.2 Factors affecting reliability

Bus service reliability is affected by two types of factors: controllable factors and uncontrollable factors (Cham 2003, Uniman 2009). According to Uniman (2009), controllable factors include route length, signalized intersection frequency, stop frequency, stop location, zoning, frequency of service, spatial and temporal variation in demand, and driver behaviour. Uncontrollable or environmental factors include weather effects and service during special events (Uniman 2009). Those factors cause randomness in a service, which results in unreliability. Normally, randomness in roadway traffic conditions as well as dwell times varies over time. Agencies will set bus service frequency at least partly based on demand. With high demand, agencies increase the frequency of service, which may cause bus "bunching" or build-up and result in unreliability (Daganzo and Pilachowski 2011). Reliability can be affected by factors such as operator's absenteeism, communication gap, and lack of experience (Uniman 2009). Heavy rainfall, snowfall, and any natural disaster can cause an outage of bus service. Special events can also cause fluctuation in demand, inducing randomness in service.

2.1.3 Assessment of reliability

A significant number of reliability measures exist in the literature. Bus service reliability is often evaluated under two circumstances: 1) before-and-after analysis of any service change and 2) evaluation of current service levels. The literature review on reliability metrics is divided into four categories: variation in 1) travel time, 2) schedule adherence, 3) headway and 4) wait time.

Travel Time Variation

The variation in travel time is the primary cause of variation in other attributes. According to Hollander (2006), variation in travel time between two points along a bus route is responsible for variation in headways, arrival or departure time at stops, and wait time for passengers. From the passenger's point of view, the journey time is the sum of the travel time and waiting time; unreliable service results in a longer journey time, which reduces the attractiveness of bus service. In this case, the bus travel time is considered, not the journey time. Various methods for measuring the variation in travel time have been discussed in the literature, shown in Table 2-1.

Table 2-1 Reliability metrics for assessing travel time variation

Performance Measure	Definition	Application Body	Source
Travel time variability	Inverse of the standard deviation of travel times	Agency and passenger	(Sterman and Schofer 1976, Polus 1978)
CoV of travel time	Ratio between the standard deviation and the average of observed travel times	Agency	(Cham 2003, El-Geneidy, Horning and Krizek 2010, Ma, Ferreira and Mesbah 2013)
Travel time window	Average and plus-minus standard deviation of observed travel times	Passenger	(Lomax, et al. 2003)
Travel time variability Index	Ratio of the differences between the upper and lower limit of 95% confidence interval of travel time during peak hours and off-peak hours	Agency and passenger	(Lomax, et al. 2003)
Run time ratio (%)	Ratio between observed and scheduled run times	Agency and passenger	(Strathman, Dueker, et al. 1999)
Running time adherence (%)	Average difference between the observed and scheduled running times relative to scheduled running time	Agency and passenger	(Lin, Wang and Barnum 2008)
Running time delay	Difference between observed and scheduled run time	Passenger and operator	(Kimpel, Strathman and Dueker, et al. 2000)
Buffer time index	Ratio between the buffer time rate and the average travel time rate	Agency	(Lomax, et al. 2003)

From Table 2-1, all measures related to travel time are suitable for measuring the performance of bus service at the route level. The definition of all eight measures is mentioned in the table along with the usefulness towards application bodies. The usefulness is determined based on the applicability. The most commonly used measure is the coefficient of variation (CoV) of travel time, shown in Table 2-1. This normalized measure can be applied to measure the variation in travel time of any types of bus service (Ma, Ferreira and Mesbah 2013). Another study used the standard deviation of travel time in an inverse form and named it the travel time variability (Sterman and Schofer 1976). Sterman and Schefer (1976) indicate that this measure is highly sensitive to travel distance, and is easy to measure. Due to the inverse form, the increase of this measure indicates higher reliability than before. Usually, travel time variation during peak hours is higher than off-peak hours due to higher passenger demand as well as flow on the road. It may be necessary to compare that variation during peak hours with off-peak hours; this comparison can be conducted using a travel variability index (Lomax, et al. 2003). The travel time window is a measure that captures the variation by presenting the maximum and minimum travel time for a certain distance (Lomax, et al. 2003). This measure is considered to be helpful for passengers for planning their journey time. Those four measures described above, are determined from observed travel times. But for schedule-based bus service, a comparison of observed and scheduled travel time can be helpful to capture observe travel time variation in terms of scheduled travel time. This can be conducted using the run time ratio (%), running time adherence (%) and running time delay. Among those three measures, run time ratio (%) and running time adherence (%) are normalized measures. Finally, the buffer time index is included in Table 2-1, which compares buffer time rate with the average travel time rate (Lomax, et al. 2003). Time rate is basically the time per distance unit. Buffer time rate is the difference between the 95^{th} percentile travel time rate and average travel time rate.

Variation in Schedule Adherence

Schedule adherence is the primary objective of a schedule-based bus service. The variation in schedule adherence captures the deviation of observed arrival or departure time of a bus from the schedule. Assessing reliability in terms of variation in schedule adherence is commonly done, as shown in Table 2-2.

Table 2-2 Reliability metrics for assessing variation in schedule adherence

Performance Measure	Definition	Application Body	Source
On-time performance (%)	Percentage of buses departed from a stop within 1 min early to 5 min late of the scheduled time	Agency and passenger	(Bates 1986, Nakanishi 1997, Camus, Longo and Macorini 2005, Kimpel, Strathman and Callas 2008, Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013)
Arrival delay	Difference between observed and schedule arrival times	Operator	(Carey 1994, Strathman, Dueker, et al. 1999, Dessouky, et al. 1999)
Departure delay	Difference between observed and scheduled departure times	Operator and passenger	(Kimpel, Strathman and Dueker, et al. 2000)
Lateness (%)	Percentage of buses departing a stop more than 5 min after schedule	Agency and passenger	(Mandelzys and Hellinga 2010)
Earliness (%)	Percentage of buses departing a stop more than 1 min before schedule	Agency and passenger	(Mandelzys and Hellinga 2010)

In Table 2-2, all measures are associated with the departure and arrival time of a bus at a stop. This is the reason why all performance measures discussed under this section are suitable for stop-level application. The most commonly used measure is on-time performance (%), which indicates the percentage of buses that departed a bus stop on-time (Bates 1986). For this measure, TCQSM developed a Quality of Service (QOS) table, a scale to quantify bus service performance from the passenger's and agency's point of view (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). Based on on-time performance, Mandelzys and Hellinga (2010) developed the % lateness and % earliness measures. These two measures can be used to distinguish both late and early buses from on-time buses. It is believed that those three measures described above are suitable for both the agency and passengers. But, the operator may not find those measures suitable to use. For them, both arrival delay and departure delay could play an important role. Arrival delay uses the observed and scheduled arrival times of a bus at a stop (Carey 1994). On the other hand, departure delay is quantified with observed and scheduled departure times (Kimpel, Strathman and Dueker, et al. 2000). Both types of delay will show the operator how much they deviated from the schedule. The value of arrival delay and departure delay is that it will help operators maintain the bus's speed based on the posted speed limit. Besides the operator, passengers could use departure delay to quantify their extra wait time.

Headway Variation

Seven performance measures have been identified to measure the variation in headway, shown in Table 2-3.

Table 2-3 Reliability metrics for assessing headway variation

Performance Measure	Definition	Application Body	Source
Headway ratio (%)	Ratio between observed and scheduled headways	Passenger	(Strathman, Dueker, et al. 1999)
Headway delay	Difference between the observed and schedule headways	Passenger	(Kimpel, Strathman and Dueker, et al. 2000)
Headway adherence	Ratio between the standard deviation and the average of observed headways	Agency and passenger	(Cham 2003, Nakanishi 1997, Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013)
Weighted delay index	Ratio of the sum of all weighted (by probability) delays and the scheduled headway	Agency	(Camus, Longo and Macorini 2005)
Percentage regularity deviation mean (%)	Average difference between the scheduled and observed headways relative to schedule headway	Agency	(Lin, Wang and Barnum 2008, Oort and Nes 2009)
Variation in headway deviation	Standard deviation of the difference between the scheduled and observed headways	Agency	(Trompet, Liu and Graham 2011)
Irregularity Index	Ratio of the average value of squared headways and the square of average headways	Agency	(Golshani 1983)

Headway-based measures are suitable for a high frequency bus service (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). All measures in Table 2-3 are suitable for application at the stop-level. The most commonly used performance measure to capture variation in headway is headway adherence, which is basically the CoV of observed headways at a stop (Nakanishi 1997). The CoV of headway can be evaluated with a scale developed by TQCSM (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). According to that scale, CoV values of headway that are more than 0.75 indicate that most buses will be bunched. Golshani (1983) adopted a different statistical measure called the irregularity index, where the ratio between the average value of squared headways and the square of average headways are used. Besides the headway adherence and irregularity index, another five measures are developed through a comparison between the observed and scheduled headway. Among those measures, headway ratio (%) and headway delay are easy to interpret, and considered suitable for passengers to evaluate their journey. On the other hand, measures such as the weighted delay index, percentage regularity deviation mean (%), and variation in headway deviation are hard to interpret, but useful to the agency. In the weighted delay index, the value of weight is denoted as the frequency of getting a specific headway (Camus, Longo and Macorini 2005). Percentage regularity deviation mean (%) compares the deviation of headway from the schedule to the scheduled headway (Lin, Wang and Barnum 2008). This might help addressing headway deviation in a normalized form. For instance, five minutes of headway deviation might be acceptable for a 30-minute headway, but not for a 10-minute headway.

Wait Time Variation

Wait time is the time passenger spent at the bus stop to take the intended bus. Thus, the time difference between the passengers' arrival time at the stop and departure time from the stop is the wait time. Finding the exact value of passengers' arrival time at the stop requires extensive survey. Therefore in previous study, passenger's wait time is usually characterized with expected wait time, excess wait time, and budgeted wait time. Since wait time is the end product of the variation in bus service, measures related to wait time are formulated with the headway and departure time. Four performance measures related to reliability are tabulated in Table 2-4.

Table 2-4 Reliability metrics for assessing variation in wait time

Performance Measure	Definition	Application Body	Source
Expected wait time	A function of average observed headway and CoV of observed headway	Agency and passenger	(Furth, Hemily, et al. 2006, Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013)
Schedule-based excess wait time	Difference between the observed and scheduled departure times	Passenger	(Furth, Hemily, et al. 2006, Furth and Muller 2007, Furth and Muller 2009, Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013)
Headway-based excess wait time	Difference between observed and scheduled wait times, which are a function of observed and scheduled headway, respectively	Passenger	(Trompet, Liu and Graham 2011)
Budgeted wait time	Sum of excess platform time and potential waiting time, which are a function of observed and scheduled departure times	Passenger	(Furth, Hemily, et al. 2006, Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013)

Expected wait time is a function of the average and CoV of observed headways (Osuna and Newell 1972). According to Osuna and Newell (1972), a passenger's wait time is half of the observed headway, but it will vary with the CoV of headways. Using this measure is suggested for a high frequency service (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). In this study, excess wait time is defined in two ways such as headway-based excess wait time and schedule-based excess wait time, based on the formulations given in different studies. Schedule-based excess wait time is identified as the difference between the observed and scheduled departure time, as seen in Table 2-4. According to TCQSM, schedule-based excess wait time can be used to assess reliability of a schedule-based low frequency service (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). Besides that, headway-based excess wait time is also calculated using the observed and scheduled headways (Trompet, Liu and Graham 2011). Trompet, Liu, and Graham (2011) formulated an equation for determining scheduled wait time and actual wait time by using scheduled and actual headway, respectively. The difference between the scheduled and actual wait times is the headway-based excess wait time. Due to the variation in bus departure times, passengers are usually required to arrive earlier than the scheduled departure time by following the two extreme values of observed departure times: 1) 2^{nd} percentile value and 2) 95^{th} percentile value (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). So the extra wait time associated with this phenomenon is captured by the budgeted waiting time, the sum of the excess platform time and potential waiting time. For graphical illustration, readers are referred to Chapter 3 [p-35]. The excess platform time is the extra time spent by passengers arrived at the stop before the scheduled departure time. It is assumed that the passenger will arrive at the bus stop at the 2^{nd} percentile departure time to avoid missing the intended bus (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). On the other hand, the potential wait time is the excess time spent by a passenger at the stop to catch extreme late buses, after scheduled departure time. The extreme late departure is identified as the 95^{th} percentile departure time, which indicates a departure time that will be greater than any actual departure time 95% of the time.

2.2 Efficiency

There are four perspectives of efficiency in transportation industry such as the mobility and safety, utility, productivity and accessibility (Levinson 2003). In this literature review, mobility perspective of bus service efficiency is covered. According to the definition by Hatry (1980), efficiency can be defined by the relationship between the amount of input and the desirable amount of output. For example, scheduled travel time of a bus is set as X minutes, which is the input. With variation in service, observed travel time or output is identified as Y minutes. If Y is greater than X, then system has a loss. Eight performance measures related to route level efficiency are shown in Table 2-5. Seven of those performance measures are related to travel time, and one is related to schedule adherence.

Table 2-5 Efficiency metrics used in different studies in the literature

Performance Measure	Definition	Application Body	Source
Travel time of Origin-destination	Sum of wait time, dwell time, and travel time	Passenger	(Nakanishi 1997)
Transit-Auto travel time ratio	Ratio between the transit and auto travel times	Agency and passenger	(Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013)
Travel time index	Ratio of average observed travel time and free flow travel time	Agency and passenger	(Pu 2011)
Time rate	Ratio between the average travel time and the covered distance	Agency and passenger	(Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013)
Travel time ratio	Ratio between the average and the scheduled travel times	Agency and passenger	(Strathman, Dueker, et al. 1999)
Delay per traveller	Difference between the actual and free flow travel times expressed as annual hours	Agency and passenger	(Cambridge Systematics, Inc.; Dowling Associates, Inc.; System Metrics Group, Inc.; Institute, Texas Transportation 2008)
Planning time index	Ratio between the 95th percentile travel time and free flow travel time (travel time using posted speed)	Agency and passenger	(Cambridge Systematics, Inc.; Dowling Associates, Inc.; System Metrics Group, Inc.; Institute, Texas Transportation 2008, Pu 2011)
Percentage of bus service cancelled (%)	Percentage of buses that are more than 8 min late and 15 min early compared to total number of buses	Agency and passenger	(Currie, Douglas and Kearns 2011)

Firstly, some performance measures are difficult to evaluate but could provide a complete picture of the system's efficiency. Measures such as the travel time of origin and destination (O-D) can provide a complete picture of a person's journey time (Nakanishi 1997). But, this performance measure requires information such as the wait time or transfer time, dwell time, and travel time, and collecting such data is expensive. Another travel time-based performance measure is transit-auto travel time, which compares the travel times of transit and auto, and helps to compare efficiency levels across different modes. Travel time index is a measure that compares the average travel time with the free flow travel time, and can indicate the service efficiency level (Pu 2011). A normalized measure such as time rate can assess system reliability per unit of distance from the agency's and passenger's point of view. A comparison of the average travel time with the scheduled travel time can provide the efficiency level of a bus system. Cambridge Systematics, Inc.; Dowling Associates, Inc.; System Metrics Group, Inc.; Institute, Texas Transportation (2008) mentioned two specific measures called the delay per traveller and planning time index. Delay per traveller is used to find the travel time delay of a passenger compared to free flow travel time. The average travel time will always be higher than the free flow travel time, so this measure can be used for comparative analysis. On the other hand, the planning time index compares two extreme values of travel time: 1) 95th percentile travel time and 2) free flow travel time. Measuring efficiency in this way can show the maximum trade-off travel in a system. Finally, the percentage of bus service cancelled (%) can present efficiency loss more directly than any other performance measure. Since all of the measures are associated with the travel time, a route-level efficiency assessment is possible. Most interestingly, none of those measures are considered to be suitable for the operator.

Manually or automatically collected transit data, especially operation-related data are important for quantifying those measures. Operation-related historical data can be automatically collected from the automatic vehicle location (AVL) and automatic passenger counting (APC) system (Dessouky, et al. 1999). AVL is a system that provides the real-time location of a bus and transmits this information to a base station. On the other hand, the APC system collects information about the boarding and alighting automatically. These systems can provide a rich quantity and quality of transit data. Collected operation related data are mentioned as AVL-APC transit data for a bus system with both AVL and APC. From the literature review, it is observed that AVL-APC transit data are used for analyzing and modelling bus service reliability (Abkowitz and Engelstein 1983, Hammerle, Haynes and McNeil 2005, Kimpel, Strathman and Callas 2008, Mandelzys and Hellinga 2010). According to Furth, Hemily, et al. (2006), sometimes the APC system is not able to provide high-resolution data due to a lower penetration rate in the system. The aggregation of data can help overcome this hurdle.

2.3 Bus service improvement using Timing Points

2.3.1 Introduction

Holding strategy is a process of regulating buss' departure based on schedule at timing point (Strathman, Kimpel and Dueker 2001). Timing point is a bus stop which acts as a holding point, where early buses are hold up to schedule departure time and late buses depart immediately after dwelling activity (Wirasinghe and Liu 1995). According to Vandebona & Richardson (1986), there are three types of holding strategies: 1) schedule-based holding strategy, 2) headway-based holding strategy and 3) demand responsive holding strategy. Schedule-based holding strategy is a passive holding strategy, where faster vehicles are held at timing points until its scheduled departure time. In passive holding strategy, slack time is always fixed (Vandebona and Richardson 1986). Slack time is the buffer time allocated within schedule to stabilize a system (Zhao, Dessouky and Bukkapatnam 2006). It is also assumed that if the schedule is maintained then an even headway will prevail (Cham 2003). Headway-based holding strategy is an active strategy where threshold headway is maintained between the preceding and current buses. For an active holding strategy, slack time can vary based on the situation (Vandebona and Richardson 1986). Demand responsive method is also an active holding strategy where headway between consecutive buses is regulated with respect to the passenger demand at current stop. According to previous studies, application of these holding strategies varies with the route's operating conditions, including the passenger demand, frequency of service, variability of route running times, and other factors. For a bus route service with low frequency, schedule-based holding strategy is considered to be favourable for maintaining reliable service. While, headway-based strategy is suitable for high frequency service. Usually, passengers follow schedule for a low frequency service, while passenger arrives randomly for a high frequency service (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). Setting timing point with slack time is a part of schedule-based holding strategy.

The process of schedule development starts with the selection of bus route geography which can be classified as corridor, route and network based structure. Most of the researchers formulated their problems for a bus route. Senevirante (1990) developed a simulation model to find optimal number and location of timing point along a bus route which is 16 km long with 36 bus stops in total. Wirasinghe & Liu (1995) developed an optimization model to determine a reliable schedule for a hypothetical bus route with multiple stops. Lin et al. (1995) simulated a hypothetical bus route with 10 bus stops to test schedule-based holding strategy. For schedule design with timing point, Liu and Wirasinghe (2001) simulated a bus route of 6.5 km long with 14 stops. Hickman (2001) developed an optimization model with a hypothetical bus route with 10 stops, where slack time is determined. Zhao et al. (2006) used a hypothetical transit system with a single loop bus route with multiple stops. Initially optimization model was applied with one timing point and later it was extended to multiple timing points. Furth and Muller (2007) & (2009) formulated an optimization model with a hypothetical bus route with 16 segments and 17 bus stops to find schedule with holding strategy. Fattouche (2007) developed schedules for a high frequency bus route under Chicago Transit Authority (CTA). Cats et al. (2011) evaluated schedule-based holding strategies for a high demand bus route with BusMezzo, a mesoscopic transit simulation software. Yan et al. (2012) formulated a hypothetical bus route to design schedule with timing point. Later, the model is applied to a real bus route of 13.2 km long with 25 bus stops. Zhao et al. (2013) developed problem for a high frequency loop-type bus route which is 48.8 km long with 35 bus stops. The problem formulation for a corridor-based structure is almost same as route based structure. Mazloumi et al. (2012) designed schedule for a hypothetical bus corridor, and applied to 8 km section of a bus route in Melbourne, Australia. Vandebona & Richardson (1986) investigated the effect of schedule-based holding strategy for a bus network, where two routes originated from different places merged into a single route. Same concept of holding strategy is adopted for different modes of public transit. Such as, Carey (1994) developed optimized schedule for train service with a single line with single train and multiple trains. Oort et al. (2010) investigated the effect of schedule-based holding strategy on passenger travel time for a high frequency tram line of 14 km with 32 stops. Next step of schedule-based holding strategy is to set the location of timing point(s).

2.3.2 Location of timing point

The selection of a bus stop as a timing point depends on various factors such as passenger demand profile, transfer potentiality, and variation of service characteristics shown in Table 2-6.

Table 2-6 Timing point location strategies

Source	Timing Point Location Strategy
Based on hypothesis	
(Strathman and Hopper 1992)	• At 5 min intervals along the corridor. • At stop(s) close to either transfer points or major intersections
(Lin, et al. 1995)	• At stop before the group of bus stops with high boarding passenger activity.
(Hickman 2001)	• At upstream of a peak loading point or heavy loaded segment
(Furth and Muller 2007)	• At stops with high demand (boarding & alighting) concentration (twice the neighbouring bus stops)
(Oort, Boterman and Nes 2012)	• At the beginning of the corridor
(Zhao, et al. 2013)	• At major transit station
Based on assumption	
(Zhao, Dessouky and Bukkapatnam 2006)	• Single stop then multiple stop
(Yan, et al. 2012)	• Four timing points are chosen including start and end stop
Based on modelling	
(Lesley 1975)	• Deterministic model • At stops with a variance of headways twice the average variance of headway along the corridor
(Abkowitz and Engelstein 1984)	• Analytical model • At stop with maximum value of the product of standard deviation of origin-based travel time and the ratio of boarding passenger to on-board passenger
(Abkowitz, Eiger and Engelstein 1986)	• Simulation model • At stops with high number of boarding passenger
(Vandebona and Richardson 1986)	• Simulation model • Severity of the timing point depends on the standard deviation of travel time from schedule travel time
(Senevirante 1990)	• Simulation model • At stop followed by a stop with standard deviation of headway more than 60 sec
(Wirasinghe and Liu 1995)	• Dynamic optimization model • At stop with higher percentage of early buses • At stop with higher boarding passenger
(Fattouche 2007)	• Descriptive model • At stop with higher boarding passenger than on-board passenger
(Mazloumi, et al. 2012)	• Heuristic optimization • Bus stops close to major intersections (transfer point)

Sometimes timing points are selected directly based on the hypotheses related to those factors. One hypothesis directly addresses that the timing point should be the bus stop with higher transfer capability (Strathman and Hopper 1992, Zhao, et al. 2013). Zhao, et al. (2013) selected major transit station as timing point. Strathman and Hopper (1992) selected bus stop close to major intersection and major transit station as the timing point. Based on passenger demand profile, the studies such as (Lin, et al. 1995) and (Hickman 2001) suggested to pick bus stop located upstream of a heavy loaded segment. Lin, et al. (1995) defines heavy load in terms of boarding activity. According to Oort, Boterman and Nes (2012), passenger boarding activity is usually higher at the beginning of a bus route than other bus stops. Thus, bus stops at the beginning should be chosen as the timing point(s). Some studies such as (Zhao, Dessouky and Bukkapatnam 2006) and (Yan, et al. 2012) are selected timing points without any hypothesis, and those two studies are mentioned under "*Based on assumption*" section in Table 2-6. However, Zhao, Dessouky and Bukkapatnam (2006) mentioned to choose major transfer point and stop with high passenger arrival rate as the timing point from economic point of view. Beside these literatures, some studies determine the location of timing point through modeling approach, based on necessary hypotheses. Lesley (1975) used a deterministic model to find the location of timing point, where controlling factor is the variation in headway shown in Table 2-6. Another study used simulation model to choose the timing point, and the criteria is to choose stop(s) with standard deviation of headway more than 60 seconds (Senevirante 1990). Abkowitz and Engelstein (1984) adopted a combined relation of travel time variation and passenger activity in an analytical model to find the location of timing point. Travel time variation is also used by Vandebona and Richardson (1986) under a simulation modeling approach. The concept of earliness is adopted by Wirasinghe and Liu (1995) along with the passenger demand profile, to find the location of timing point(s). According to them, stop(s) with higher proportion of early buses and higher boarding demand are suitable for the schedule-based holding strategy. In that study, earliness is defined as the proportion of buses which departed from an ordinary bus stop (non-timing point) earlier than the schedule departure time. After selecting timing point(s), the next step is to set slack time at the timing point(s).

2.3.3 Slack time setting

Slack time is the buffer time allocated within scheduled travel time, and used to stabilize a system by absorbing the variation of service characteristics along the bus corridor (Zhao, Dessouky and Bukkapatnam 2006). It is observed that the variation of delay is propagated and increased along the corridor (Oort, Boterman and Nes 2012). Since the timing point influences departure of buses by holding early buses, the propagation of delay can be absorbed by setting a schedule with slack (Wirasinghe and Liu 1995, Hickman 2001, Yan, et al. 2012, Zhao, et al. 2013). Slack time could result an extended departure time at the timing point which eventually reduces the percentage of late departure. Besides that, holding behavior of the timing point ensures on-time departure of early buses other than late buses. According to Cham (2003), a schedule with high slack time at timing point and proper monitoring will ensure higher percentage of on time departure, but it will increase in-vehicle travel time of passenger. Excess in-vehicle travel time will make passengers unattractive to the bus system. On the other hand, a schedule with very low slack time makes timing point inactive because then most of the buses will be late at that point. So, setting a schedule with an optimal slack time requires proper modelling approach.

Both optimization model and simulation model are used to design schedule with holding strategy as mentioned in Table 2-7. Not only schedule-based holding strategy but also headway-based holding strategy requires modeling to find threshold headway based on the Table 2-8. Every model is included with an optimization process, where an objective function is minimized or maximized to find optimal schedule with slack time (Wirasinghe and Liu 1995, Hickman 2001, Yan, et al. 2012, Zhao, et al. 2013). Some of the previous studies developed analytical models by considering a simple network with one or two buses where all stops are considered as timing point (Newell 1971, Osuna and Newell 1972, Newell 1974, Barnett 1974). However those problems are simple, but applicability is limited in real world (Wirasinghe and Liu 1995, Hickman 2001). According to Table 2-7, most of the models associated with schedule-based holding strategy are stochastic optimization model. Three studies such as (Wirasinghe and Liu 1995), (Hickman 2001) and (Zhao, Dessouky and Bukkapatnam 2006) solved this problems analytically with some necessary assumptions to make problem analytically tractable.

Table 2-7 Schedule-based holding strategies

Source	Type of Model	Model Description				
		Assumption(s)		*Objective(s): Minimizing*	*Decision variable(s)*	*Solution platform*
		Bus arrival time	*Passenger Arrival Pattern*			
(Vandebona and Richardson 1986)	Stochastic simulation	Normal distribution	Effectively random distribution	Travel times of bus as well as passenger	Slack time	TRAMS (Transit Route Animation and Modelling by Simulation)
(Senevirante 1990)	Stochastic simulation	Normal distribution	Poisson Distribution	Standard deviation of headway	Speed and schedule travel time	Monte Carlo simulation in C Language
(Carey 1994)	Stochastic optimization	Random distribution	N/A	Expected cost of travel time and schedule adherence	Scheduled arrival and departure time	Cyclic coordinate descent algorithm
(Wirasinghe and Liu 1995)	Analytical optimization	Lognormal distribution	Normal distribution	Expected travel cost of wait time, riding time, delay penalty and operation	Slack time	Dynamic programming in C Language
(Lin, et al. 1995)	Stochastic simulation	Continuous distribution	Poisson distribution	Total cost of wait and in-vehicle travel time of passenger, and travel and layover time of bus	Slack time	Simulation in TRAF-NETSIM
(Liu and Wirasinghe 2001)	Stochastic simulation	Gamma distribution	Poisson distribution	Total cost of wait time, delay, late/early penalty and operation	Location of timing point and slack time	Semi-enumeration method
(Hickman 2001)	Analytical optimization with stochastic property	Lognormal distribution	Negative exponential distribution for arrival and binomial distribution for alighting	Total wait time because of headway and loading variation	Slack time	Line search technique

Source	Type of Model	Model Description				
		Assumption(s)		*Objective(s): Minimizing*	*Decision variable(s)*	*Solution platform*
		Bus arrival time	*Passenger Arrival*			
(Zhao, Dessouky and Bukkapatnam 2006)	Analytical optimization	Exponential distribution	Random distribution	Expected wait time of passenger	Slack time in terms of slack ratio	Numerical approximation through recursion
(Furth and Muller 2007)	Stochastic optimization	Lognormal distribution	Symmetric demand profile	Total cost of riding, wait, potential travel time and operating cost	Slack time for running and cycle time	Optimization in Matlab
(Fattouche 2007)	Stochastic simulation	Distribution based on AVL data	Random distribution	Expected total cost of expected wait time, expected in-vehicle travel time and hourly operating cost	Scheduled segment running time	Trip Time Analysis in Public Transport (TriTAPT), a simulation software for scheduling
(Furth and Muller 2009)	Stochastic optimization	Lognormal distribution	Non-uniform demand profile	Total cost of riding, wait, potential travel time and operating	Schedule running time	Optimization in Matlab
(Oort, Boterman and Nes 2012)	Stochastic optimization	Gaussian distribution	Symmetric demand profile	Extra wait and in-vehicle travel time	Schedule travel time, and number and location of timing point	TriTAPT
(Yan, et al. 2012)	Stochastic optimization	Lognormal distribution	N/A	Expected generalized and random schedule deviation	Scheduled travel time with slack time	CPLEX (Monte-Carlo Simulation)
(Mazloumi, et al. 2012)	Heuristic optimization	Lognormal distribution	N/A	Expected total cost of boarding passenger's wait time, on-board passenger's wait time, delay penalty and operational time	Slack time and location of timing point	Ant Colony Algorithm (ACA) and Genetic Algorithm (GA)
(Zhao, et al. 2013)	Stochastic heuristic optimization	Lognormal distribution	N/A	Generalized schedule deviation, a function of late and early deviations	Slack time	Monte-Carlo Simulation based GA

Table 2-8 Headway-based holding strategies

Source	Type of Model	Model Description				
		Assumption(s)		*Objective(s): Minimizing*	*Decision variable(s)*	*Solution platform*
		Bus Arrival Pattern	*Passenger Arrival Pattern*			
(Osuna and Newell 1972)	Analytical optimization	Normal distribution	Uniform distribution	Expected waiting time per passenger	Headway and fleet size	Approximation with Markov process and first degree optimization
(Barnett 1974)	Analytical optimization	Two points distribution	Poisson distribution	Weighted cost of both boarding and onboard passengers	Headway	First order optimization
(Newell 1974)	Analytical optimization	N/A	Poisson distribution	Average wait time	Headway	First derivative test with diffusion approximation
(Bly and Jackson 1974)	Stochastic simulation	Random	Poisson distribution	Average wait time	Headway	Route level Simulation
(Koffman 1978)	Stochastic simulation	Shifted lognormal distribution	Fixed value	Wait time	Headway	Simulation
(Bursaux 1979)	Analytical optimization	Normal distribution	Fixed value	Total wait time along the line	Timing point location and headway	Second derivative test
(Turnquist and Blume 1980)	Analytical optimization	Gamma distribution	Poisson distribution	Wait time and travel time	Timing point location and headway	Probability model
(Abkowitz and Lepofsky 1990)	simulation model and field implementation	Beta distribution	N/A	Total wait time along the route	Candidate route, timing point and threshold headway	Monte-carlo simulation and min-min function
(Eberlein, Wilson and Bernstein 2001)	Analytical optimization	Deterministic	Deterministic	Total wait time	Headway	Heuristic algorithm in a rolling horizon scheme

Modelling slack time at the timing point(s) is usually started with the assumption of bus and passenger arrival pattern referred to Table 2-7. A significant number of literatures considered the distribution of the arrival time of bus as gamma distribution (Guenthner and Sinha 1983, Guenthner and Hamat 1988, Senevirante 1990, Strathman and Hopper 1992, Wirasinghe and Liu 1995, Dessouky, et al. 1999). Besides gamma distribution, the log-normal distribution is also used in the studies under schedule-based holding strategy as referred to Table 2-7. Random distribution such as Poisson distribution is commonly assumed for expressing the arrival pattern of passenger based on Table 2-7 and Table 2-8. However, Bowman and Turnquist (1981) suggested that passenger arrival pattern is usually depends on the service types. According to them, a service with high frequency is observed with random arrival of passengers such as Poisson distribution. On the other hand passengers are more responsive to schedule when frequency is low (Turnquist 1978, Bowman and Tranquist 1981). Based on this hypothesis, Bowman and Turnquist (1981) developed a probability density function of the passenger arrival time through logit model. This is a function of the utility of arrival time of a passenger, which is a nonlinear function of expected waiting time.

The cost associated with bus service can be classified as the fixed costs and variable costs. Therefore, the objective of schedule development models is to minimize the variable cost results from the variation of service. Passenger costs such as the in-vehicle travel time, waiting time at bus stop and penalty for early or late arrival at destination are commonly considered in the objective function referred to Table 2-7. The part of agency's cost is presented by the operating cost which is basically a function of total travel time (Wirasinghe and Liu 1995). Since the variable costs are normally resulted from the variation of service, the minimization of service variation is another way to present the objective function. Senevirante (1990) used the minimization of the standard deviation of headway to find scheduled travel time. Another study minimized schedule deviation to develop schedule with schedule-based holding strategy (Yan, et al. 2012). It is true that most of the study used the total cost which is the summation of the cost associated with both passenger and agency as the objective function referred to Table 2-7.

Typically the slack time is used as the decision variable, as shown in Table 2-7. The decision variable influences the objective function, and can be regulated by the user. Multiple decision variables such as timing point location and slack time can be combined into one problem (Liu and Wirasinghe 2001). Besides using slack time as a decision variable, scheduled running time can also be used (Senevirante 1990, Fattouche 2007, Furth and Muller 2009, Oort, Boterman and Nes 2012, Yan, et al. 2012). Scheduled running time is the summation of expected (average) travel time and slack time. Most commonly used constraint in different models is the slack time, referred to Table 2-7. Normally during simulation modeling, different user-defined values of slack time are tested. Vandebona and Richardson (1986) constrained slack time in between -1 to 2 minutes, and simulated conditions with one minute increment. Senevirante (1990) used the scheduled travel time and journey speed as two constraints, and varies travel time in one minute increments and speed in 5 kph increments. Although Liu and Wirasinghe (2001) considered maximum 5 minutes of slack time at a timing point, they mentioned about an equation to find the maximum slack time. The equation indicates the total available time for a half cycle interval, which is a function of the fleet size, headway, average half cycle travel time and recovery time at one end of the route. The summation of average half cycle travel time and recovery time can be considered as the half cycle time. Yan, et al. (2012) used the same equation to find threshold value of slack time. But they used 95th percentile travel time as the half cycle time. Similar concept of threshold slack time is used by Zhao, et al. (2013). Besides slack time, schedule travel time, speed, headway, and loading conditions are also used as constraints in various studies especially during stochastic modeling (Hickman 2001, Zhao, Dessouky and Bukkapatnam 2006, Fattouche 2007). Different solution algorithms and platforms used to solve these problems are shown in Table 2-7.

2.4 Transit Signal Priority

Transit signal priority (TSP) is a proven method to improve reliability and efficiency of the bus service (Chang, et al. 2003). Transit signal priority can be defined as a process of providing priority to the transit vehicles at intersection by modifying signal phasing (Feng, Perrin and Martin 2003, Smith, Hemily and Ivanovic 2005, Ekeila, Sayed and Esawey 2009). Transit signal priority (TSP) consists of four subsystems: 1) vehicle detection, 2) main components, 3) priority control strategies and 4) TSP system management (Smith, Hemily and Ivanovic 2005). Priority control strategies are passive priority, active priority and adaptive priority. By adopting the ideology of TSP, it is believed that application of holding strategy along a bus corridor with TSP would increase reliability as well as efficiency of a bus service.

Active TSP is a process of giving priority to specific buses based on detection and subsequent priority request activation (Smith, Hemily and Ivanovic 2005). Active TSP includes strategies such as the green extension, red truncation, queue jumping and phase insertion. Among four strategies, green extension and red truncation are used in this study. Green extension is the strategy of extending green time to a predefined amount at the end of the phase at which bus is detected (Smith, Hemily and Ivanovic 2005, Econolite 2009). On the other hand, red truncation is the process of reducing red time of a priority phase by reducing green time of non-priority phase, so that bus can get early green (Smith, Hemily and Ivanovic 2005, Econolite 2009). A study also used the advantage of TSP during scheduling a bus route (Altun and Furth 2009). Altun and Furth (2009) developed a method for finding the route running time schedule with a conditional TSP, where only late buses will get priority.

2.5 Summary

Bus service reliability can be assessed in various ways. Variation in service can be observed for different known and unknown factors. In order to find the possible factor behind the variation, reliability should be assessed from different levels (stop, corridor, route, direction and network). A single specific measure is not suitable to all levels. Moreover, performance of a bus route service has impact on agency, operator and passenger. It is necessary to use appropriate performance measure(s) for each application bodies. The appropriateness of a performance measure towards application bodies is defined by the applicability and understanding of each measure. Sometimes, performance measures are depends on the frequency of a bus service. Measures related to headway are suitable for high frequency service. For low frequency service, scheduled-based measures are advisable. These are the reasons of having a significant number of measures in transit industry to measure reliability. Different approaches for efficiency measurement are also discussed. In addition, studies related to the schedule-and headway-based holding strategies are covered. Schedule-based holding strategy is reviewed comprehensively, with various modeling approaches. A brief discussion about transit signal priority (TSP) concludes the literature review.

CHAPTER 3. BUS SERVICE PERFORMANCE ASSESSMENT

This chapter presents a framework for assessing bus service performance, and includes five steps: 1) identify performance measures, 2) evaluate the quality of these measures, 3) prepare data, 4) calculate measures, and 5) present measures in an informative manner.

3.1 Performance measure selection

32 performance measures were identified in Chapter 2. From those 32 performance measures, 16 measures were selected, which were judged to best reflect bus service reliability and efficiency (Table 3-1).

Table 3-1 Selected performance measures

Property	Service Characteristics	Measures	Application level	Sources
Reliability	Travel time	Coefficient of variation of travel time	Segment & route	(Ma, Ferreira and Mesbah 2013)
		Travel time variability index	Segment & route	(Lomax, et al. 2003)
		Buffer time index	Segment & route	(Lomax, et al. 2003)
	Schedule adherence	Coefficient of variation of departure time	Stop	
		% Earliness and % Lateness	Stop	(Mandelzys and Hellinga 2010)
		Arrival delay	Stop	(Strathman, Dueker, et al. 1999)
	Headway	Coefficient of variation of headway	Stop	(Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013)
		Regularity deviation mean	Stop	(Oort and Nes 2009)
		Headway delay	Stop	(Kimpel, Strathman and Dueker, et al. 2000)
	Wait time	Coefficient of variation of headway-based	Stop	(Trompet, Liu and Graham 2011)

		excess wait time		
		Schedule-based excess wait time	Stop	(Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013)
		Budgeted wait time	Stop	(Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013)
Efficiency	Travel time	Travel time ratio	Segment & route	(Strathman, Dueker, et al. 1999)
	Delay	Delay per traveller	Segment & route	(Cambridge Systematics, Inc.; Dowling Associates, Inc.; System Metrics Group, Inc.; Institute, Texas Transportation 2008)
	Capacity	Capacity utilization	Segment & route	
	Trip planning	Planning time index	Segment & route	(Pu 2011)

The service characteristics for which performance measures are provided include travel time, schedule adherence, headway, wait time, delay, and bus passenger capacity. The characteristics and applicability of these 16 measures depend on the concerned body (agency, operator, and passenger), service type (high and low frequency) and analysis level (stop, corridor, route and network). These will be discussed in the evaluation section, along with their relationship with each measure. Since the reliability of a service is affected by the variation of characteristics, the coefficient of variation (CoV) is taken as the common evaluation measure. The definitions and reason for selecting the measures listed in the table above are provided below.

3.1.1 Travel time variation

Travel time variability is assessed using three performance measures: the coefficient of variation of travel time, travel time variability index, and buffer time index.

Coefficient of variation (CoV) of travel time

The coefficient of variation (CoV) of travel time is the ratio between the standard deviation of travel times and the average travel time. This is a normalized (i.e. unitless) measure to assess variation or dispersion of travel times. The use of CoV of travel time removes the effect of mean travel time from the standard deviation of travel time (Reed, Lynn and Meade 2002).

$$CoV_{T,i-1,i} = \frac{\sigma_{T,i-1,i}}{\mu_{T,i-1,i}} \quad (1)$$

Where

- $CoV_{T,i-1,i}$ is the CoV of travel time between stop $i-1$ and i;
- $\sigma_{T,i-1,i}$is the standard deviation of travel times from stop $i-1$ to i;
- $\sigma_{T,i-1,i} = \sqrt{\frac{1}{\mathrm{N}}\sum\left(T_{i-1,i} - \mu_{T,i-1,i}\right)^2}$
- $\mu_{T,i-1,i}$is the average travel time from stop $i-1$ to i;
- $\mu_{T,i-1,i} = \frac{\sum T_{i-1,i}}{N}$
- $N$is the size of the dataset; and
- $T_{i-1,i}$is the travel time between stop $i-1$ to i.

Travel time variability index (TTVI)

The travel time variability index (TTVI) is the ratio of the difference between the upper and lower limit of the 95% confidence interval to the difference between the peak hour and off-peak hour travel time. This measure compares the spreads of travel time during peak hour with the off-peak hour. Since the spread or difference between the upper and lower limit for the peak hour is typically greater than for the off-peak hour, the value of TTVI is usually greater than one (Lomax, et al. 2003). TTVI can be expressed as follows (Lomax, et al. 2003):

$$TTVI_{T,i-1,i} = \frac{\left(T_{i-1,i_{U95p}} - T_{i-1,i_{L95p}}\right)_{Peak}}{\left(T_{i-1,i_{U95p}} - T_{i-1,i_{L95p}}\right)_{off-Peak}} \quad (2)$$

Where

- $TTVI_{T,i-1,i}$ is the travel time variability index of travel time between stop $i-1$ and i;

- $T_{i-1,i_{U95p}}$ is the upper value of travel time at the 95 percent confidence limit between stop $i-1$ and i, where $T_{i-1,i_{U95p}} = \mu_{T,i-1,i} + 1.96 * \frac{\sigma_{T,i-1,i}}{\sqrt{N}}$; and
- $T_{i-1,i_{L95p}}$ is the lower value of travel time at the 95 percent confidence limit between stop $i-1$ and i, where $T_{i-1,i_{L95p}} = \mu_{T,i-1,i} - 1.96 * \frac{\sigma_{T,i-1,i}}{\sqrt{N}}$

These equations assume that the sample mean is normally distributed with population mean $\mu_{T,i-1,i}$ and standard deviation of $\frac{\sigma_{T,i-1,i}}{\sqrt{N}}$.

Buffer time index

Buffer time index (BTI) is the ratio between the buffer time rate and the average travel time rate. The time rate is the inverse of a speed (distance/time). The buffer time rate is calculated as the difference between the 95th percentile travel time rate and the average travel time rate. The value of the buffer time index increases with the variability of travel time. In other words, if the variability of travel time increases, then the difference between the 95th percentile travel time and the average travel time will increase as well. Although the CoV of travel time and buffer time index is same conceptually, buffer time index is more sensitive than CoV of travel time. Mean is sensitive to extremely large or small value. Buffer time index is capable to capture a small change in the variation of travel time. The equation of BTI is given below (Lomax, et al. 2003):

$$BTI_{T,i-1,i} = \frac{\frac{T_{i-1,i_{95p}}}{D_{i-1,i}} - \frac{\mu_{T,i-1,i}}{D_{i-1,i}}}{\frac{\mu_{T,i-1,i}}{D_{i-1,i}}} \quad (3)$$

Where

- $BTI_{T,i-1,i}$ is the buffer time index of travel time between stop $i-1$ and i;
- $T_{i-1,i_{95p}}$ is the 95th percentile travel time between stop $i-1$ and i; and
- $D_{i-1,i}$ is the distance between stop $i-1$ and stop i.

3.1.2 Variation in Schedule adherence

Since ETS is a schedule-based transit service, variations in arrival and departure times have negative impacts on the passenger's perception of bus service. Variation in schedule adherence is measured using three performance measures: coefficient of variation of departure times, percent earliness and lateness, and arrival delay.

Coefficient of variation (CoV) of departure time

The coefficient of variation of departure time is defined as the ratio of the standard deviation of departure times and the average value of departure times at a certain bus stop. All major bus stops under the ETS bus service have scheduled departure times, and buses should depart these stop at the scheduled departure time. The variation or spread of the departure time can be captured by this measure. Thus, the measurement of this performance measure is considered an effective way to evaluate departure reliability at stop level. The CoV of departure time is presented as follows:

$$CoV_{ADT,i} = \frac{\sigma_{ADT,i}}{\mu_{ADT,i}} \tag{4}$$

Where

- $CoV_{ADT,i}$ is the CoV of departure time at stop at stop i;
- $\sigma_{ADT,i}$is the standard deviation of actual departure times at stop i;
- $\mu_{ADT,i}$is the average departure time at stop i; and
- ADT_i is the actual departure time at i.

% Earliness and lateness

Percent (%) earliness is defined as the percentage of buses departing a stop one minute before the scheduled departure time, while % lateness is the percentage of buses departing a stop five minutes after the scheduled departure time. Therefore, the on-time performance of a bus route at stop level is defined by the percentage of buses that depart a bus stop within one minute early to five minutes late. These measures compare the departure time of buses with the scheduled departure time. The effectiveness of a schedule can be explored with this measure. For instance, if buses are always late or early in terms of the departure time, it is possible to have lower CoV of departure time. But, on-time performance of that bus route will be poor. In this framework, the percentages of early and late buses are determined at stop level. The expressions for % earliness and lateness are given below (Mandelzys and Hellinga 2010):

$$\%E_i = \frac{N_{E,i}}{N_{T,i}} * 100;\ N_{E,i} \in N_{T,i}\ \{-1 \geq ADT_i\} \tag{5}$$

$$\%L_i = \frac{N_{L,i}}{N_{T,i}} * 100;\ N_{L,i} \in N_{T,i}\ \{ADT_i \geq 5\} \tag{6}$$

Where

- $\%E_i$ & $\%L_i$ are the % earliness and lateness at stop i, respectively;
- $N_{E,i}$is the number of buses departing early at stop i;
- $N_{L,i}$ is the number of buses departing late at stop i; and
- $N_{T,i}$ is the total number of buses departed at stop i.

Arrival Delay

Arrival delay is defined as the difference between the scheduled arrival time and the actual arrival time of a specific bus at a specific bus stop. Normally at a timing point, slack time is assigned to absorb variability in a service, as well as to provide some rest time to the operator. At those points, the scheduled arrival time is published. Arrival time of bus has a definite influence on the departure time not only at a general bus stop but also at timing point. The early or late departure of buses from a timing point can be influenced by the arrival time. If buses arrive so late at a timing point, more occurrences of lateness would be observed. If buses are always arriving early or late at a timing point, this indicates that a schedule revision may be required. Arrival delay can be expressed as follows:

$$AD_i = SAT_i - AAT_i \tag{7}$$

Where

- AD_i is the arrival delay at stop i;
- SAT_i is the scheduled arrival time at stop i; and
- AAT_i is the average observed arrival time at stop i.

3.1.3 Headway variation

The availability of a bus service can be characterized by the frequency, duration, and accessibility or density of a service (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). Maintaining uniform headway between buses is a challenging task for a high frequency service. The variation in headway affects reliability to a great extent, and it is estimated using three performance measures under this framework: coefficient of variation of headway, regularity deviation mean, and headway delay.

Coefficient of variation (CoV) of headway

The coefficient of variation of headway is the ratio of the standard deviation of headways and the average headway observed in the field. For high frequency service, passengers typically arrive at the bus stop randomly and their waiting time solely depends on the variation in headway (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). ETS has some high frequency bus routes during peak hours. Conceptually, the probability of bus bunching for a high frequency service is increased with the variation in headway (Daganzo and Pilachowski 2011). For this reason, a performance measure such as CoV of headway is helpful in assessing the reliability of high frequency as well as low frequency service. The expression for CoV of headway is given below (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013):

$$CoV_{H_{A,i}} = \frac{\sigma_{H_{A,i}}}{\mu_{H_{A,i}}} \tag{8}$$

Where

- $CoV_{H_{A,i}}$ is the CoV of headway at stop i;
- $\sigma_{H_{A,i}}$ is the standard deviation of actual headways of consecutive buses on a route at stop i;
- $\mu_{H_{A,i}}$ is the average actual headway of consecutive buses of the same route at stop i; and
- $H_{A,i}$ is the actual headway of consecutive buses of the same route at stop i.

Regularity deviation mean (RDM)

Regularity deviation mean can be defined as the average headway deviation relative to the scheduled headway of a specific bus route at a specific bus stop. The headway deviation is the absolute difference between the actual headway and scheduled headway (Oort and Nes 2009). The scheduled headway is determined based on scheduled departure times. For a schedule-based bus service, this measure quantifies the deviation of observed headway from scheduled headway of a specific bus route. It is possible to have a high magnitude of RDM with low CoV of headway, and this suggests adjusting schedule of bus service. The equation for RDM can be expressed as follows (Oort and Nes 2009):

$$RDM_i = \left(\frac{\sum_m \left| \frac{H_{A,i} - H_{S,i}}{H_{S,i}} \right|}{m_i} \right) \tag{9}$$

Where

- RDM_i is the regularity deviation mean at stop i;
- $H_{s,i}$ is the scheduled headway of consecutive buses of the same route at stop i; and
- m_i is the number of buses of a specific route serving stop i.

Headway delay (HD)

Headway delay is defined as the difference between the actual headway and the scheduled headway of a specific bus route at a specific bus stop. Previous measure called RDM gives the average deviation of observed headway from scheduled headway. But, it is necessary to have an idea about the positivity ($H_{A_i} > H_{S_i}$) or negativity ($H_{A_i} < H_{S_i}$) of those deviations, especially for schedule adjustment. Therefore, headway delay is used. This is a simple measure, but considered to be effective for presenting the deviation of headway to the passenger and the operator. The equation for HD is given below (Kimpel, Strathman and Dueker, et al. 2000):

$$HD_i = H_{A,i} - H_{S,i} \tag{10}$$

Where

- HD_i is the headway delay at stop i;

3.1.4 Wait time variation

The wait time is measured using excess wait time and budgeted wait time. Excess wait time is defined as the extra time a passenger requires waiting for the intended bus. Budgeted wait time is defined as the extra time, a passenger includes in his/her journey time to get the intended bus. Three performance measures have been used to assess the variation in wait time: the coefficient of variation of headway-based excess wait time, the schedule-based excess wait time, and the budgeted wait time.

Coefficient of variation (CoV) of headway-based excess wait time

Because of the interrelationship among different service characteristics, wait time can be formulated in terms of headway variation or schedule deviation (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). For high frequency service, wait time is assumed to be half of the headway. Based on this, observed and scheduled wait times can be determined from observed and scheduled headway. The term "headway-based excess wait time" used here is expressed as the difference between the average actual wait time and the average scheduled wait time. The ratio of the standard deviation of the headway-based excess wait time and the average headway-based excess wait time is the coefficient of variation (CoV) of headway-based excess wait time at a specific bus stop (Trompet, Liu and Graham 2011). A bus route service with higher variation in headway will result higher CoV of headway-based excess wait time. The equation for CoV of excess wait time is given below:

$$CoV_{HEWT,i} = \frac{\sigma_{HEWT,i}}{\mu_{HEWT,i}} \quad (11)$$

$$HEWT_i = (AWT_i - SWT_i) \quad (12)$$

$$AWT_i = \frac{\sum_N (H_{A,i})^2}{2 * \sum_N H_{A,i}} \quad (13)$$

$$SWT_i = \frac{\sum_N (H_{S,i})^2}{2 * \sum_N H_{S,i}} \quad (14)$$

Where

- CoV_{EWT_i} is the CoV of excess wait time at stop i;
- $HEWT_i$is the headway-based excess wait time at stop i;
- $AWT_i$is the average actual wait time at stop i; and
- $SWT_i$is the average scheduled wait time at stop i.

Schedule-based excess wait time

Schedule-based excess wait time can be defined in terms of the departure time for timetable-based low frequency service (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). Here, the schedule-based excess wait time is the difference between the actual departure time and the scheduled departure time.

Normally for scheduled-based bus service, passenger is supposed to arrive at the stop by following the scheduled departure time. Thus, the schedule-based excess wait time indicates the time a passenger is required to wait for schedule deviation. The equation for schedule-based excess wait time is given below:

$$SEWT_i = ADT_i - SDT_i \quad (15)$$

Where

- $SEWT_i$ is the schedule-based excess wait time at stop i;
- ADT_i is the actual departure time of a bus at stop i; and
- SDT_i is the scheduled departure time of a bus at stop i.

Budgeted wait time

Budgeted wait time is the extra time a passenger includes in his/her journey time. This includes excess platform time and the potential wait time resulting from the variation in departure times. The concept of excess platform time and potential wait time is illustrated in the following figure:

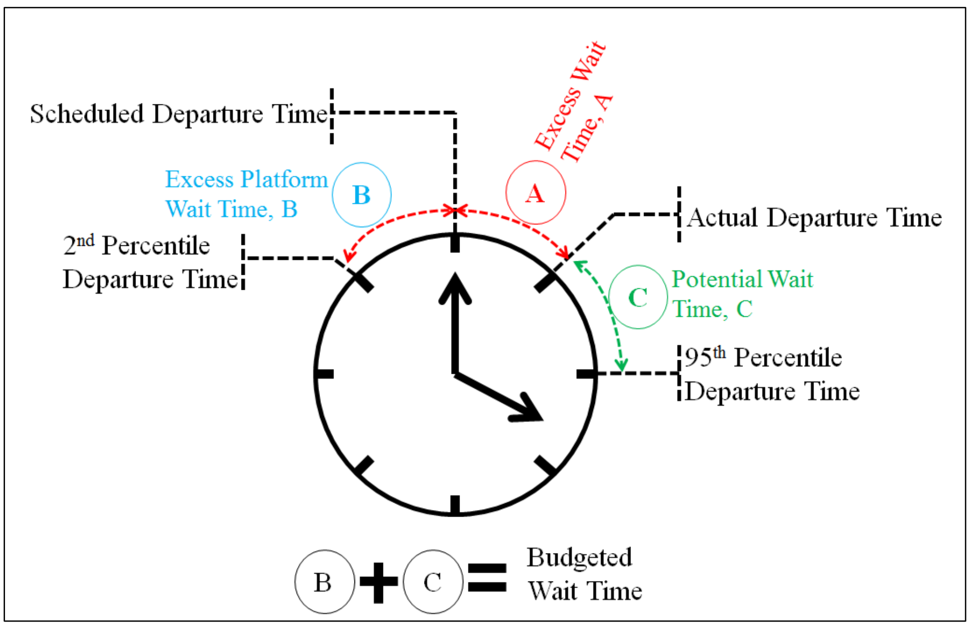

Figure 3-1 Components of passenger wait time (adapted from Kittelson & Associates, Inc. et al. (2013))

Due to the variation in bus departure times, passengers are usually required to budget that extra time by following the two extreme values of observed departure times: 1) 2nd percentile value and 2) 95th percentile value (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH

Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). The excess platform time is the difference between the scheduled departure time and the 2nd percentile departure time. The potential waiting time is obtained by using the difference between the 95th percentile departure time and scheduled departure time. The value of budgeted wait time will be increased with the variation in departure time of bus, because of the increase in the time difference between 2nd and 95th percentile departure times with the schedule departure time. The equation for budgeted wait time can be expressed as follows (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013):

$$BWT_i = EPT_i + PWT_i \tag{16}$$

$$EPT_i = SDT_i - ADT_{2,i} \tag{17}$$

$$PWT_i = ADT_{95,i} - SDT_i \tag{18}$$

Where

- BWT_i is the budgeted wait time at stop i;
- EPT_i is the excess platform time at stop i;
- PWT_i is the potential wait time at stop i;
- $ADT_{2,i}$ is the 2nd percentile departure time at stop i; and
- $ADT_{95,i}$ is the 95th percentile departure time at stop i.

3.1.5 Efficiency

Four performance measures have been selected to measure efficiency in terms of travel time, delay, capacity and trip planning.

Travel time ratio

Travel time ratio can be defined as the ratio between the average travel time and the scheduled travel time (Strathman, Dueker, et al. 1999). The scheduled travel time is determined using the scheduled departure times of a specific bus at two subjectively chosen bus stops. Here, a value of travel time ratio greater than 1 indicates efficiency loss. The equation of the travel time ratio can be presented as follows:

$$TTR_{i-1,i} = \frac{\mu_{T,i-1,i}}{STT_{i-1,i}} \tag{19}$$

Where

- $TTR_{i-1,i}$ is the travel time ratio for buses travelling between $i-1$ and i;
- $STT_{i-1,i}$is the scheduled travel time from stop $i-1$ to stop i, $STT_{i-1,i} = SDT_i - SDT_{i-1}$

Delay per traveller

Delay per traveller includes the comparison between the actual travel time and the free flow travel time per kilometre. The difference between the average travel time and the free flow travel time within one kilometre of travelling is defined as the delay per traveller. This difference is expressed as annual hours where only delay during 250 weekdays is considered (Cambridge Systematics, Inc.; Dowling Associates, Inc.; System Metrics Group, Inc.; Institute, Texas Transportation 2008). Free flow travel time is the time required by a bus travelling at the posted speed limit. Thus, this measure mainly captures the excess travel time, resulted for the signal control, heavy traffic (congestion) and stop level passenger activity. The equation for delay per traveller per kilometre in annual hours is given below:

$$d_{i-1,i} = \frac{\left(\mu_{T,i-1,i} - T_{f,i-1,i}\right)}{D_{i-1,i} * 60} * 250 \tag{20}$$

Where

- $d_{i-1,i}$ is the delay per traveller for passengers travelling between $i-1$ and i;
- $T_{f,i-1,i}$ is the free flow travel time from stop $i-1$ to stop i, and $T_{f,i-1,i} = \frac{D_{i-1,i}}{V_{i-1,i}}$

Capacity utilization

The capacity utilization can be defined as the ratio between the average on-board passengers and capacity of a bus travelling between two bus stops. Here, capacity of the bus is indicated by the number of available seats on a regular diesel bus. According to TCQSM (2013), passenger load on a bus has a significant impact on the quality of service (QoS) based on the perception of passenger and agency. Passengers relate their value of time with the availability of seat, and agency uses occupancy to evaluate the productivity of the service. Up to 80% capacity utilization, passengers' perceived travel time will be equal to the actual travel time. Their impression towards service (travel time) degrades beyond that level. For agency, service is considered as unproductive if capacity utilization is up to 50%. Capacity utilization higher than

80% is considered to be productive. The equation for capacity utilization can be expressed as follows:

$$CU_{i-1,i} = \frac{n_{ob,i-1,i}}{C_S} \tag{21}$$

Where

- $CU_{i-1,i}$ is the capacity utilization for buses travelling between $i-1$ and i;
- $n_{ob,i-1,i}$ is the average on-board passengers travelling between stop $i-1$ and stop i; and
- $C_S$is the seat capacity of a regular diesel bus.

Planning time index

Planning time index compares the worst case travel times (defined as the 95th percentile) and free flow travel times. Extreme values such as those are considered helpful in setting the schedule too. Furth et al. (2006) suggested using the 95th percentile travel time for setting the half cycle time for a route instead of mean travel time. This performance measure indicates the required travel time for planning a specific trip by including expected and unexpected delay (Cambridge Systematics, Inc.; Dowling Associates, Inc.; System Metrics Group, Inc.; Institute, Texas Transportation 2008). The equation for the planning time index is given below:

$$PTI_{i-1,i} = \frac{T_{95p,i-1,i}}{T_{f,i-1,i}} \tag{22}$$

Where

- $PTI_{i-1,i}$ is the planning time index for passengers travelling between $i-1$ and i;
- $T_{95p,i-1,i}$ is the 95th percentile travel time from stop $i-1$ to stop i; and
- $T_{f,i-1,i}$ is the free flow travel time from stop $i-1$ to stop i.

3.2 Evaluation of performance measures

The quality of the previously described performance measures is evaluated based on concerned bodies, application level, and service type. Currie, Douglas, and Kearns (2011) and Ma, Ferreira, and Mesbah (2013) proposed evaluation processes, on which this one is based. The concerned body includes the agency, operator, and passengers. Service is provided by the agency, carried out by the operator, and finally, used by passengers. All performance measures are evaluated in terms of their relevance to each concern group, as well as the measure's ease of understanding for evaluating service quality. The result of the evaluation process of reliability-based measures is summarized in Table 3-2.

Table 3-2 Evaluation of reliability-based performance measures

Travel time			Schedule adherence		
1	2	3	4	5	6
CoV of travel time	Travel time variability index	Buffer time index	CoV of departure time	% Earliness and lateness	Arrival delay
Headway			**Wait time**		
7	8	9	10	11	12
CoV of headway	Regularity deviation mean	Headway delay	CoV of headway-based excess wait time	Schedule-based excess wait time	Budgeted wait time

Categories	Travel Time			Schedule Adherence			Headway			Wait time		
	1	2	3	4	5	6	7	8	9	10	11	12
Concern Bodies												
Agency	■	■	■	■	■	■	■	■		■		■
Operator					■	■			■			
Passenger		■	■		■	■			■		■	■
Application Level												
Stop/ Timing Point	■	■	■	■	■	■	■	■	■	■	■	■
Segment/ Corridor	■	■	■	■	■	■	■	■	■			
Route Direction	■	■	■	■	■	■	■	■	■			
Entire Route	■	■	■	■	■	■	■	■	■			
Network	■	■	■	■	■	■	■	■	■			
Service Type												
High Frequency (H<10 min)	■	■	■				■	■	■	■		
Low Frequency (H≥10 min)	■	■	■	■	■	■		■	■	■	■	■

A reliability assessment using the CoV of any service characteristic is considered suitable for the agency, but more difficult for a passenger or operator to interpret. Segments and stops with high CoV indicate high variability (or low reliability) of the service characteristics. Therefore, the agency can directly focus on those problematic segments and stops during service improvement. Often a performance measure may have greater importance to a specific body, but no impact on others. For example, the travel time variability index and buffer time index are considered helpful for planning a trip. They help the agency set the fleet size, and advice passengers plan their journey time. Since the operator's schedule is prepared by the agency, the operator has no interest in those measures. Percent earliness and lateness are simple but effective measures to evaluate the reliability of the schedule. An unreliable schedule makes passengers arrive at the stop earlier than the scheduled departure time. The agency could make adjustments to the schedule based on those measures. Measures such as arrival delay and headway delay are more intuitive, and are considered suitable for both passengers and operators. Departing passengers can evaluate their delay penalty (early or late arrival at the destination) from arrival delay. Headway delay helps boarding passenger to quantify their delay before starting the trip. Both of those measures help the operator manage the schedule. Since the regularity deviation mean is the normalized version of headway delay, it could be used for all concerned bodies under this framework. The determination of excess wait time and budgeted wait time would help passengers to allocate extra time when planning their journey. The agency could also use these measures to evaluate timing points along a route. Later, 12 reliability-based measures are evaluated based on the analysis level.

The analysis level is classified as stop or timing point level, segment or corridor level, route direction level, route level, and network level. The analysis level of the 12 measures is related with the service characteristics. Measures related to travel time are suitable for assessing route- or corridor-level performance. Schedule-, headway-, and wait time-based measures are convenient for stop-level performance measurement. However, stop-level measures can be modified to evaluate route- or corridor-level performance by using a weighted average in terms of on-board passengers (Chen, et al. 2009). Eventually, the same procedure could be applied to find network-level performance from route-level performance (Chen, et al. 2009).

The applicability of a performance measure also depends on service types (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). Here, service type is classified as high and low frequency service. Some measures can be applied for both services. For instance, travel time-based measures are applicable to both types of service. Travel time is considered to be important for any passenger using any type of bus service. For schedule-based bus service, schedule adherence is necessary. Especially for low frequency service, passengers do not want to miss their intended bus. Therefore, schedule adherence-based measures have higher applicability to low frequency service where passengers consult with the schedule. For high frequency service, passengers do not consult with the schedule and their perception towards service depends on the headway. Therefore, headway-based measures have higher potential in this case. Although the regularity deviation mean and headway delay are function of both headway (observed headway) and schedule (scheduled headway), these can be used for low frequency service as well. For the same reason, the CoV of headway-based excess wait time is applicable to both types of service. However, schedule-based excess and budgeted wait times are suitable for only low frequency service, as both measures are developed by assuming that passengers have consulted the schedule. The result of the evaluation process of efficiency-based measures is summarized in Table 3-3.

Table 3-3 Evaluation of efficiency-based performance measure

Categories	Travel time ratio	Delay per traveler	Capacity utilization	Trip planning
	1	2	3	4
Concern Bodies				
Agency	■	■	■	■
Operator	■			
Passenger	■	■	■	■
Analysis Level				
Stop/ Timing Point				
Segment/ Corridor	■	■	■	■
Route Direction	■	■	■	■
Entire Route	■	■	■	■
Network	■	■	■	■
Service Type				
High Frequency (H<10 min)	■	■	■	■
Low Frequency (H≥10 min)	■	■	■	■

The travel time ratio is a simple way to compare average observed travel time with the scheduled travel time. Thus, from the viewpoint of efficiency, the travel time ratio is considered appropriate for the agency, operators, and passengers. A specific route or corridor with a travel time ratio other than one for a significant period of time indicates that the agency might consider adjusting the schedule. For passengers, it indicates that they should readjust their planned journey time or change their route to another available and suitable bus route. Operators can re-adjust their operating speed by following the posted speed limit decided upon in the travel time ratio. The performance measure of delay per traveller would provide a complete scenario of passengers' cost over the year during weekdays. The agency could use this measure for future planning of bus service or for the comparison of service level to attract more consumers to use the service. Use of this performance measure is similar for passengers, without relation to the operator. Capacity utilization has influence on the quality of service (QoS) from passenger' and agency's perspective. Passengers perceive high value of time for a crowded bus and their impression towards service (travel time) degrades beyond 80% capacity utilization. Agency uses occupancy to evaluate the productivity of the service, and service is considered as unproductive if capacity utilization is lower than 50%. Therefore, this measure is useful to the agency and passengers. Similar to the travel time ratio, the planning time index is considered appropriate for the agency and passengers in assessing efficiency as well as for planning purposes.

The travel time ratio, delay per traveller, and planning time index are related to travel time. Thus, these three measures are applicable to all levels (corridor, direction, route, and network) except stop level. The capacity utilization is determined by using the number of on-board passengers travelling along a segment. Therefore, this measure is also not applicable to stop level only. In this framework, all three efficiency-based measures are related to the travel time and occupancy (no specific relation with the schedule or headway), so all of them are considered to be applicable for high and low frequency service.

3.3 Data processing

The Automatic Passenger Counter (APC) system installed on buses can provide operational, spatial, and temporal historical data on a large scale (Furth, Hemily, et al. 2006). According to Rucker (2003), the development of APC system started during the mid-1970s in North America. But, it has not been widely acceptable until 2003 (Rucker 2003). Rucker (2003) also added that only ten agencies were using this system for data collection purpose during 1993. Since the year of 2000, APC data have been used for assessing bus service performance (Kimpel, Strathman and Dueker, et al. 2000). The APC system is an automatic process of collecting passenger-related information at stop level (Dessouky, et al. 1999), and can collect both location- and passenger-specific data. Since APC will not collect stop-level data when there is no passenger activity, the resolution of the data depends on the sampling or penetration rate (Furth, Hemily, et al. 2006). ETS bus service performance is assessed using APC data. The study route is Route 1, which runs between the West Edmonton Mall Transit Centre and Capilano Transit Centre, shown in Figure 3-2.

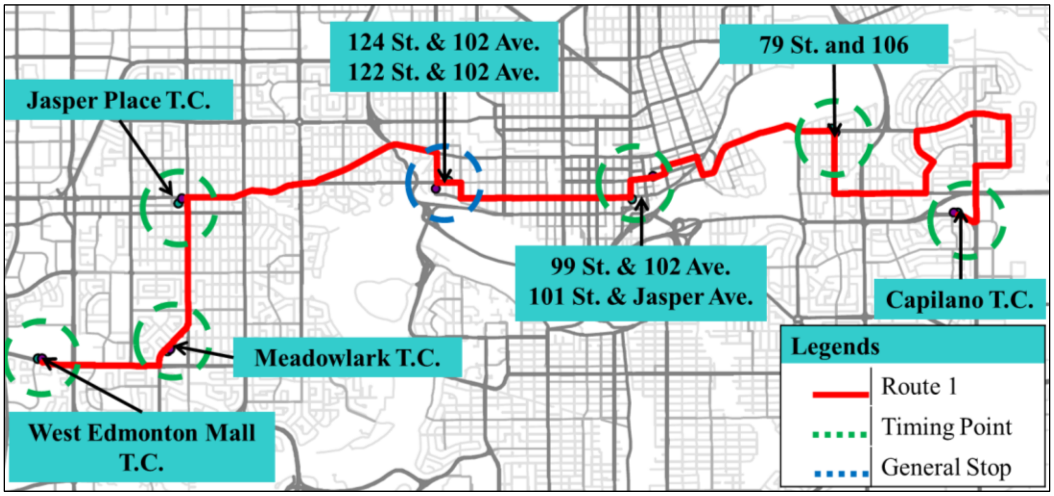

Figure 3-2 The map of Route 1

Stop-level APC data are collected for 158 bus stops along the entire route. ETS stores APC data in five intervals for a year, and those are September Signup (start of September to end of November), December Signup (start of December to end of January), February Signup (start of February to end of April), April Signup (end of April to end of June), and June Signup (end of June to end of August). In this framework, June Signup data from 6/29/2014 to 8/30/2014 have been used. Besides signups, stop-level APC data from ETS are classified into seven time periods throughout the day: Early Morning (03:00-05:29), AM Peak (05:30-08:59), Midday (09:00-14:59), PM Peak (15:00-17:59), Early Evening (18:00-21:59), Late Evening (22:00-00:59), and Owl (1:00-2:59). Selected key stops along each direction are listed in the following Table 3-4.

Table 3-4 Selected bus stops for the framework

Westbound				Eastbound		
Stop ID	*Description*	*Acronym*		*Stop ID*	*Description*	*Acronym*
2301	Capilano T.C.	Cap		5009	West Edmonton Mall T.C.	WEM
2267	79 St. and 106 Ave.	79/106		5302	Meadowlark T.C.	ML
1620	101 St. and Jasper Ave.	101/JA		5110	Jasper Place T.C.	JP
1746*	122 St. and 102 Ave.	122/102		1242*	124 St. and 102 Ave.	124/102
5101	Jasper Place T.C.	JP		1707	99 St. and 102 Ave.	99/102
5301	Meadowlark T.C.	ML		2591	79 St. and 106 Ave.	79/106
5009	West Edmonton Mall	WEM		2301	Capilano T.C.	Cap

CHAPTER 3: BUS SERVICE PERFORMANCE ASSESSMENT

Among seven bus stops along eastbound and westbound, most of the bus stops are timing points, except stops 122/102 and 124/102 indicated with star (*). These two regular bus stops are major transfer points with high passenger volumes. Stop-level APC data from ETS are included in a location report that contains information about time interval (start & end date of data collection), bus stop identification number (ID), location of the bus stop, duration of database, time period, route number, run number, scheduled arrival time, scheduled departure time, observed arrival time, observed departure time, schedule adherence, action, arrival status, departure status, number of boarding passengers, number of alighting passengers, number of departing passengers, ramp deployment, observed date and weekday, and calendar events (k-day). A screenshot of the location report for an individual bus stop is illustrated in Appendix A.

Each specific data point of the location report can be identified with a specific combination of time period, route number, run number, scheduled departure time, and observed date. A specific combination of that information is necessary to identify service properties such as travel time, schedule adherence, and headway. Matlab programs have been developed to extract specific information to calculate travel time, schedule adherence, and headway.

Not all the data points in a location report are usable. Activity information (data point) of an APC-equipped bus can be absent from a location report if that bus stop has no passenger activity or the APC device did not work properly at a specific time. The travel time calculation between two timing points requires arrival and departure time information of same bus tabulated in two location reports. For instance, the departure time of an APC-equipped bus from a downstream bus stop is available, but that bus was not stopped (or APC device has not worked properly) at the upstream bus stop. Then the arrival time of that bus at the upstream bus stop will be not available. The data point related to that bus, in the location report of the downstream bus stop has no use for travel time calculation. Thus, data points with the same time period, route number, run number, and observed date as well as consecutive scheduled departure times are taken into consideration for travel time calculation. After defining those specific pairs of data points, the arrival time of downstream bus stops and the departure time of upstream bus stops are identified. Later, observed travel time is calculated as the difference between the observed arrival time at the upstream bus stop and the observed departure time at the downstream bus stop. Same procedure is followed during calculating scheduled travel time, except scheduled departure and arrival times are used instead of observed departure and arrival times.

For schedule adherence and headway calculation, only an individual bus stop's location report is used. Departure-based schedule adherence is the difference between observed departure and scheduled departure time. Observed and scheduled arrival times are used for arrival-based schedule adherence. Each data point in all location reports has observed and scheduled arrival and departure time. From each location report, data points related to Route 1 are selected to find schedule adherence.

Headway calculation also requires one location report. From each report, two data points with similar time period, route number, and observed date as well as consecutive schedule departure times are used to find headway. Here, observed headway is defined as the difference between the observed departure times of two consecutive buses departing from the same bus stop. During scheduled headway calculation, the scheduled departure times are used.

Washington, Karlaftis, and Mannering (2003) describe data samples using 12 measures. These include the number of observations, mean, median, mode, standard deviation, variance, coefficient of variation, maximum value, minimum value, upper quartile, lower quartile, and Kurtosis. The number of observations, mean, median, mode, Kurtosis value and distribution types of the data sample have been evaluated, and the results are shown in Appendix A. Here, the mean, median, and mode are compared to understand the distribution of the data sample as well as skewness (Washington, Karlaftis and Mannering 2003). The Kurtosis parameter helps identify flatness of the distribution, and normal distribution can be identified with an exact value of zero. A negative value of the Kurtosis parameter indicates a flatter peak, while a positive value indicates peakedness of the frequency distribution. Distribution with a flatter peak can be considered a uniform distribution. The characteristics of the frequency distribution of the data samples are addressed in the comment section of all descriptive statistics tables presented in Appendix A.

Most of the segment-based travel time samples extracted along both westbound and eastbound follow positive skewness with peakedness in terms of frequency distribution. Flatter distribution of travel time is observed mostly during off-peak hours. For schedule adherence at bus stops, the descriptive statistics clearly show a positively skewed frequency distribution with peak during most time periods. Besides that, negatively skewed distribution is mainly observed during early and late off-peak hours.

By observing the number of observations, data resolution is higher during the AM peak, midday peak, PM peak, and early evening. This indicates two things: high penetration of APC-installed buses during those periods and higher passenger activity. Normally, ACP devices cannot collect location information when there is no passenger activity. Sample data related to headway have lower numbers of observations, because each piece of headway data includes the departure time of two consecutive buses. Therefore, the probability of getting two consecutive buses equipped with APC devices requires a higher penetration rate. According to ETS staff, 20% of buses are APC device equipped, and resulting in low observations of bus headways available in the dataset. According to Furth, Hemily, et al. (2006), this type of data insufficiency can be resolved by assigning more APC-equipped buses along the corridor being studied. Based on the results shown in Appendix A, most of the headway data sample has no mode value, which indicates uniform distribution of the data over the time period. Also, mean and median values of the data sample are close to each other, which explain lower extreme (outlier) values within the dataset.

Based on the tables presented in Appendix A, the number of observations during early morning, late evening and owl periods is low. The performance measures generated using data from those periods would not be statistically significant given the data quantity and quality issues identified. Thus, performance measures during AM peak, midday, PM peak, and early evening are calculated and presented in the next section. Furthermore, there are far less headway data compared to travel time and schedule adherence data. Thus, headway-based measures reported below should also be considered carefully. All selected performance measures are evaluated in the next section. “I/D” indicates that there was insufficient data to populate the metric.

3.4 Calculation of Performance Measures

The assessment results of the 16 performance measures are presented in this section. The objective of this assessment is to quantify the service quality of Route 1. Appropriate and relevant scales for all performance measures are identified based on previous studies and engineering judgment, and are shown in Table 3-5.

Table 3-5 Performance measure scales

Performance Measure	**Low**	**Medium**	**High**
Coefficient of variation	0.25	0.375	0.5
Travel time variability index	0	2.5	5
Buffer time index	0	0.5	1
% Earliness and lateness	0	15	30
Arrival delay (min)	0	-2.5	-5
Regularity deviation mean	0	0.5	1
Headway delay (min)	0	7.5	15
Schedule-based excess wait time (min)	0	2.5	5
Budgeted wait time (min)	6	10.5	15
Travel time ratio	1	1.25	1.5
Delay per traveller (hr/year/km)	5	12.5	20
Capacity utilization	0.8	0.4	0
Planning time index	1	5.5	10

In this assessment framework, most commonly used measure is coefficient of variation (CoV). The scale for CoV is adopted from a study by Alvey and Kilss (1987) on administrative records research. They mentioned that a CoV value equal to or lower than 0.25 is acceptable. The value will be greater than 0.5, when service is poor. The middle value indicates the average of low and high value of any performance measure. For travel time variability index, it is assumed that five times more variation during peak hour than off-peak hour indicates lowest performance. The lower limit of travel time variability index is taken as 0, when there is no variation in service. Travel times with no variation will result same value for upper and lower value of 95% confidence limit (P-28). For buffer time index, 95th percentile travel time is assumed as twice of mean travel time during highest variability situation. This results one for higher limit of buffer time index scale (P-29). With no variation in travel time, the 95th percentile travel time will be equal to mean travel time. Thus, lower limit of this measure is zero. The scale for % earliness and lateness is determined by using the scale for on-time performance, mentioned in the Transit Capacity and Quality of Service Manual (TCQSM) (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013).

According to the scale in the TCQSM, 100% on-time performance is the best performance scenario for a bus route service, and this results 0% earliness and lateness. The TCQSM indicates worst scenario with 70% or lower on-time performance. Thus, a summation % earliness and lateness of 30% or higher indicates the same situation. This study assumed that a bus service with 30% or more earliness or lateness at a stop, indicates lowest performance. Mandelzys and Hellinga (2010) assumed 15% or more earliness or lateness as the lowest performance. But, this assumption is very restrictive, and it is released in this study to 30% level. The concept of % lateness is used during the determination of the scale for arrival delay (P-30). Late arrival of a bus at a stop (especially timing point) has a direct influence on the departure time. When arrival delay of a bus is five minutes or more, bus might leave stop after five minutes from the scheduled departure. The scale for the regularity deviation mean is determined by using the formula of this measure (P-32). When variation is absent, actual headway will be same as scheduled headway, and these results in zero regularity deviation mean. It is assumed that service with highest variation will cause actual headway equal or greater than scheduled headway. Therefore, the highest scale for regularity deviation mean is one. Similar assumption is applied with the equation of headway delay, and scale is presented in Table 3-5. The concept of % lateness is again used for developing schedule-based excess wait time scale. Passengers will experience more than five minutes of excess wait time, if bus departed from stop anytime after five minutes from the schedule. Early departure of bus will also cause more than five minutes of excess wait to the passengers who are supposed to wait for next bus. Thus, it is not desirable to have more than five minutes of excess wait time. The allowable departure time can vary from one minute early to five minutes late from schedule departure time, and this creates the lower limit of budgeted wait time scale. For instance, 2^{nd} percentile departure time is (-) 1 minute (early) and 95^{th} percentile departure time is (+) 5 minutes (late). Based on the equation of budgeted wait time (P-35), the total wait time will be 6 min, which is allowable. Thus, lower limit of budgeted wait time scale is 6 minutes. The maximum budgeted wait time is assumed as 15 minutes (regular headway of Route 1). For travel time ratio, a service with no variation will result equal mean and scheduled travel time. The mean travel time is assumed as 1.5 times the scheduled travel time or more. One minute of delay during travelling with Route 1 is not very high. This one minute delay results five hours of total delay per kilometre in 250 weekdays in a year. This is the lower limit of delay per traveller scale. From TCQSM, five minutes of delay is acceptable. Regular five minutes of delay per kilometre will result 20 hours of delay in 250 days. That is the upper limit of this scale. An empty bus will result zero capacity utilization, which is not economical in terms of capacity utilization scale. Thus, zero capacity utilization is the upper limit of the scale. According to TCQSM, the level of service of a bus will be economical at or above 80% occupancy. Thus, scale considers 0.8 as the upper limit. From passengers' point of view, more than 80% occupancy is not comfortable (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). The scale for planning time index is developed by using similar types of assumption used in travel time travel time ratio.

3.4.1 Travel Time variation

Performance measures associated with travel time are assessed for both origin- and segment-based travel time. Origin-based travel time is defined as the travel time from the first bus stop to the other six bus stops along the route. First, the variation of travel time is addressed by CoV of travel times. All application bodies (agency, operator and passenger) will observe different travel times with a segment with high CoV. The CoV of origin-based travel times along the westbound direction is shown in Table 3-6.

Table 3-6 Coefficient of variation (CoV) of origin-based travel time westbound

Segment	Cap to 79/106	Cap to 101/JA	Cap to 122/102	Cap to JP	Cap to ML	Cap to WEM
Distance (km)	6.9	10.7	13.5	17.9	20.2	22.2
Time Period		**0.25**	**0.375**		**0.5**	
AM Peak (05:30-08:59)	0.26	0.16	0.1	0.29	0.19	0.12
Midday (09:00-14:59)	0.16	0.09	0.14	0.26	0.15	0.08
PM Peak (15:00-17:59)	0.35	0.2	0.16	0.27	0.17	0.12
Early Evening (18:00-21:59)	0.23	0.13	0.09	0.28	0.11	0.07

All results are lower or close to 0.25 except CoV of travel times from Cap to 79/106 during PM peak. The coefficient of variation (CoV) of origin-based travel time during peak hours is higher than during off-peak hours, due to higher traffic flow during peak hours, as shown in Table 3-6. Variation does not increase proportionately with distance along the route, due to six timing points along the corridor. Thus, it can be added that the holding at timing points is working to some extent to minimize the variation of service propagation. CoV of travel times from Cap to JP are comparatively higher than other segments during all periods mentioned in Table 3-6. The distance of this segment (Cap to JP) is 17.9 kilometres with four timing points (122/102 is a general bus stop). In this segment, variation in travel time along Cap to 79/106 is higher than Cap to 101/JA. Timing point 79/106 captures some variation along Cap to 79/106. After 79/106, CoV of travel times are further reduced by 101/JA. Variation in travel times is again increased after 122/102, and 122/102 is not a timing point after all. Thus, no variation is captured in between 101/JA and JP. Among the two off-peak periods, higher variation is observed in between Cap and JP during early evening.

According to previous discussion about CoV origin-based travel time, variation of origin-based travel time is comparatively higher during peak period than off-peak period. The relation between the variations in peak and off-peak period is presented by travel time variability index, and the results for westbound direction are shown in Table 3-7.

Table 3-7 Origin-based travel time variability index westbound

Segment	Cap to 79/106	Cap to 101/JA	Cap to 122/102	Cap to JP	Cap to ML	Cap to WEM
Distance (km)	6.9	10.7	13.5	17.9	20.2	22.2
Time Period	0		2.5		5	
AM Peak	3.23	2.7	1.7	2.09	2.59	2.91
PM Peak	4.49	3.24	2.55	1.93	2.7	3.3

To determine this measure, both AM and PM peak hour travel times have been compared against the same off-peak hour dataset. The off-peak hour dataset is developed by gathering data related to travel times during all four off-peak hours. Based on the results and scale shown in Table 3-7, all values are greater than one, which indicates origin-based travel time variation in the westbound direction during both AM peak and PM peak are higher than off-peak hours. Moreover, variation during the PM peak is comparatively higher than AM peak. Therefore, application bodies will observe Route 1 less reliable during peak hours (especially PM peak) than off-peak hours. Because of this variation in travel, both agency and passengers are required to budget more time as buffer time during planning their trip.

The buffer time index compares the buffer time with the average travel time (Page-29). The origin-based buffer time indices along the westbound direction are estimated with the origin-based travel time and results are shown in Table 3-8.

Table 3-8 Origin-based buffer time index westbound

Segment	Cap to 79/106	Cap to 101/JA	Cap to 122/102	Cap to JP	Cap to ML	Cap to WEM
Distance (km)	6.9	10.7	13.5	17.9	20.2	22.2
Time Period	0		0.5		1	
AM Peak (05:30-08:59)	0.5	0.29	0.16	0.42	0.29	0.18
Midday (09:00-14:59)	0.3	0.17	0.14	0.48	0.27	0.13
PM Peak (15:00-17:59)	0.89	0.5	0.33	0.52	0.32	0.22
Early Evening (18:00-21:59)	0.47	0.24	0.15	0.45	0.18	0.11

Based on the results, the agency and passengers must budget 89% of mean travel time with the mean travel time, in order to reach destination (79/106) without delay during PM peak. Similar pattern of results is observed in every origin-based segment, which supports the idea that an increase in travel time variation will be accompanied by an increase in the buffer time index. As observed in Table 3-8, the PM peak has the highest buffer time index values for all travel time segments, and three of these values are greater than 0.5. Passengers travelling between Cap and JP during any time periods, have to budget 50% of mean travel time along with mean travel time. Directional service quality can be assessed by comparing the westbound and eastbound CoV of origin-based travel time. The CoV of origin-based travel time along the eastbound direction is presented in Table 3-9.

Table 3-9 Coefficient of variation (CoV) of origin-based travel time eastbound

Segment	WEM to ML	WEM to JP	WEM to 124/102	WEM to 99/102	WEM to 79/106	WEM to Cap
Distance (km)	2	4.3	8.6	12	15.1	22
Time Period	0.25		0.375		0.5	
AM Peak (05:30-08:59)	0.36	0.22	0.04	0.1	0.08	0.13
Midday (09:00-14:59)	0.3	0.26	0.13	0.08	0.08	0.08
PM Peak (15:00-17:59)	0.23	0.34	0.1	0.08	0.08	0.12
Early Evening (18:00-21:59)	0.21	I/D	0.12	0.06	0.06	0.14

In the eastbound direction, variation during AM peak is comparatively higher than variation during PM peak. Travel time variation of Route 1 between WEM and JP is higher than other downstream segments. Variation in travel time drastically reduced after JP, which indicates the effectiveness of JP as a timing point. Thus, reliability of Route 1 is comparatively better after JP along eastbound. Highest CoV value is observed between WEM and ML during AM peak. Besides that, other CoV values are in acceptable limit showing in green colour. Based on the results shown in Table 3-9, variation during midday is founded to be higher than early evening. Along eastbound direction, CoV during peak hours are greater than off-peak hours, but difference is not that high as in the westbound direction. Origin-based travel time variability index is used for this comparison and results are shown in Table 3-10.

Table 3-10 Origin-based travel time variability index eastbound

Segment	WEM to ML	WEM to JP	WEM to 124/102	WEM to 99/102	WEM to 79/106	WEM to Cap
Distance (km)	2	4.3	8.6	12	15.1	22
Time Period	0		2.5		5	
AM Peak	2.9	1.27	0.61	2.26	1.98	1.98
PM Peak	1.76	3.32	0.65	2.07	2.2	2.28

Table 3-10 indicates that performance of Route 1 in the eastbound direction is generally better than westbound, compared to Table 3-7. But, most of the values of the travel time variability index along the eastbound direction are greater than one, which explains higher variation during peak hour than off-peak hour. One exceptional case is observed with trips running from WEM to 124/102. Along this segment, travel time variability indices (0.61 & 0.65) are lower than one, shown in Table 3-10. This is due to higher variation during off-peak hours than peak hours. Origin-based buffer time indices in the eastbound direction are presented in Table 3-11.

Table 3-11 Origin-based buffer time index eastbound

Segment	WEM to ML	WEM to JP	WEM to 124/102	WEM to 99/102	WEM to 79/106	WEM to Cap
Distance (km)	2	4.3	8.6	12	15.1	22
Time Period		0		0.5	1	
AM Peak (05:30-08:59)	0.67	0.36	0.05	0.15	0.12	0.22
Midday (09:00-14:59)	0.58	0.39	0.2	0.11	0.11	0.14
PM Peak (15:00-17:59)	0.39	0.35	0.17	0.14	0.13	0.18
Early Evening (18:00-21:59)	0.44	I/D	0.21	0.12	0.1	0.25

The values of origin-based buffer time index reduced after JP, which agrees with the results presented in Table 3-9 and Table 3-10. Compared to the CoV of travel time, higher values of the buffer time index are observed upstream of JP. Passengers travelling from WEM to ML have to budget higher buffer time during AM (highest = 0.67) and midday.

Segment-based travel time is measured between two key consecutive bus stops, and can help to identify the exact location travel time variation. Sources of this variation might be variations in passenger demand, control delays, and traffic on the road segment. First, segment based travel time is used to measure the CoV of segment-based travel time and results are presented in Table 3-12.

Table 3-12 Coefficient of Variation (CoV) of segment-based travel time westbound

Segment	Cap to 79/106	79/106 to 101/JA	101/JA to 122/102	122/102 to JP	JP to ML	ML to WEM
Distance (km)	6.9	3.8	2.8	3	2.3	2
Time Period		0.25	0.375		0.5	
AM Peak (05:30-08:59)	0.26	0.14	0.13	0.13	0.22	0.18
Midday (09:00-14:59)	0.16	0.13	0.13	0.15	0.18	0.24
PM Peak (15:00-17:59)	0.35	0.13	0.14	0.17	0.24	0.23
Early Evening (18:00-21:59)	0.23	0.12	0.13	0.16	0.28	0.28

According to the CoV scale, most of the results in Table 3-12 are very acceptable. However, higher variation is observed along the first segment and last two segments. The distance between Cap and 79/106 is about 6.9 km, the longest segment of Route 1. Due to this long distance, this segment can be characterised with higher variation in passenger activity, control delay and traffic during the PM peak. Similar types of variation can cause increase in variation along last two segments. In addition, during early evening, higher variation in travel time is observed than midday.

In order to compare peak hour variation with the off-peak hour variation, segment-based travel time variability index was used. The results of this performance measure along the westbound direction are shown in Table 3-13.

Table 3-13 Segment-based travel time variability index westbound

Segment	Cap to 79/106	79/106 to 101/JA	101/JA to 122/102	122/102 to JP	JP to ML	ML to WEM
Distance (km)	6.9	3.8	2.8	3	2.3	2
Time Period	0		2.5		5	
AM Peak	3.61	1.94	2.33	1.33	1.61	1.21
PM Peak	4.93	1.66	2.37	2.02	1.98	1.7

The values of the travel time variability index are comparatively higher for the PM peak than the AM peak, and the highest travel time variability index is observed along Cap to 79/106. Also, every value mentioned in Table 3-13 is greater than one, which suggests higher travel time variation during peak hours than off-peak hours. But, this difference is reduced after 122/102. The increase of variation in travel time results an increase in buffer time for the agency and passenger. The results of buffer time index along the westbound direction are presented in Table 3-14.

Table 3-14 Segment-based buffer time index westbound

Segment	Cap to 79/106	79/106 to 101/JA	101/JA to 122/102	122/102 to JP	JP to ML	ML to WEM
Distance (km)	6.9	3.8	2.8	3	2.3	2
Time Period	0		0.5		1	
AM Peak (05:30-08:59)	0.5	0.21	0.22	0.29	0.42	0.23
Midday (09:00-14:59)	0.3	0.18	0.23	0.18	0.32	0.46
PM Peak (15:00-17:59)	0.89	0.22	0.21	0.31	0.58	0.57
Early Evening (18:00-21:59)	0.47	0.19	0.22	0.21	0.56	0.61

Due to higher variation in travel time during the PM peak period compared to any other time period, the magnitude of the buffer time index is higher in that period, as shown in Table 3-14. Interestingly, the buffer time index during early evening is higher than the AM peak after JP to WEM. Again, this might explain the higher demand for West Edmonton Mall as a transfer hub. Based on the segment-based travel time variation assessment, reliability of Route 1 is comparatively lower during PM peak, especially along Cap to 79/106, JP to ML and ML to WEM. The results of CoV of segment-based travel time along the eastbound direction are shown in Table 3-15.

Table 3-15 Coefficient of Variation (CoV) of segment-based travel time eastbound

Segment	WEM to ML	ML to JP	JP to 124/102	124/102 to 99/102	99/102 to 79/106	79/106 to Cap
Distance (km)	2	2.3	4.3	3.4	3.1	6.9
Time Period		0.25	0.375		0.5	
AM Peak (05:30-08:59)	0.36	0.26	0.25	0.13	0.24	0.12
Midday (09:00-14:59)	0.3	0.46	0.25	0.13	0.22	0.15
PM Peak (15:00-17:59)	0.23	0.53	0.34	0.12	0.2	0.3
Early Evening (18:00-21:59)	0.21	I/D	0.25	0.13	0.14	0.18

Table 3-15 indicates higher variation during the AM peak, midday, and PM peak. Segment based travel time variation is getting better after JP (Jasper Place TC). Along the eastbound direction, travel time variation during midday is higher than any other off-peak periods. Segment based travel time variability index eastbound is shown in Table 3-16.

Table 3-16 Segment-based travel time variability index eastbound

Segment	WEM to ML	ML to JP	JP to 124/102	124/102 to 99/102	99/102 to 79/106	79/106 to Cap
Distance (km)	2	2.3	4.3	3.4	3.1	6.9
Time Period		0	2.5		5	
AM Peak	2.9	0.83	2.11	1.77	2.53	1.11
PM Peak	1.76	3.32	3.1	1.93	2.19	4.28

For the segment between WEM and ML, the maximum variation in segment-based travel time is observed during the AM peak, compared to all the other periods. As a result, the travel time variability indices during that time is higher than in the PM peak, shown in the Table 3-16. Segment-based buffer time index in the eastbound direction is shown in Table 3-17.

Table 3-17 Segment-based buffer time index eastbound

Segment	WEM to ML	ML to JP	JP to 124/102	124/102 to 99/102	99/102 to 79/106	79/106 to Cap
Distance (km)	2	2.3	4.3	3.4	3.1	6.9
Time Period		0	0.5		1	
AM Peak (05:30-08:59)	0.67	0.43	0.46	0.23	0.45	0.24
Midday (09:00-14:59)	0.59	0.56	0.33	0.23	0.35	0.25
PM Peak (15:00-17:59)	0.39	0.6	0.51	0.2	0.26	0.6
Early Evening (18:00-21:59)	0.44	I/D	0.35	0.22	0.26	0.3

The eastbound buffer time indices are consistent with the CoV of travel time and travel time variability index along the eastbound direction. The values of the buffer time index along the eastbound direction are higher along the first and last parts of the route than other segments, shown in Table 3-17. Lower values of the buffer time index are observed along Jasper Ave. between 124/102 to 99/102.

From the above results, it is clear that the bus service reliability can be explained by the variation in travel time. Bus service reliability is comparatively lower during peak hours than off-peak hours due to higher variation in passenger demand, control delay, and traffic along the route. Directional demand impacts service reliability as well. In other words, some segments in a particular direction show better service reliability during midday but become the worst during early evening, and vice versa. Therefore, in this study, certain impacts of the time period, direction of travel, and segment length on the travel time variation are explained above to some extent.

3.4.2 Variation in Schedule Adherence

Coefficient of variation (CoV) of departure time measures the variation of departure times at key bus stops. The results of CoV of departure time at seven key bus stops along westbound are shown in Table 3-18.

Table 3-18 Coefficient of variation (CoV) of departure time westbound

Bus Stop	Cap	79/106	101/JA	122/102	JP	ML	WEM
Distance (km)	0	6.9	10.7	13.5	17.9	20.2	22.2
Time Period		0.25		0.375		0.5	
AM Peak (05:30-08:59)	0.009	0.024	0.016	0.02	0.015	0.02	0.006
Midday (09:00-14:59)	0.004	0.014	0.01	0.014	0.009	0.01	0.004
PM Peak (15:00-17:59)	0.007	0.013	0.009	0.012	0.009	0.011	0.003
Early Evening (18:00-21:59)	0.003	0.009	0.005	0.014	0.009	0.008	0.001

Based on the results shown in Table 3-18, a lower coefficient of variation of departure time is observed at most of the westbound bus stops, because six out of seven bus stops are timing points. At stop 122/102, which is not a timing point, the highest CoV of departure times is observed. In addition to that, higher variation is observed during the AM peak compared to other peak hours. The results of % lateness and earliness calculations for westbound are shown in Table 3-19.

Table 3-19 % Earliness and Lateness westbound

Bus Stop	Cap		79/106		101/JA		122/102		JP		ML		WEM	
Distance (km)	0		6.9		10.7		13.5		17.9		20.2		22.2	
					0		15			30				
Time Period	%E	%L	%E	%L	%E	%L	%E	%L	%E	%L	%E	%L	%E	%L
AM Peak	38	2	4	1	76	1	6	1	9	2	3	1	42	1
Midday	31	4	6	8	26	10	7	20	6	15	2	18	31	6
PM Peak	51	1	9	6	15	14	9	23	17	17	1	23	24	7
Early Evening	36	1	7	2	34	2	5	9	23	1	2	6	12	1

Although CoV of departure time is very low (Table 3-18) at every key bus stops, the on-time performance is not satisfactory in the westbound direction. Most interestingly, a higher proportion of buses departed stops more than one minute before the scheduled departure time, particularly from Cap. Similar performance is observed at 101/JA and WEM. Different pattern is observed at the regular bus stop 122/102. Higher percentage of late departure is observed at that stop.

Arrival delay compares schedule arrival time with the actual arrival time. Three of the key bus stops have scheduled arrival time, and arrival delay at these bus stops is estimated. The results of arrival delay westbound are presented in Table 3-20.

Table 3-20 Arrival delay (minutes) westbound

Bus Stop	Cap	79/106	101/JA	122/102	JP	ML	WEM
Distance (km)	0	6.9	10.7	13.5	17.9	20.2	22.2
Time Period		0		- 2.5	- 5		
AM Peak (05:30-08:59)	1.78 (81, 19)				0.32 (60, 40)		1.80 (81, 19)
Midday (09:00-14:59)	-3.07 (29, 71)				-1.82 (41, 59)		-1.36 (50, 50)
PM Peak (15:00-17:59)	-3.31 (40, 60)				-0.67 (44, 56)		-2.20 (41, 59)
Early Evening (18:00-21:59)	-3.09 (35, 65)				-0.03 (58, 42)		-0.52 (43, 57)

Since the arrival delay is the difference between the scheduled and observed arrival time of bus, the positive value indicates early arrival and vice versa. The percentages of early and late arrival are given under the delay value in specific cells of the Table 3-20 within a bracket (early, late). Percentage of early arrival is the percentage of buses arrived earlier than scheduled arrival time. Rest of the arrived buses are considered under the percentage of late arrival buses. A specific pattern of arrival delay is observed along the westbound direction, based on the results shown in Table 3-20. During morning peak, buses arrived early at three timing point. After morning peak, late arrival is observed during all three time periods. Based on the results shown in Table 3-19 and Table 3-20, although buses arrived late at Cap, but higher percentage of buses departed Cap early. This will cause a small time frame for dwelling purpose. Moreover, it is observed that high percentage of buses arrive earlier than the scheduled arrival time and leave stops earlier than the scheduled departure time during AM peak.

The results for the coefficient of variation (CoV) of departure time at seven key bus stops along the eastbound direction are shown in Table 3-21.

Table 3-21 Coefficient of variation (CoV) of departure time eastbound

Bus Stop	WEM	ML	JP	124/102	99/102	79/106	Cap
Distance (km)	0	2	4.3	8.6	12	15.1	22
Time Period		0.25		0.375		0.5	
AM Peak (05:30-08:59)	0.006	0.002	0.002	0.044	0.031	0.035	0.009
Midday (09:00-14:59)	0.004	0.002	0.002	0.03	0.021	0.023	0.004
PM Peak (15:00-17:59)	0.003	0.003	0.003	0.022	0.018	0.019	0.007
Early Evening (18:00-21:59)	0.001	0.002	0.002	0.021	0.018	0.018	0.003

The patterns of the coefficient of variation of departure time along the eastbound direction follows the same patterns as westbound. Higher variation is observed during the AM peak, as shown in Table 3-21. Since 124/102 is the only stop that is not a timing point, highest variation in departure time is observed at that bus stop.

After calculating variation in departure time, it is necessary to present the effect of that variation in terms of earliness and lateness along eastbound. The results of % earliness and lateness along the eastbound direction are presented in Table 3-22.

Table 3-22 % Earliness and Lateness eastbound

Bus Stop	WEM		ML		JP		124/102		99/102		79/106		Cap	
Distance (km)	0		2		4.3		8.6		12		15.1		22	
					0		15		30					
Time Period	%E	%L	%E	%L	%E	%L	%E	%L	%E	%L	%E	%L	%E	%L
AM Peak	42	1	8	0	13	0	25	3	43	2	20	1	38	2
Midday	31	6	4	6	14	2	1	21	4	44	6	35	31	4
PM Peak	24	7	1	12	9	5	0	44	0	60	0	63	51	1
Early Evening	12	1	2	2	10	1	1	13	1	28	2	27	36	1

Although low CoV of departure time at WEM and Cap is observed in Table 3-21, a higher percentage of buses departed early from both stops, according to Table 3-22. This is similar to the results presented for the CoV of departure time along the westbound direction (Table 3-19). This clearly indicates that buses are departed earlier from those stops most of the time. During AM peak, five out of seven key bus stops has high proportion of early departure. However the general bus stop 124/102 is mostly affected by the late departure. About 44% of buses departed late from 124/102 during the PM peak hour, which indicates very poor on-time performance (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). The results of arrival delay along the eastbound direction are presented in Table 3-23.

Table 3-23 Arrival delay (minutes) eastbound

Bus Stop	WEM	ML	JP	124/102	99/102	79/106	Cap
Distance (km)	0	2	4.3	8.6	12	15.1	22
Time Period			0	- 2.5	- 5		
AM Peak (05:30-08:59)	1.8 (81, 19)		1.54 (81, 19)				1.78 (81, 19)
Midday (09:00-14:59)	-1.36 (50, 50)		-0.56 (44, 56)				-3.07 (29, 71)
PM Peak (15:00-17:59)	-2.20 (41, 59)		-1.52 (27, 73)				-3.31 (40, 60)
Early Evening (18:00-21:59)	-0.52 (43, 57)		0.37 (63, 37)				-3.09 (35, 65)

The same arrival pattern is observed along the eastbound direction compared to the westbound direction (Table 3-20). According to Table 3-23, most of the time buses arrive early during the AM peak, which can explain the on-time performance at those three bus stops, referred to Table 3-22. Most interestingly, all three bus stops have same percentage of early and late arrived buses. But, the magnitude of early arrival is higher at WEM and Cap. This can explains higher proportion of early departure from those two bus stops than JP. After AM peak, high proportion of buses is arrived late, and this explains the magnitude of arrival delay. The problem of small time window for dwelling purpose is also prevailed along eastbound, especially during midday, PM peak and early evening.

Similar results for schedule adherence are found in both the eastbound and westbound directions of bus route 1. Although the variation or spread in departure time is very low, the on-time performance is not that satisfactory at timing points. At general bus stops, high proportion of late departures is observed at general bus stop. During AM peak, buses are not only arrived early but also depart early from timing point. After AM peak, a high proportion of buses are arrived late at Cap and WEM. Although Cap and WEM are timing points, a high proportion of buses are departed earlier than the scheduled departure time. This will reduce the effectiveness of those timing points and the reliability of Route 1 along both directions.

3.4.3 Headway variation

The coefficient of variation (CoV) of headway captures the variation (or spread) in observed headway at key bus stops along westbound and eastbound. The regularity deviation mean shows the variation in the headway compared to the scheduled headway. Finally, the headway delay is the difference between the observed and scheduled headway. For simplicity, it is considered helpful to both passengers and operators to evaluate the performance of bus service. First, the CoV of headway at seven key bus stops westbound is determined, and results are shown in Table 3-24.

Table 3-24 Coefficient of variation (CoV) of headway westbound

Bus Stop	Cap	79/106	101/JA	122/102	JP	ML	WEM
Distance (km)	0	6.9	10.7	13.5	17.9	20.2	22.2
Time Period		0.25		0.375		0.5	
AM Peak (05:30-08:59)	0.42	0.24	0.22	0.24	0.22	0.23	0.27
Midday (09:00-14:59)	0.25	0.21	0.23	0.27	0.25	0.25	0.24
PM Peak (15:00-17:59)	0.58	0.31	0.29	0.35	0.37	0.36	0.22
Early Evening (18:00-21:59)	0.28	0.13	0.15	0.25	0.21	0.22	0.23

Based on the results shown in Table 3-24, a higher coefficient of variation in headway along the westbound direction is observed during peak hours, especially during the PM peak, which indicated greater delay to the passenger during the PM peak. In addition, variation in headway is also related to the holding at timing points, the road environment, and traffic conditions. Since the results of the CoV in departure times from Table 3-18 show better performance at those timing points, higher variation in passenger activity, traffic conditions and the road environment in between those timing points can explain the variation in headway at those timing points. Also, the absence of holding at 122/102 adds more variation of headway in the system. The regularity deviation mean at key bus stops westbound are estimated and presented in Table 3-25.

Table 3-25 Regularity deviation mean westbound

Bus Stop	Cap	79/106	101/JA	122/102	JP	ML	WEM
Distance (km)	0	6.9	10.7	13.5	17.9	20.2	22.2
Time Period		0		0.5		1	
AM Peak (05:30-08:59)	0.24	0.08	0.18	0.09	0.12	0.12	0.2
Midday (09:00-14:59)	0.19	0.15	0.17	0.21	0.18	0.18	0.19
PM Peak (15:00-17:59)	0.58	0.2	0.22	0.27	0.25	0.24	0.16
Early Evening (18:00-21:59)	0.21	0.11	0.11	0.17	0.13	0.11	0.12

Since the westbound segment-based travel time variation is higher during PM peak (referred to Table 3-12), the regularity deviation mean during PM peak shows higher values than other time periods, as seen in Table 3-25. The variation in headway results headway delay, and results of headway delay along westbound are given below:

Table 3-26 Headway delay (minutes) westbound

Bus Stop	Cap	79/106	101/JA	122/102	JP	ML	WEM
Distance (km)	0	6.9	10.7	13.5	17.9	20.2	22.2
Time Period		0		7.5		15	
AM Peak (05:30-08:59)	3.99	1.28	2.77	1.36	1.76	1.76	2.96
Midday (09:00-14:59)	2.9	2.21	2.53	3.11	2.7	2.75	2.87
PM Peak (15:00-17:59)	8.74	2.8	3.01	3.96	3.77	3.57	2.47
Early Evening (18:00-21:59)	3.25	1.69	1.79	2.58	2.03	1.69	1.82

The variation in headway is also reflected in headway delay, which is simply the difference between the actual headway and the scheduled headway. According to Table 3-26, most of the values are positive which indicates longer actual headway than scheduled headways.

The directional variation in performance of Route 1 is already observed through previous measures, especially travel time related measures. Thus, the difference in the directional variation in headway can be determined by similar measures along eastbound. The results of CoV of headway along the eastbound direction are shown in the following Table 3-27.

Table 3-27 Coefficient of variation (CoV) of headway eastbound

Bus Stop	WEM	ML	JP	124/102	99/102	79/106	Cap
Distance (km)	0	2	4.3	8.6	12	15.1	22
Time Period		0.25		0.375		0.5	
AM Peak (05:30-08:59)	0.27	0.07	0.23	0.29	0.34	0.39	0.42
Midday (09:00-14:59)	0.24	0.19	0.13	0.14	0.27	0.31	0.25
PM Peak (15:00-17:59)	0.22	0.21	0.27	0.3	0.42	0.45	0.58
Early Evening (18:00-21:59)	0.23	0.23	0.18	0.22	0.36	0.38	0.28

According to Table 3-27, the CoV of observed headways is also significant along the eastbound direction. Not only that, variation increases in the downstream direction of the route, which explains the propagation of delay along the route. This variation in observed headway in the eastbound direction can be compared with the scheduled headway of buses under Route 1 running in the eastbound direction. The results from that comparison are shown in Table 3-28 as the regularity deviation mean.

Table 3-28 Regularity deviation mean eastbound

Bus Stop	WEM	ML	JP	124/102	99/102	79/106	Cap
Distance (km)	0	2	4.3	8.6	12	15.1	22
Time Period		0		0.5		1	
AM Peak (05:30-08:59)	0.2	0.05	0.09	0.14	0.2	0.09	0.24
Midday (09:00-14:59)	0.19	0.15	0.1	0.12	0.2	0.23	0.19
PM Peak (15:00-17:59)	0.16	0.17	0.17	0.18	0.3	0.35	0.58
Early Evening (18:00-21:59)	0.12	0.11	0.08	0.15	0.24	0.28	0.21

Higher values of regularity deviation mean are observed after the 124/102 stop (general stop), and this follows the same pattern as the CoV of headway along eastbound (Table 3-27).

The PM peak shows a higher value of regularity deviation mean and the values increase along the route, especially after 124/102. For schedule-based bus system, passengers might follow the scheduled headway especially during the high-frequency situation. Thus, the comparison of actual and schedule would be easier to find the effect of the variation in headway in terms of headway delay. The results of headway delay at key bus stops along the eastbound direction are shown in Table 3-29.

Table 3-29 Headway Delay (minutes) eastbound

Bus Stop	WEM	ML	JP	124/102	99/102	79/106	Cap
Distance (km)	0	2	4.3	8.6	12	15.1	22
Time Period		0		7.5		15	
AM Peak (05:30-08:59)	2.96	0.75	1.38	2.07	3.09	1.54	3.99
Midday (09:00-14:59)	2.87	2.23	1.44	1.78	2.99	3.5	2.9
PM Peak (15:00-17:59)	2.47	2.6	2.34	2.51	4.08	4.69	8.74
Early Evening (18:00-21:59)	1.82	1.63	1.17	2.08	3.49	3.97	3.25

Due to higher variation during the PM peak hour, higher headway delay is observed at that time period in the eastbound direction. Based on the results shown in Table 3-29, all eastbound headway delays are positive, which indicated higher actual headways than scheduled headways. This in turn indicates extra waiting time for passengers travelling eastbound on Route 1. Similar to Table 3-27 and Table 3-28, higher headway delays are observed after 124/102.

The reliability of bus service in terms of headway is useful not only for passengers, but also for the agency and operators. Passengers must arrive at bus stops earlier than the scheduled departure time to account for varied arrival times that result from varied headways, which would increase their wait time, as well as journey time. It is observed from Table 3-24 and Table 3-27 that all values are lower than 0.75, which indicates that bus service is satisfactory in terms of bunching (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). Additionally, the positive value of headway delays at all key bus stops along the westbound and eastbound direction indicates extra waiting time after scheduled departure time. Higher CoV of headway, regularity deviation mean, and headway delay are observed at the general key bus stop (122/102 & 124/102) in the both eastbound and westbound direction. This bad performance continues upstream of those general bus stops, especially along the eastbound direction.

3.4.4 Wait time variation

Edmonton experiences almost six months of winter, which makes waiting at bus stops very unpleasant. It is also true that extra wait time for passengers resulted from the variation of other service characteristics such as travel time, departure time, and headway; and the framework already measures those variations. Therefore, excess wait time can be explained from previous results in a conceptual way, which needs to be validated, as in this study. First, the coefficient of variation (CoV) of headway-based excess wait times at key bus stops are calculated with scheduled and observed headway; the results are given in Table 3-30.

Table 3-30 Coefficient of variation (CoV) of headway-based excess wait time westbound

Bus Stop	Cap	79/106	101/JA	122/102	JP	ML	WEM
Distance (km)	0	6.9	10.7	13.5	17.9	20.2	22.2
Time Period		0.25		0.375		0.5	
AM Peak (05:30-08:59)	0.61	0.95	0.67	0.64	0.89	0.73	1.03
Midday (09:00-14:59)	0.86	1.12	0.95	0.72	0.98	0.96	0.31
PM Peak (15:00-17:59)	0.79	1.15	0.73	0.65	1.04	1.16	0.98
Early Evening (18:00-21:59)	0.86	0.67	0.81	1.05	0.87	0.93	0.89

High CoV in headway-based excess wait time is observed along the westbound direction, shown in Table 3-30. The CoV of headway-based excess wait time is very sensitive measure to capture the variation in headway. This measure captures the same variation in headway with small mean. The excess wait time is the difference between the half of the observed headway and the half of the scheduled headway. The excess wait time has similar standard deviation as the observed headway with smaller mean value. Therefore, the CoV values are high. The results shown in Table 3-24 support this statement. Besides headway variation, the variation in slack time can cause higher CoV of headway-based excess wait time.

Under schedule-based excess wait time, excess wait time for both late and early buses has been combined and expressed as the average value in Table 3-31. For late buses, schedule-based excess wait time occurs when the actual departure time was greater than the scheduled departure time. In this calculation, early buses are those which left the stop earlier than one minute from the schedule departure time. It is assumed that early departure affects a significant portion of passenger who are going to miss the intended bus, and then schedule-based excess wait time will be the whole headway (time next bus will arrive). For early departure, schedule-based excess wait time is assumed as the headway for the specific timing period. The frequency of Route 1 changes with time period. It is also assumed that buses departed within one minute early to exact scheduled departure time did not cause any schedule-based excess wait time.

Table 3-31 Schedule-based excess wait time (minutes) westbound

Bus Stop	Cap	79/106	101/JA	122/102	JP	ML	WEM
Distance (km)	0	6.9	10.7	13.5	17.9	20.2	22.2
Time Period		0		2.5		5	
AM Peak (05:30-08:59)	7.3	1.9	12.5	2.4	2.7	2.1	8.1
Midday (09:00-14:59)	6.8	2.9	7.2	4.2	3.9	3.5	6.4
PM Peak (15:00-17:59)	9.0	3.7	5.5	5.0	5.2	3.6	5.7
Early Evening (18:00-21:59)	6.5	2.9	8.0	2.9	4.9	2.8	1.4

The % earliness has a significant impact on the excess wait time. Based on the results in Table 3-31, high schedule-based excess wait time is observed at Cap, 101/JA, and WEM because of high proportion of early buses at those timing points. Besides earliness, high proportion of lateness at 122/102 (general bus stop) also creates schedule-based excess wait time during midday and PM peak. Because of the better on-time performance at 79/106 and ML results lower schedule-based excess time at those bus stops. A higher schedule-based excess wait time is observed during PM peak. This explains the higher variation in departure time during that period. The results of the budgeted wait time in the westbound direction are shown in Table 3-32.

Table 3-32 Budgeted wait time (minutes) westbound

Bus Stop	Cap	79/106	101/JA	122/102	JP	ML	WEM
Distance (km)	0	6.9	10.7	13.5	17.9	20.2	22.2
Time Period/ Scale		6		10.5		15	
AM Peak (05:30-08:59)	11.35	3.84	5.64	5.43	7.46	3.73	11.35
Midday (09:00-14:59)	10.01	7.61	8.85	7.15	9.74	10.76	10.01
PM Peak (15:00-17:59)	19.97	7.95	8.56	10.86	13.15	14.94	19.97
Early Evening (18:00-21:59)	10.13	4.82	4.91	6.19	7.43	7.81	10.13

Variation in departure time, % earliness, and % lateness explain the budgeted wait time. Since all the variations in departure time are in allowable limit, the % earliness and % lateness, has the major impact on the budgeted wait time for Route 1. Based on the results of % earliness and lateness in Table 3-19, passengers will arrive early at Cap and WEM. This high percentage of early departure created a major difference between the 2nd percentile departure time and scheduled departure time (referred to p-35). This results high budgeted wait time. Besides earliness, lateness can explain high budgeted wait time at ML and JP during PM peak. Moreover, high budgeted wait time is observed at general stop 122/102 during PM peak because of higher lateness than any other period. Finally, it is observed from Table 3-32 that the passenger's budgeted wait time is higher during PM peak than other time periods. The results of the CoV of excess wait time along the eastbound direction are shown in Table 3-33.

Table 3-33 Coefficient of variation (CoV) of headway-based excess wait time eastbound

Bus Stop	WEM	ML	JP	124/102	99/102	79/106	Cap
Distance (km)	0	2	4.3	8.6	12	15.1	22
Time Period		0.25		0.375		0.5	
AM Peak (05:30-08:59)	1.03	0.65	0.64	0.99	0.61	1.03	1.29
Midday (09:00-14:59)	0.73	0.85	0.92	0.68	0.90	0.97	0.86
PM Peak (15:00-17:59)	0.98	0.95	0.99	1.11	0.93	0.96	0.79
Early Evening (18:00-21:59)	0.89	0.77	0.82	0.78	0.73	0.72	0.86

According to Table 3-33, a higher CoV of headway-based excess wait time is observed in the eastbound direction, which can be explained by higher CoV of headways along eastbound, shown in Table 3-27. In addition to that, 124/102 has higher variation compared with other bus stops along the eastbound direction. Variation in departure time from scheduled departure time results excess wait time along eastbound direction, and results are shown in Table 3-34.

Table 3-34 Schedule-based excess wait time (minutes) eastbound

Bus Stop	WEM	ML	JP	124/102	99/102	79/106	Cap
Distance (km)	0	2	4.3	8.6	12	15.1	22
Time Period		0		2.5		5	
AM Peak (05:30-08:59)	8.1	2.6	4.0	6.1	8.7	7.1	7.3
Midday (09:00-14:59)	6.4	2.6	3.9	3.8	6.0	5.7	6.6
PM Peak (15:00-17:59)	5.7	3.3	3.4	5.1	7.0	7.4	9.0
Early Evening (18:00-21:59)	3.2	2.1	2.7	3.0	4.3	4.2	6.5

The influence of % earliness and % lateness is clearly revealed in Table 3-34. Passengers who are using four timing points such as the WEM, 99/102, 79/106, and Cap will experience high schedule-based excess wait time. For general bus stop 124/102, high schedule-based excess wait time is observed during AM peak, midday, and PM peak. This stop has high percentage of earliness during AM peak, while midday and PM peak are observed with high lateness, referred to Table 3-22. Passengers travelling during the PM peak will experience higher schedule-based excess wait time, based on the results shown in Table 3-34. Similar to the westbound passengers, eastbound passengers are also required to budget extra time to catch their intended bus. The results of budgeted wait time along the eastbound direction are shown in Table 3-35.

Table 3-35 Budgeted waiting time (minutes) eastbound

Bus Stop	WEM	ML	JP	124/102	99/102	79/106	Cap
Distance (km)	0	2	4.3	8.6	12	15.1	22
Time Period		6		10.5		15	
AM Peak (05:30-08:59)	7.26	2.27	3.07	4.11	5.42	4.01	7.26
Midday (09:00-14:59)	8.16	5.88	5.63	9.45	8.77	9.15	8.16
PM Peak (15:00-17:59)	8.99	7.87	7.07	11	10.78	9.42	8.99
Early Evening (18:00-21:59)	4.9	4.07	4.09	5.58	6.38	5.18	4.9

A clear relation between the on-time performance (% earliness and lateness) and budgeted wait time is observed in Table 3-35. Passengers who are starting their journey from WEM, 99/102, 79/106, and Cap have to budget more time to use Route 1. The highest budgeted wait time is observed at the general stop 124/102 during PM peak. In that time period, 124/102 is captured with a combination of comparatively higher CoV of departure time and % lateness than other time periods, referred to Table 3-21 and Table 3-22. According to the results shown in Table 3-35, passengers travelling along eastbound will need to budget more time for their journey, especially during the PM peak.

Based on the above results, the reliability of bus service in terms of the passenger wait time is not reasonable for most of the time periods. This is because of the inefficient utilization of timing points along the Route 1. Therefore, a considerable amount of delay is observed at those timing points. The agency should give attention to bus service during the PM peak along both directions. In addition to that, key bus stops with no holding strategy show higher extra wait time for passengers. This encourages adjustment of the current schedule, as well as the magnitude of slack time at those timing points. The inclusion of 124/102 and 122/102 as timing points may also improve service reliability along the route. However, bus travel times may increase with this change (Cham 2003).

3.4.5 Efficiency

Travel time ratio

Origin-based travel time is used for the travel time ratio calculation. Therefore, observed origin-based travel time is compared with the scheduled origin-based travel time, and the results of this performance measure are shown in Table 3-36.

Table 3-36 Origin-based travel time ratio westbound

Segment	Cap to 79/106	Cap to 101/JA	Cap to 122/102	Cap to JP	Cap to ML	Cap to WEM
Distance (km)	6.9	10.7	13.5	17.9	20.2	22.2
Time Period		1	1.25		1.5	
AM Peak (05:30-08:59)	1.21	1.07	1.14	1.23	1.08	1.03
Midday (09:00-14:59)	1.04	0.95	1.04	1.01	0.93	0.92
PM Peak (15:00-17:59)	1.31	1.14	1.18	1.19	1.12	1.08
Early Evening (18:00-21:59)	1.07	0.98	1.05	1.06	0.98	0.94

From results shown in Table 3-36, observed travel time is greater than scheduled travel time for most of the westbound cases, except during off-peak hours. In addition to that, a higher value is observed during the PM peak compared to other peak hours along westbound, as shown in Table 3-36. The highest value of travel time ratio is observed along the segment between the Cap and 79/106 during PM peak, which is also indicated with highest CoV of travel time, referred to Table 3-6. Similar pattern is observed for travel times between Cap and JP. Thus, origin-based segments with high CoV of travel time are suffered with higher travel time than scheduled travel time. Among two off-peak hours, a higher travel time ratio is observed during early evening along westbound. The origin-based travel time ratio in the eastbound direction follows the same pattern as the westbound direction, and the results of the origin-based travel time ratio along the eastbound direction are given in Table 3-37.

Table 3-37 Origin-based travel time ratio eastbound

Segment	WEM to ML	WEM to JP	WEM to 124/102	WEM to 99/102	WEM to 79/106	WEM to Cap
Distance (km)	2	4.3	8.6	12	15.1	22
Time Period		1	1.25		1.5	
AM Peak (05:30-08:59)	1.34	0.88	0.96	1.11	1.09	1
Midday (09:00-14:59)	1.25	0.86	1.19	1.1	1.05	0.93
PM Peak (15:00-17:59)	1.22	0.85	1.13	1.13	1.11	1.11
Early Evening (18:00-21:59)	1.09	I/D	1.13	1.01	0.99	0.91

Along eastbound, high CoV of travel time is accompanied with high travel time ratio. Based on Table 3-9, higher CoV of travel time is observed between WEM and ML, compared to other origin-based segments. Passengers travelling along this segment will experience high travel time, and the highest travel time ratio is also observed along this segment during AM peak. Further analysis shows that the peak hour travel time ratios are higher than the off-peak hour ratios shown in Table 3-37. However, travel time ratios during midday are higher than during the PM peak up to 124/102. Along the eastbound direction, origin-based travel time ratios during midday are higher than during early evening, opposite of westbound results.

Based on the above discussion, the higher variation in travel time can be explained with the higher value of travel time ratio. Various factors are working behind this travel time variation such as passenger demand, control delay, traffic condition, and others. Higher variation in those factors can directly increase travel time or efficiency-loss in the system. The efficiency-loss or travel time ratios are higher during peak hours compared to off-peak hours. The loss of operational (travel time) efficiency is higher during PM peak than AM peak in the both westbound and eastbound direction. Directional variation in efficiency loss can be explained by the opposite pattern of travel time ratio observed during midday and early evening along westbound and eastbound direction.

Delay per traveller

The delay per traveller is calculated through the comparison of average observed travel time with the free flow travel time for origin-based segments. Free flow travel time is determined using distance and the speed limit, which is 50 kph. This measure captures the excess travel time caused mostly by the signal controller and stop-level passenger activity. Delay per traveller is presented in Table 3-38 and Table 3-39 and is normalized based on the distance from Cap.

Table 3-38 Delay per traveller westbound (origin-based) (hours/year/km)

Segment	Cap to 79/106	Cap to 101/JA	Cap to 122/102	Cap to JP	Cap to ML	Cap to WEM
Distance (km)	6.9	10.7	13.5	17.9	20.2	22.2
Time Period		5	12.5		20	
AM Peak (05:30-08:59)	7.6	9.4	10.9	14.1	12.2	10.9
Midday (09:00-14:59)	5.8	7.8	9.6	10.9	10	9.2
PM Peak (15:00-17:59)	8.7	10.2	11.3	13.6	12.8	11.5
Early Evening (18:00-21:59)	6.2	8.2	9.7	11.7	10.7	9.5

Comparing results from Table 3-6 and Table 3-38, a relationship between the CoV of travel and delay per traveller is established. Segments with higher CoV of travel time are observed with higher delay per traveller. From Table 3-6, travel times along the segment (Cap to JP) are captured with higher variation. Passengers travelling from Cap to JP experienced higher delay compared to other origin-based segments along westbound. In addition to that, higher delay values are observed after the general bus stop 122/102. Westbound delay is higher in the peak hours than the off-peak hours. Delays during the PM peak are higher than during the AM peak, except along the segment Cap to JP. Moreover, passengers travelling westbound during the early evening will experience more delay than during other off-peak period.

Table 3-39 Delay per traveller eastbound (origin-based) (hours/year/km)

Segment	WEM to ML	WEM to JP	WEM to 124/102	WEM to 99/102	WEM to 79/106	WEM to Cap
Distance (km)	2	4.3	8.6	12	15.1	22
Time Period		5		12.5	20	
AM Peak (05:30-08:59)	11	9.1	6.8	11.1	10.6	10.5
Midday (09:00-14:59)	9.9	8.8	9.7	11	10	9.4
PM Peak (15:00-17:59)	9.5	8.6	9	11.5	10.8	12.1
Early Evening (18:00-21:59)	7.9	I/D	9	9.8	9.1	9.2

Along eastbound, similar relationship between the CoV of travel time and delay per traveller is observed, referred to Table 3-9 and Table 3-39. Passenger travelling between WEM and ML experienced higher delay than travelling between WEM and JP. Eastbound passengers who travelled from WEM to Cap experienced higher delay after the general stop 124/102 during all four time periods. Based on the results shown in Table 3-39, delays during the PM peak are comparatively higher than during the AM peak after JP. Delay during midday is higher than early evening referred to the results shown in Table 3-39 .

Peak hour buses will face more traffic congestion than during other time periods. It may take more time for them to travel the same distance, which is reflected by this performance measure. The delay for passengers is proportional to the delay or loss of the agency or operator. In other words, it would take more time for an operator to finish his/her job, due to the delay. Based on the results shown in the above tables, bus service performance in terms of efficiency is better during off-peak hours compared to peak hours.

Capacity utilization

The term "capacity" refers to the passenger carrying capacity of a bus. This measure compares the average on-board passenger volume to the seat capacity of a regular diesel bus. Thus, the average number of on-board passengers at all 80 bus stops is determined for each direction. Then, the average on-board passenger number between each set of timing points is determined using the average number of on-board passenger departing bus stops in between those timing points. Normally, clean diesel buses run on Route 1, and those buses have a seat capacity of 40.

Table 3-40 Capacity utilization westbound (segment-based)

Segment	Cap to 79/106	79/106 to 101/JA	101/JA to 122/102	122/102 to JP	JP to ML	ML to WEM
Distance (km)	6.9	3.8	2.8	4.4	2.3	2
Time Period		0.8	0.4	0		
AM Peak (05:30-08:59)	0.24	0.5	0.41	0.44	0.36	0.27
Midday (09:00-14:59)	0.28	0.4	0.56	0.52	0.52	0.45
PM Peak (15:00-17:59)	0.39	0.45	0.74	0.66	0.68	0.54
Early Evening (18:00-21:59)	0.47	0.5	0.75	0.72	0.63	0.54

Based on the results shown in Table 3-40, all capacity utilization values are lower than 0.8, which is favorable for passengers regarding their comfort. But ratios lower than 0.5 indicates unproductive service from the agency's point of view. Bus capacity is favourably utilized after midday along westbound, especially at the upstream of 122/102. Capacity utilization is comparatively higher for segments between the downtown (101/JA) and JP. Moreover, the capacity of buses is highly utilized along Jasper Avenue between 101/JA and 122/102 after AM peak. The capacity utilization during early evening is higher than during the AM peak. The result of the capacity utilization in eastbound direction is shown in Table 3-41.

Table 3-41 Capacity utilization eastbound (segment-based)

Segment	WEM to ML	ML to JP	JP to 124/102	124/102 to 99/102	99/102 to 79/106	79/106 to Cap
Distance (km)	2	2.3	4.3	3.4	3.1	6.9
Time Period		0.8		0.4	0	
AM Peak (05:30-08:59)	0.24	0.34	0.48	0.56	0.25	0.21
Midday (09:00-14:59)	0.41	0.46	0.5	0.52	0.36	0.29
PM Peak (15:00-17:59)	0.68	0.71	0.61	0.64	0.75	0.46
Early Evening (18:00-21:59)	0.73	0.73	0.72	0.7	0.66	0.43

In terms of capacity utilization, the same trend is observed along eastbound. Capacity utilization is lower during the morning than during any other period throughout the day. Also, capacity utilization is comparatively higher along segments between JP and 99/102 based on the results shown in Table 3-41.

The thorough discussion of capacity utilization of Route 1 reveals that passengers can comfortably use this bus route for everyday travelling. But, the productivity of this route is moderate from the perspective of agency. Passengers mostly used this bus route for travelling between downtown (99/102) and Jasper Place Transit Centre. However, significant capacity utilization is observed for entire route along westbound and eastbound direction during PM peak and early evening. Therefore, the capacity utilization of Route 1 is quite satisfactory, especially after the AM peak.

Planning time index

Planning time index assesses the efficiency of Route 1 by comparing the maximum and minimum time required to complete a certain distance. The maximum travel time is assumed as the 95th percentile value of observed travel times, and the minimum time is taken as the free flow travel time. The maximum travel time will be greater than minimum travel time, and this can be explained by the values shown in Table 3-42 and Table 3-43, which are all greater than one. A higher value indicates longer travel time should be planned by the passenger, in order to reach their destination on time.

Table 3-42 Planning time index westbound (origin-based)

Segment	Cap to 79/106	Cap to 101/JA	Cap to 122/102	Cap to JP	Cap to ML	Cap to WEM
Distance (km)	6.9	10.7	13.5	17.9	20.2	22.2
Time Period	1		5.5		10	
AM Peak (05:30-08:59)	3.89	4.28	4.14	5.97	4.78	3.97
Midday (09:00-14:59)	2.9	3.44	3.68	5.16	4.1	3.38
PM Peak (15:00-17:59)	5.33	5.31	4.89	6.21	5.09	4.28
Early Evening (18:00-21:59)	3.37	3.78	3.76	5.28	3.97	3.37

A direct and positive relationship between the variation in travel time and planning time index is observed after comparing results in Table 3-12 and Table 3-42. Based on the results shown in Table 3-42, higher values are observed during the AM and PM peak hours along westbound. Therefore, passengers travelling in those time periods have to allocate more time to journey planning. The results also indicate that passengers who are travelling during early evening need to allocate more extra time than those who are travelling during other off-peak hours.

Table 3-43 Planning time index eastbound (origin-based)

Segment	WEM to ML	WEM to JP	WEM to 124/102	WEM to 99/102	WEM to 79/106	WEM to Cap
Distance (km)	6.9	10.7	13.5	17.9	20.2	22.2
Time Period	1		5.5		10	
AM Peak (05:30-08:59)	4.85	3.66	2.42	3.7	3.43	3.98
Midday (09:00-14:59)	4.34	3.68	3.41	3.57	3.29	3.45
PM Peak (15:00-17:59)	3.7	3.52	3.18	3.78	3.53	4.24
Early Evening (18:00-21:59)	3.4	I/D	3.3	3.31	3.06	3.7

For eastbound, the planning time index values during peak hours are higher than during off-peak hours in most cases based on the results shown in Table 3-43. However, higher values of the planning time index are observed during midday than during the PM peak up to 124/102. In addition, the planning time index values are comparatively higher during midday compared to all other off-peak hours.

3.5 Summary

The performance assessment framework developed in this chapter focuses on the reliability and efficiency of Route 1 in the City of Edmonton. The framework evaluated and calculated 16 selected measures. Variation of service or reliability is categorized into the variation in travel time, schedule adherence, headway and wait time. Based on the travel time variation results, Route 1 performance is quite satisfactory based on the developed scale, except in the WB segment from Capilano (Cap) to 79 Street & 106 Avenue (79/106) during PM peak, and WEM to JP (eastbound) during both AM and PM peak. The results of the variation in schedule adherence showed that CoV of departure times of Route 1 is satisfactory at all timing points, but the on-time performance (% earliness and lateness) is not satisfactory at timing point. This indicates that holding strategy at timing point and schedule of Route 1 are required to improve. The headway variation along westbound shows similar pattern compared to travel time variation along westbound. Along eastbound direction, higher variation in headway is observed after 124/102 during AM peak, PM peak and early evening periods. High CoV of headway-based excess wait time is observed along both bounds during all four time periods. The value of schedule-based excess wait time varies between 2 minute and 10 minutes for passenger travelling along westbound direction. Besides excess wait time, passengers are required to budget maximum 4 minutes to 20 minutes of buffer time. For eastbound direction, the schedule-based excess wait time varies from 2 minute to 13 minutes, and the budgeted wait time varies from 2 minutes to 11 minutes. The efficiency of Route 1 is evaluated with the travel time ratio, delay per traveller, capacity utilization and planning time index. Variation in service affects efficiency of Route 1. Therefore, locations, directions and time periods with high variation in service present lower efficiency than other cases.

CHAPTER 4. RELIABILITY IMPROVEMENTS USING SLACK TIME

This chapter introduces a framework for improving the reliability of a bus route, by developing schedules that include slack times. A stochastic optimization process is applied to find optimal slack times at predefined stops along a bus route. Schedule adherence, bus driver's behaviours towards schedule adherence and model robustness are considered in the model. The optimization model results are tested in the VISSIM simulation model. Simulation results are analyzed to evaluate bus service performance with slack times.

4.1 Introduction

The framework proposed a planning-level approach to improve reliability of a bus route service through scheduling. A stochastic optimization model is used to determine the optimal slack times to build into a bus schedule on a given route. Schedule is defined as the scheduled travel time of a bus route, which is the summation of average travel time and slack time. A well-chosen slack time can balance lateness and earliness of buses at a timing point. In other words, an optimal scheduled travel time will help to reduce the difference between the scheduled departure time and actual departure time, also called schedule deviation. In this modeling framework, robustness of a slack time is also considered. A robust slack time is that slack time which will reduce the variation of schedule deviation. Thus, in the objective function of the optimization model, variation in schedule deviation is minimized to increase the applicability of newly developed schedules.

4.2 Modeling Framework

The slack time optimization model is adopted from Yan, et al. (2012). Stochastic optimization has been applied to solve the schedule-based holding problem in the literature (Carey 1994, Furth and Muller 2007, Oort, Boterman and Nes 2012, Zhao, et al. 2013). In this particular framework, a general bus corridor is considered, presented in Figure 4-1.

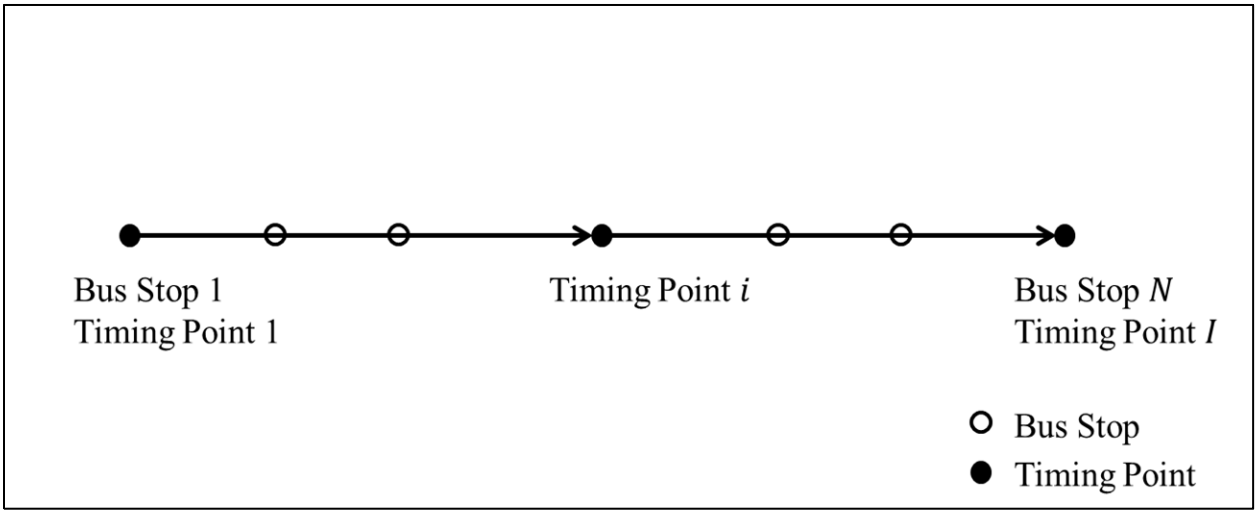

Figure 4-1 Model bus corridor

The bus corridor consists of N bus stops. Some of these stops are timing points, including the origin and destination stops. The number of timing points I, is always less than the number of bus stops n, along the corridor. Only one bus route is considered here. Travel time between two consecutive timing points, $i-1$ and $i-$ $T_{i-1,i}$ – is defined as the difference between the arrival times at those timing points. So, $T_{i-1,i}$ includes link travel time as well as dwell time (difference between stop arrival and departure times) at timing point $i-1$. Another important assumption in this model is that $T_{i-1,i}$ is a random variable with known probability distribution. The equation for the travel time between stops $i-1$ and i is expressed as (Yan, et al. 2012):

$$T_{i-1,i} = AAT_i - AAT_{i-1}, \qquad i \in I, i = 1, \dots, I \tag{23}$$

Where

- $T_{i-1,i}$ is the travel time between stops $i-1$ and i; and
- AAT_i is the actual arrival time at timing point i, $AAT_i \geq 0$.

The scheduled travel time between two consecutive timing points is the sum of expected travel time and the allocated slack time. It is assumed that the bus is always available for departure at the starting bus stop. Thus, bus will always arrive at the starting stop at the scheduled arrival time. Based on this assumption, the scheduled arrival time at first timing point is a known quantity. The scheduled travel time is given by the following expression:

$$ST_{i-1,i} = E(T_{i-1,i}) + \tau_{i-1,i}, \qquad i \in I, i = 1, \dots, I \tag{24}$$

Where

- $ST_{i-1,i}$ is the scheduled travel time between $i-1$ and i;
- $E(T_{i-1,i})$ is the expected travel time from $i-1$ to i; and
- $\tau_{i-1,i}$ is the slack time considered between timing points $i-1$ and i.

This scheduled travel time can be used to find the schedule arrival time at the destination timing point i:

$$SAT_i = SAT_{i-1} + ST_{i-1,i}, \qquad i \in I, i = 1, \dots, I \tag{25}$$

Where

- SAT_i is the scheduled arrival time at i.

Schedule deviation is the time difference between the schedule arrival time and the actual arrival time at a timing point, expressed as:

$$SD_i = SAT_i - AAT_i, \qquad i \in I, i = 1, \dots, I \tag{26}$$

Where

- SD_i is the schedule deviation at i.

SD_i can be positive or negative. In this model, positive schedule deviation indicates that a bus is early at timing point i, while negative values indicate lateness. The next important assumption is that bus operators will speed up to minimize their lateness and slow down to minimize earliness to timing points. This behaviour is captured by an adjustment quantity (Yan, et al. 2012):

$$A_{i-1,i} = \beta_{i-1,i}(SAT_{i-1} - AAT_{i-1}), \qquad i \in I, i = 1, \dots, I \tag{27}$$

Where

- $A_{i-1,i}$ is the adjustment in schedule deviation by operator travelling from $i-1$ to i; and
- $\beta_{i-1,i}$ is the operator adjustment factor, which is randomly distributed from 0 to 1.

Usually, the behaviour of operators towards schedule adherence varies. Therefore, $\beta_{i-1,i}$ is a random variable. Based on equation (24), the operator's adjustment $A_{i-1,i}$ mainly depends on the schedule deviation SD_i. If operator observed high schedule deviation at $i-1$, his or her tendency would be to catch up to the scheduled arrival time at i. Since schedule deviation at starting stop is always assumed to be zero, the adjustment factor $\beta_{1,2} = 0$. However, operators must abide by traffic laws and therefore may not always be able to entirely absorb schedule deviations. This remaining schedule deviation will then propagate downstream. The remaining schedule deviation (after the operator's efforts) can be expressed as:

$$RA_{i-1,i} = (1 - \beta_{i-1,i})(SAT_{i-1} - AAT_{i-1}), \qquad i \in I, i = 1, \dots, I \tag{28}$$

Where

- $RA_{i-1,i}$ is the remaining schedule deviation at i.

By replacing the SAT_i and AAT_i in equation (24), the equation for schedule deviation is rewritten as follows:

$$SD_i = E\left(T_{i-1,i}\right) + \tau_{i-1,i} - T_{i-1,i} + \left(1 - \beta_{i-1,i}\right) SD_{i-1} \tag{29}$$

Since both travel time and the operator adjustment factor are random variables, schedule deviation is also a random variable. Both earliness and lateness count as schedule deviation, but their impact on reliability differs. Therefore, it is necessary to account for both, but separately. This is done through the "generalized schedule deviation", which is the summation of schedule deviations for both early and late buses at a timing point i (Yan, et al. 2012). Different weighting factors are used for earliness and lateness, in order to be able to regulate for their individual impacts. The equation for generalized schedule deviation is expressed below (Yan, et al. 2012):

$$\begin{aligned} GSD_i(\tau, T, \beta, \gamma_1, \gamma_2) \\ = \gamma_1 * \max(SD_i(\tau, T, \beta), 0) + \gamma_2 * \max(-SD_i(\tau, T, \beta), 0) \end{aligned} \tag{30}$$

Where

- GSD_i is the generalized schedule deviation at i; and
- γ_1, γ_2 are the weighting factors for early and late buses, respectively, $\gamma_1, \gamma_2 \in \mathbb{R}$.

The primary objective of this problem is to find slack times that minimize schedule deviation. When slack times are increased, bus lateness is reduced but buses will also arrive early more frequently. Early arrival of bus at timing point will increase wait time for on-board passengers. A timing point with high percentage of early arrival indicates that assigned slack time is excessive, and then it is required to reduce that slack time. Determination of slack time based on only the minimization of schedule deviation can increase variation in schedule deviations. Therefore, it will be favourable to find a slack time which can not only reduce the schedule deviation bus also reduce the variation in schedule deviation. According to Yan, et al. (2012), the minimization of variation in schedule deviation can help to increase robustness of a model, and this is included as the objective of this model. Therefore, the objective of this model is to minimize the sum of $GSD_i(\tau, T, \beta, \gamma_1, \gamma_2)$ and variability in schedule deviation. The variability in schedule deviation is the average of absolute differences between the absolute schedule deviations and average of absolute schedule deviation.

The objective function is written as follows (Yan, et al. 2012):

$$\min_{\tau_{i-1,i}} \left(\sum_{i=1}^{I} \left[E\left(GSD_i(\tau, T, \beta, \gamma_1, \gamma_2)\right) + \lambda \times E\left(\left| |SD_i(\tau, T, \beta)| - E(|SD_i(\tau, T, \beta)|) \right| \right) \right] \right) \quad (31)$$

Subject to:

$$\sum_{i=1}^{I} \tau_{i-1,i} \leq \frac{h \times N}{2} - C \quad (32)$$

Where

- $\tau_{i-1,i}$ is the slack time considered between timing points $i-1$ and i;
- $T_{i-1,i}$ is the travel time between timing points $i-1$ and i;
- $\beta_{i-1,i}$ is the adjustment factor;
- γ_1, γ_2 are the weighting factor for early and late buses;
- λ is the weighting factor for model robustness, $\lambda \in \mathbb{R}$;
- h is the schedule headway;
- N is the number of buses deployed for a specific route; and
- C is the half cycle time assigned for a specific run.

The decision variable of this model is slack time $\tau_{i-1,i}$. The constraint sets an upper bound on the sum of all slack times along the route. The total slack time is allocated from the allowable time other than the service recovery time (Wirasinghe and Liu 1995). For a round trip, the half cycle time is the summation of average travel time for traversing entire corridor in one direction and recovery time, assigned at the end stop. The average travel time is determined by using the average speed of the bus and the distance of the corridor.

Since schedule deviation is typically assumed to be normally distributed, the expected value terms in the objective function (Equation 24) are not closed form. Therefore the problem is solved for a sufficient number of realizations. Monte-Carlo simulation is used to simulate K number of SD_i from K number of simulated travel times (Yan, et al. 2012). Then the optimization formulation for K realization of $GSD_i(\tau, T, \beta, \gamma_1, \gamma_2)$ can be expressed as (Yan, et al. 2012):

$$\min_{\tau_{i-1,i}} \left(\frac{1}{K} \times \sum_{k=1}^{K} \sum_{i=1}^{I} GSD_i\left(\tau, T^{(k)}, \beta^{(k)}, \gamma_1, \gamma_2\right) + \frac{\lambda}{K} \times \sum_{k=1}^{K} \sum_{i=1}^{I} \left| \left| SD_i\left(\tau, T^{(k)}, \beta^{(k)}\right) \right| - E\left(\left| SD_i\left(\tau, T^{(k)}, \beta^{(k)}\right) \right| \right) \right| \right), (T, \beta) \in \{(T^{(k)}, \beta^{(k)}, k = 1, \ldots, K)\} \tag{33}$$

Subject to:

$$\sum_{i=1}^{I} \tau_{i-1,i} \leq \frac{h \times N}{2} - C \tag{34}$$

4.3 Experimental Setup

The process of developing and testing a bus route schedule is illustrated in the following Figure 4-2. In this setup, a new schedule founded from optimization is tested through simulation in VISSIM.

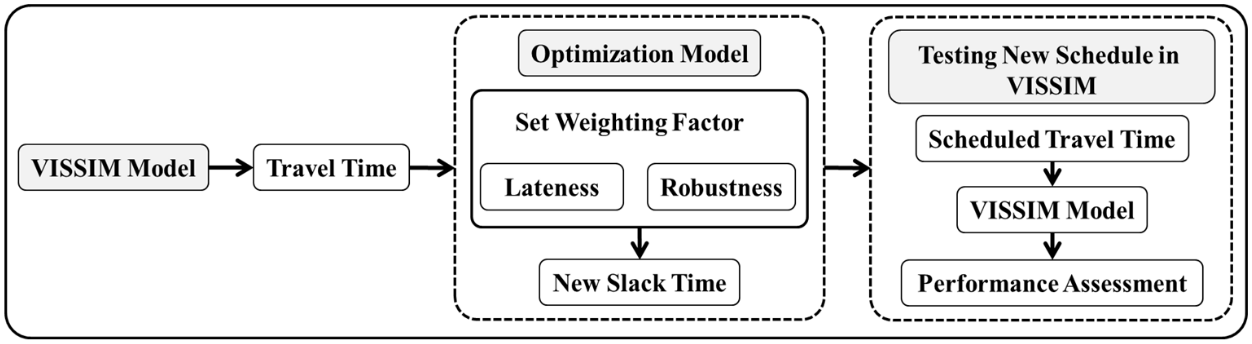

Figure 4-2 Experimental setup for schedule development and assessment

The experimental setup has two parts: optimization and simulation. The optimization is performed using MATLAB. The major input into the optimization is travel time, which in this study is generated from VISSIM, a microscopic multi-modal traffic flow simulation software package. Thus, the first step is to gather simulated travel times from VISSIM to initiate the scheduling process.

The detail process of developing simulation model of a bus corridor in VISSIM is given in Appendix C. The process includes six steps: 1) developing the roadway network, 2) traffic and pedestrian volume input, 3) configuring signal controller, 4) configuring public transit route and stop, 5) bus dwell time setting at bus stop, and 6) model calibration. This study develops schedule for two scenarios: the base case and the TSP case. Thus, two different VISSIM simulation models are developed. The base case presents a simulated corridor under existing situation, where no TSP is implemented. In the TSP case, all signalized intersections are equipped with TSP.

Travel times of an individual bus route from VISSIM are used to develop a new schedule through the optimization model described in Section 4.2. Different values of the weighting factors for lateness and robustness are applied in order to assess the impacts on the results. The increase of lateness weighting factor will increase the slack time to reduce the number of late departure from a bus stop. This will eventually increase the wait time of on-board passenger (early arrival) at timing point (holding early buses). This process of minimization of schedule deviation can increase the variation in schedule deviation. By increasing the robustness weighting factor, we can reduce the variation in schedule deviation. When slack time is increased with the increase of lateness weighting factor (because this makes lateness more “expensive”), then the increase of robustness weighting factor will reduce the slack time, to reduce the schedule deviation generated from earliness.

Based on the slack time results from the optimization model, a new schedule of a single route is developed. Here, schedule is defined as the scheduled travel time of a bus route, a summation of expected travel time and slack time (equation 24). After developing a new schedule, it is tested in VISSIM. Different service characteristics (travel time, schedule adherence and headway) are collected from the VISSIM simulation runs, to assess the performance of the bus service with the new schedule, and compare it against that of the old schedule.

4.4 Numerical Example

The experimental setup described above is applied in the eastbound direction of the West TSP corridor in the City of Edmonton. The corridor provides a vital connection between West Edmonton and the central business district. A map of the West TSP corridor is shown in the following figure.

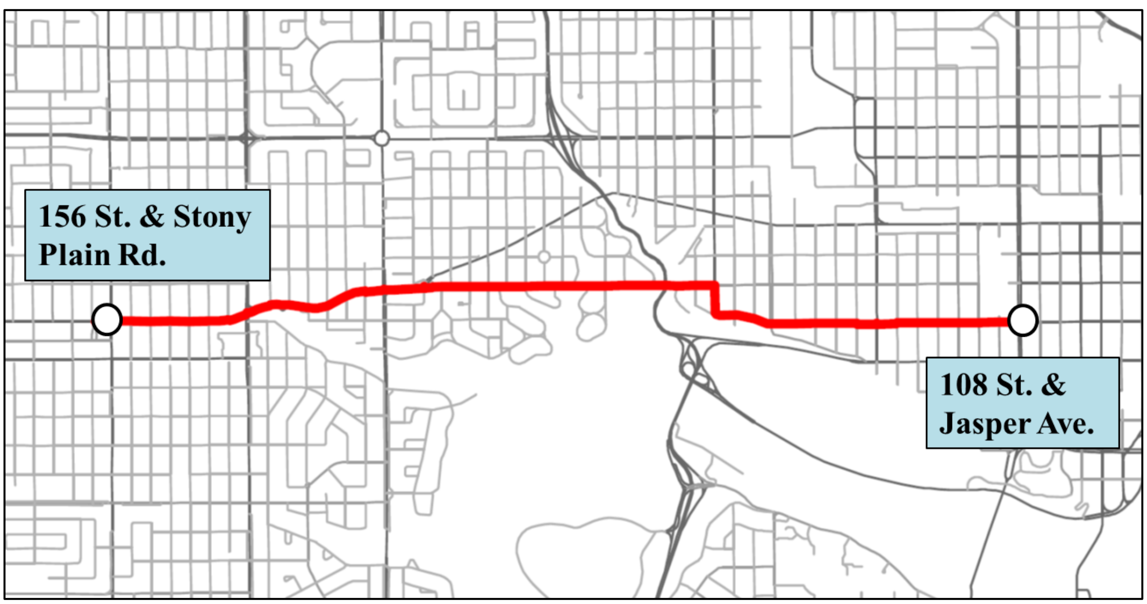

Figure 4-3 West TSP corridor

The West TSP corridor is called such as it has been identified as a candidate for TSP implementation by the Edmonton Transit Service (ETS). The corridor runs between 156 St. & Stony Plain Rd. and 108 St. & Jasper Ave. The corridor is six kilometres long with sixteen signalized intersections. There are 56 bus stops located along the corridor. 21 bus routes use this corridor, and among those bus routes, Route 1 is selected for analysis. Route 1 covers the whole corridor along eastbound direction. It goes through 26 bus stops in that direction. This experimental setup is focused on service during the AM peak travel period (6:45 AM- 8:45 AM). Two VISSIM microscopic simulation models of the West TSP corridor during AM peak were developed. One is for base condition and another is for TSP condition. In this study, active TSP was used. Active TSP includes two specific actions: 1) green extension and 2) red truncation. TSP 10 was coded in the ASC/3 emulator. TSP 10 means a TSP phase can have maximum 10 seconds green time extension or 10 seconds red time truncation, based upon bus detection. During VISSIM model building, geometry, traffic, transit, pedestrian and signal related data were provided by the City of Edmonton.

In this experimental framework, VISSIM is used to: 1) generate travel times to input in the optimization model, and 2) test the new schedule with slack times found from the optimization model. Before collecting travel times, it is necessary to validate the number of simulation runs for statistical significance. Results from Chebyshev's inequality formula indicating the number of simulation runs required for statistically significant results (Appendix C) are given in the following table:

Table 4-1 Validation of run numbers of simulation model

VISSIM Model	Simulation Run Number	k	Allowable % of obs. Within Limit	Travel Time, sec (Up-Limit)	Travel Time, sec (Lo-Limit)	% of obs. Within Limit
Base Model	20	2	75%	1391	1173	95%
TSP Model	20	2	75%	1142	992	95%

According to Chebyshev's inequality formula, 75% of travel time observations should lie between the upper and lower travel time limits. Base and TSP models were run for 20 times to collect total travel times along eastbound direction of whole corridor. After collection, Chebyshev's inequality formula was applied. Based on the results shown in Table 4-1, 95% of the observations of base and TSP model lie between the limits. Therefore, 20 simulation runs for both models are sufficient to move forward.

Next, timing points should be defined on the West TSP corridor. In this circumstance, the main focus is on some bus stops which are timing point candidates based on passenger activity and number of buses crossing the corridor. If the number of crossing buses is high, then that stop may be a major transfer point (of course, depending on the passenger activity). Based on this hypothesis, one existing bus stops is chosen as timing point. The starting and ending bus stops will also be selected as timing points. In this study, three timing points are considered for Route 1 along the West TSP corridor, and Route 1 with timing points identified is shown below:

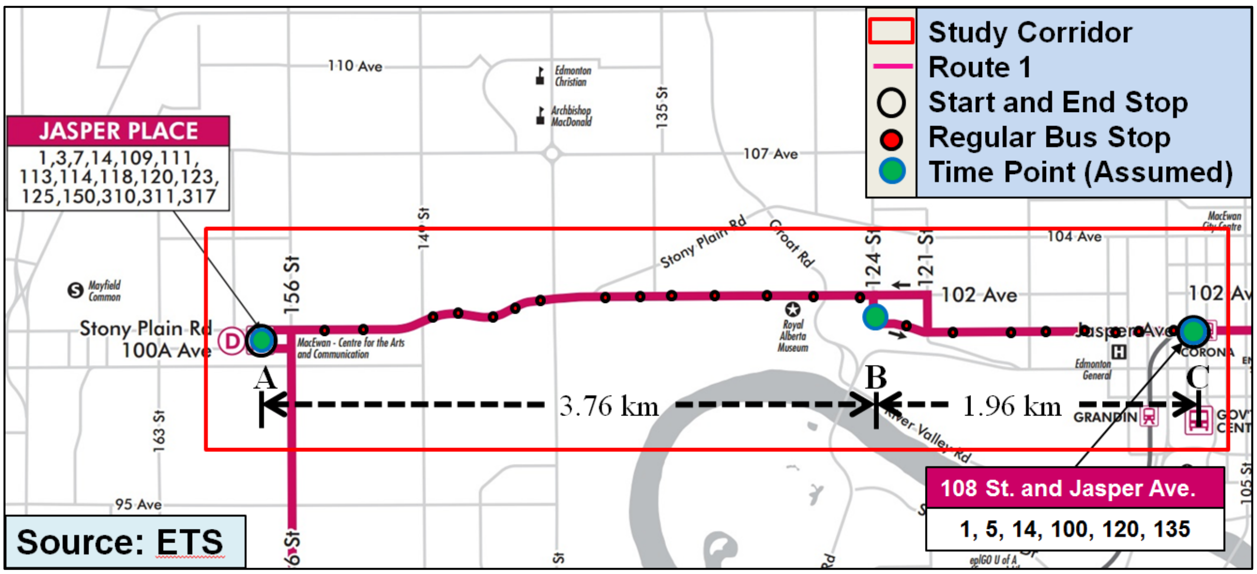

Figure 4-4 Study corridor with timing points (Eastbound direction only)

Based on Figure 4-4, Jasper Place Transit Centre (TC) is the first timing point, and it is indicated as “A”. Jasper Place TC is an existing timing point for Route 1. Two new timing points B and C are chosen for this study. Stop C is the end stop on this corridor for Route 1. Thus, stop C is taken as timing point.

It is already mentioned that Monte-Carlo (MC) simulation is used to simulate K realization of different parameters of the model. Before applying MC simulation, it is necessary to understand the distribution pattern of collected travel times between timing points. The following Figure 4-5 and 4-6 show the frequency distribution and Quantile-Quantile (Q-Q) plot of travel times from A to B and B to C.

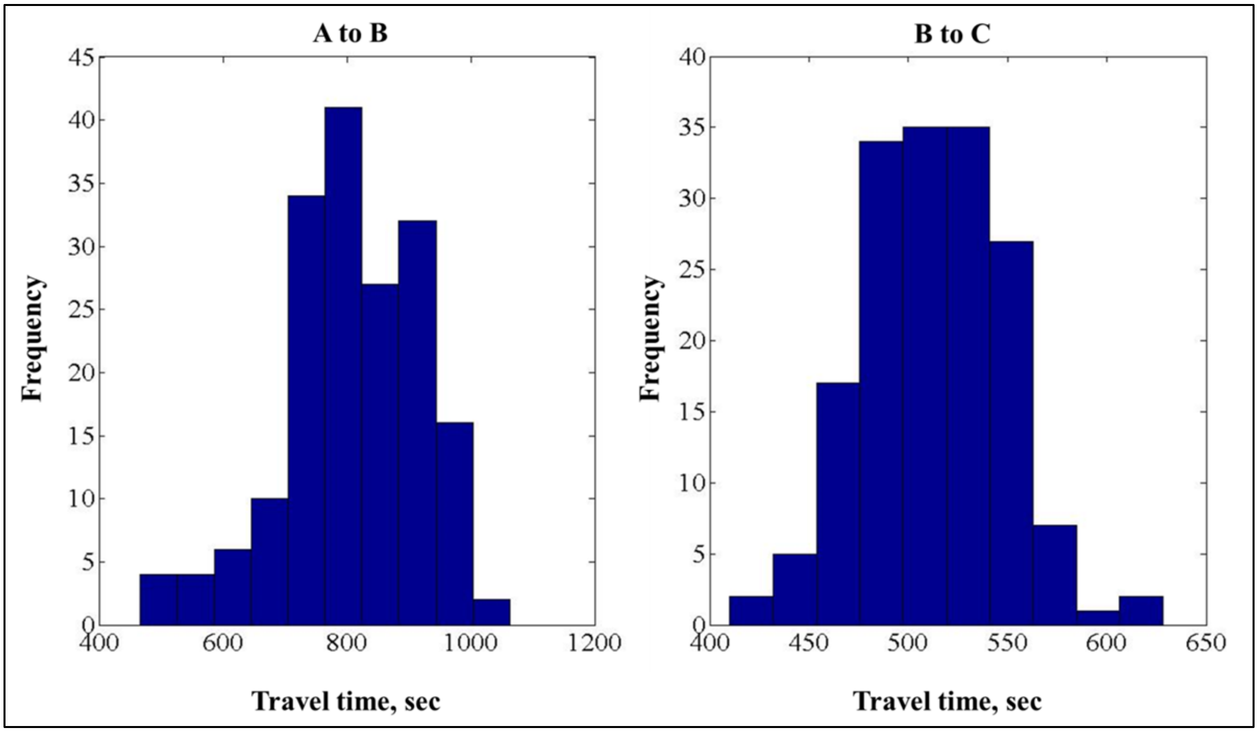

Figure 4-5 Frequency distribution of travel times

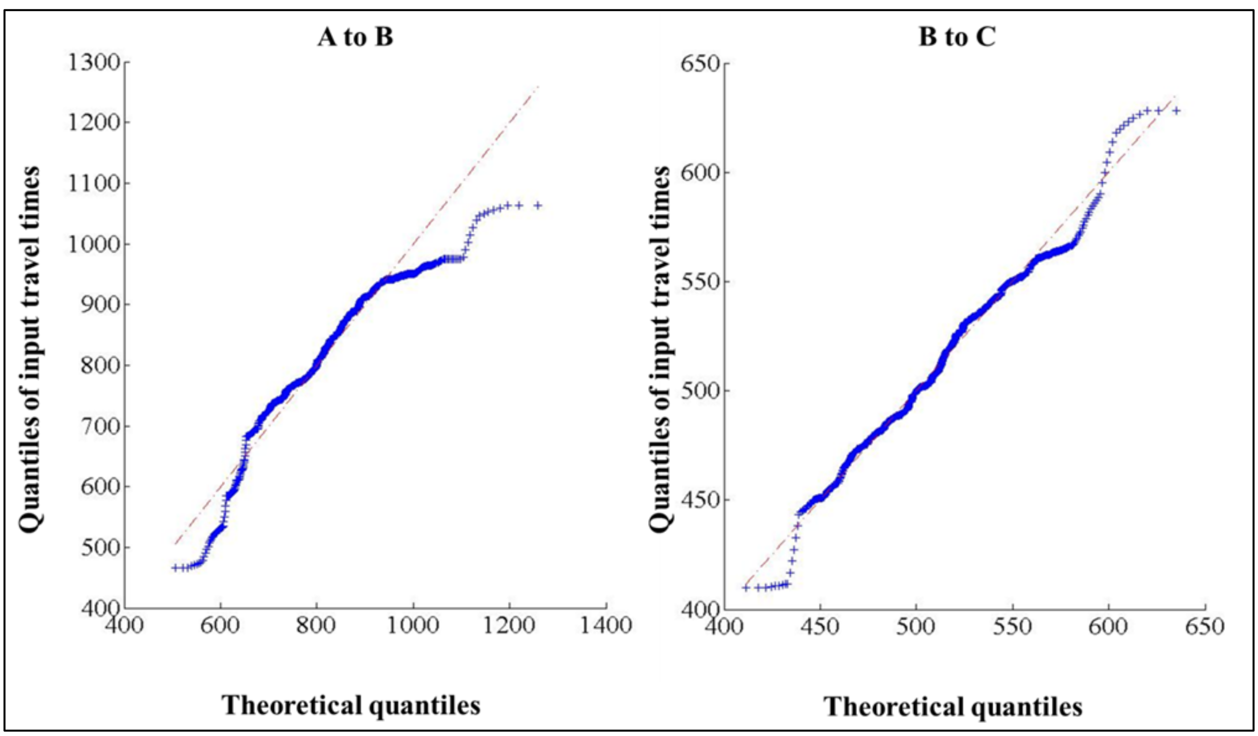

Figure 4-6 Q-Q plot of travel times

Based on the frequency distributions and Q-Q plot, distributions of travel times from A to B and B to C do not strictly follow the lognormal distribution, especially from A to B. However, many previous studies used the lognormal distribution for travel time or arrival time (Dessouky, et al. 1999, Chen and Zhou 2010, Zhao, et al. 2013). Despite the results, for simplicity the distribution of travel times between timing points were assumed to be lognormally distributed. From MC simulation, 500 travel times are generated for each segment (A to B and B to C). Lognormal sampling has two parameters, and both of them are required to draw sample. These are the log mean μ and log standard deviation σ of the MC simulated travel times. μ and σ can be expressed as the functions of mean m and variance v of sampling data. The functions are given below:

$$\mu = \log\left(\frac{m^2}{sqrt(v + m^2)}\right) \tag{35}$$

$$\sigma = sqrt\left(\log\left(\frac{v}{m^2 + 1}\right)\right) \tag{36}$$

Where

- μ is the log mean of the MC simulated data;
- σ is the log standard deviation of the MC simulated data; and
- m & v is the mean and variance of the samples respectively.

Simulated travel times between timing points are input to the optimization model to find slack times for both the base and TSP cases. Different weighting factors are considered to observe their effects on slack time (τ), generalized schedule deviation (GSD) and total cost (F). Five weighting factors are defined for this experimental setup: 1) $\gamma_{1,A,B}$, earliness weighting factor along segment A,B; 2) $\gamma_{1,B,C}$, earliness weighting factor along segment B,C; 3) $\gamma_{2,A,B}$, lateness weighting factor along segment A,B; 4) $\gamma_{2,B,C}$, lateness weighting factor along segment B,C; and 5) λ, robustness weighting factor of total system. In schedule-based holding strategy, early buses are held at the stop up to the scheduled departure time. On the other hand, schedule-based holding strategy has no influence over the late buses. Thus, weighting factor for lateness is changed to observe the effect on the system. In this numerical example, the importance of timing point B is higher than timing point C in terms of bus route reliability. If variation along segment AB is captured to a greater extent, then variation will not propagate rest of the corridor. Therefore, $\gamma_{2,A,B}$ is increased from 1 to 3 (in increments of 0.5) and keeping $\gamma_{1,A,B}$, $\gamma_{1,B,C}$, and

$\gamma_{2,B,C}$ constant at 1. The weighting factor for robustness λ is also changed from 1 to 3 (in increments of 0.5). Both $\gamma_{2,A,B}$ and λ are changed with an interval of 0.5. The effect of changing weighting factors $\gamma_{2,A,B}$ and λ on slack time $\tau_{A,B}$ at B is presented in the following Figure 4-7.

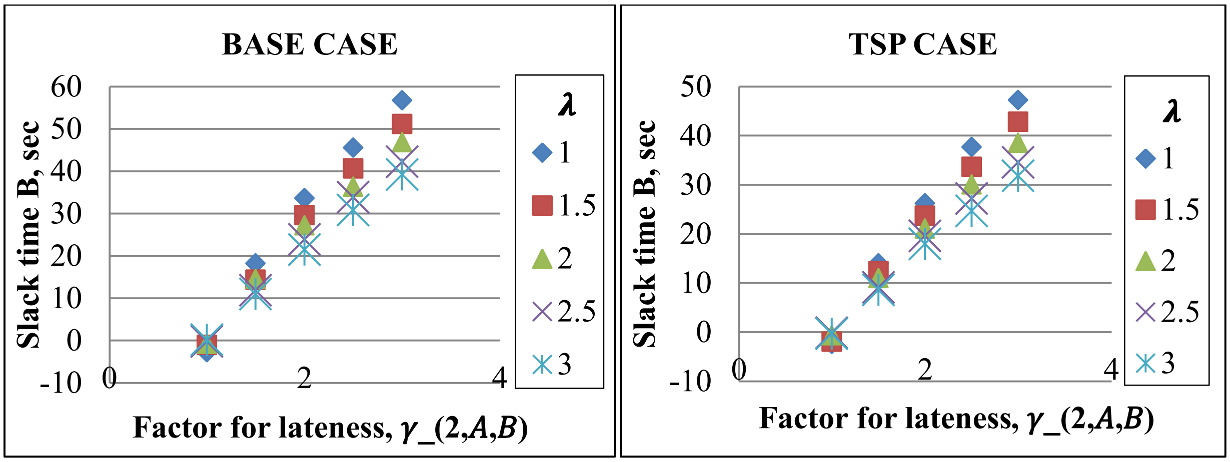

Figure 4-7 Response of slack time $\tau_{A,B}$with different strategies

Figure 4-7 presents the slack times at timing point B for the base case and TSP case. The increase of weighting factor of lateness along the segment A,B increases the slack time at B. Based on Figure 4-7, slack time values are reduced with the increase of weighting factor for robustness. Slack time increases cause increases in the variation of schedule deviation because of more bus earliness along the route. Reduction in lateness will cause increase in earliness. Since B is a timing point, it can hold those early buses. But, this will increase journey time of passengers using Route 1. The effect of changing weighting factors $\gamma_{2,A,B}$ and λ on slack time $\tau_{B,C}$ at C is presented in the following Figure 4-8.

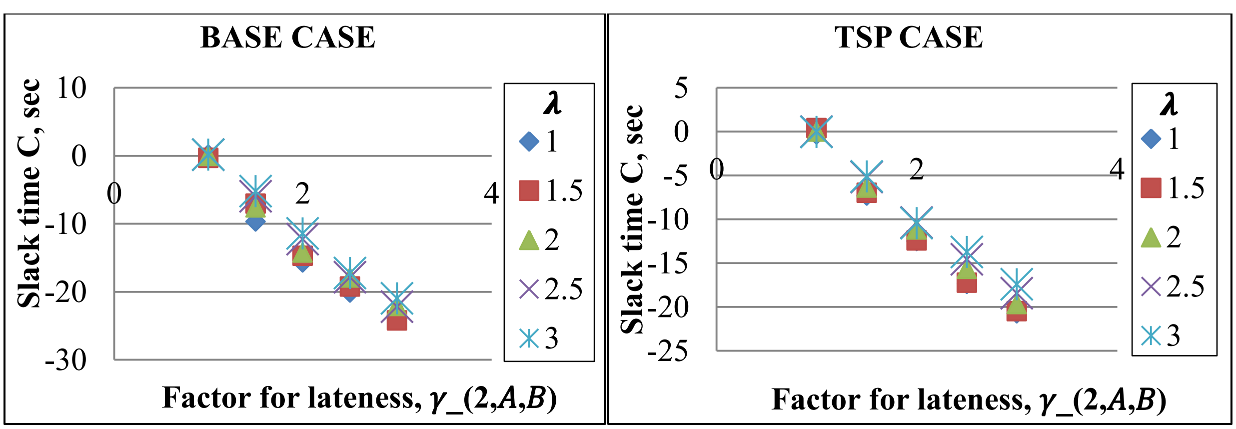

Figure 4-8 Response of slack time $\tau_{B,C}$ with different strategies

Increase of slack time at B will increase journey time for buses, especially early buses which are hold at B. This increase in journey time of buses can be suppressed by reducing slack time at timing point C, and this is observed in Figure 4-8. The increase of weighting factor for lateness along A,B decreases slack time at C. An opposite phenomenon is observed with weighting factor for robustness compared to Figure 4-7. The slack times at B is decreased with the λ, while the slack times at C is increased. The effect of changing weighting factors $\gamma_{2,A,B}$ and λ on generalized schedule deviation, GSD is presented in the following Figure 4-9.

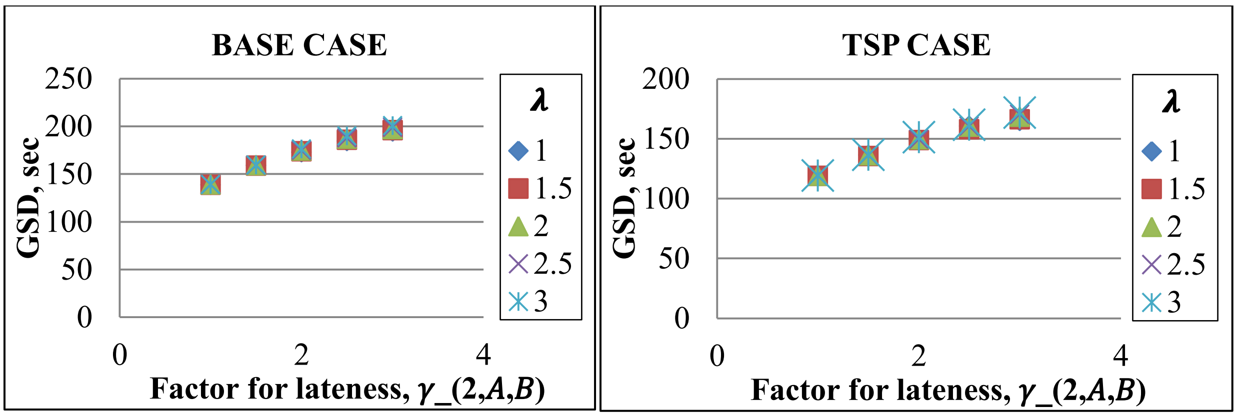

Figure 4-9 Response of GSD with different strategies

From Figure 4-9, the generalized schedule deviation is increased with increase in the weighting factor for lateness $\gamma_{2,A,B}$. However, the rate of increase in GSD is not that high. Interestingly, the effect of the weighting factor for robustness λ is marginal on GSD. The effect of changing weighting factors $\gamma_{2,A,B}$ and λ on total cost F is presented in the following Figure 4-10.

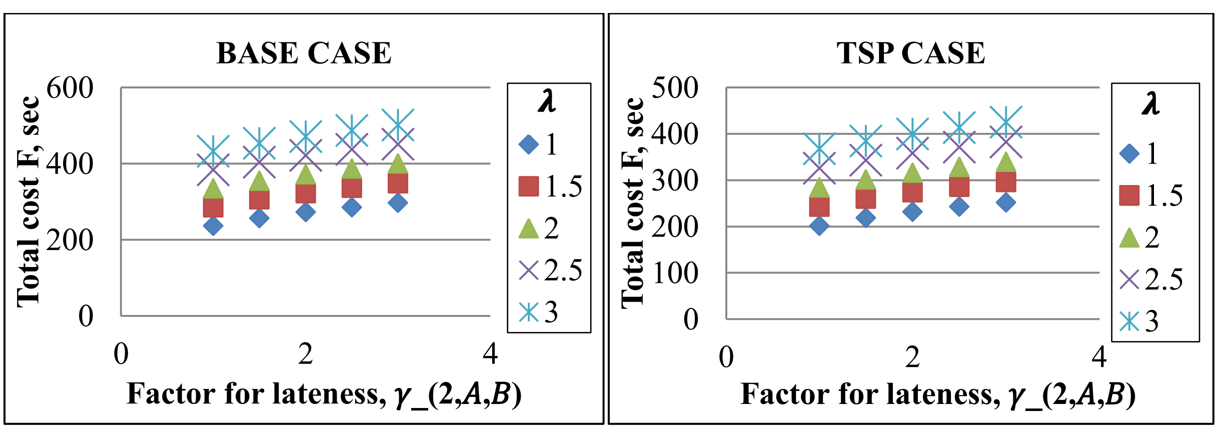

Figure 4-10 Response of F with different strategies

The value of the objective function is indicated as the total cost F, which includes total generalized schedule deviation, GSD and total variation in schedule deviation of the system. It is observed from Figure 4-10 that the increase of both $\gamma_{2,A,B}$ and λ increases the total cost. But, the rate of increase of total cost is higher for λ than $\gamma_{2,A,B}$.

For Base and TSP case, 25 slack times are determined for each timing points, for different combination of weighting factors, given in Appendix C. The scheduled travel time between timing points are determined from those slack times, by using equation 24. Four schedules based on new slack times are selected from the combinations of different schedules given in Appendix C. Table 4-2 shows those four new schedules.

Table 4-2 New schedules for further exploration in VISSIM

Schedule	Weighting Factors					Scheduled Departure Time (sec)					
	$\gamma_{1,A,B}$	$\gamma_{2,A,B}$	$\gamma_{1,B,C}$	$\gamma_{2,B,C}$	λ	Base Case			TSP Case		
						A	B	C	A	B	C
1	1	1	1	1	1	0	818	1357	0	680	1133
2	1	1	1	1	3	0	821	1360	0	682	1136
3	1	2	1	1	1	0	854	1377	0	709	1150
4	1	2	1	1	2	0	848	1372	0	703	1146

In schedule 1, all weighting factors are one, which indicates equal priority is given to lateness, earliness, and robustness. Then, maximum priority is given to the model's robustness by setting the factor to 3, while other factors are kept as one in Schedule 2. In Schedule 3, lateness of buses at timing point B is prioritized with a factor of 2, while other factors are one. Finally, similar priority is given to both the lateness at B and model's robustness. However, weighting factor for these two properties is higher than others. For different schedules, the scheduled departure times at timing points are presented in Table 4-2. Scheduled departure time is the summation of scheduled arrival time and average dwell time. Schedule arrival time at any timing point is the summation of scheduled arrival time at previous timing point and scheduled travel time between these two timing points. Here, scheduled travel time includes expected (average) travel time and slack time. Thus, scheduled departure time can be calculated by summing the expected travel time, slack time, and average dwell time. In VISSIM, timing point based schedule is coded in terms of scheduled departure time. Average dwell time was estimated from base and TSP VISSIM models. All new schedules for base case are coded in base VISSIM model, and new schedules for TSP case are coded in TSP VISSIM model. At this point, the study framework has ten VISSIM models: 1) Base model with existing schedule, 2) TSP model with no schedule, 3) Base with schedule 1, 4) Base with schedule 2, 5) Base with schedule 3, 6) Base with schedule 4, 7) TSP with schedule 1, 8) TSP with schedule 2, 9) TSP with schedule 3, and 10) TSP with schedule 4.

All ten simulation models are run 20 times in VISSIM. The Chebyshev's inequality formula is again applied for travel times resulted from all models, to verify number of runs, and satisfactory result is obtained from each model. For all models, 95% of the travel times are situated within the limit defined by the Chebyshev's inequality formula. The simulated information extracted from the VISSIM models include bus stop number, bus route number, arrival time, departure time, velocity, dwell time, boarding passenger count, alighting passenger count, and departing passenger count. Travel time, schedule adherence, and headway are calculated based on the outputs from the VISSIM models.

A comparative analysis is conducted to assess bus performance with new schedules. Some performance measures from Chapter 3 are chosen for use here. Selected performance measures are the total travel time, coefficient of variation of segment-based travel time, coefficient of variation of departure time, % earliness & lateness and coefficient of variation of headway. It is true that the total travel time and % earliness & lateness are not normalized measures. Measures such as total travel time can provide a good idea about the efficiency level. % earliness & lateness are both very popular reliability measures used in practice (Kittelson & Associates, Inc.; Brinckerhoff, Parsons; KFH Group, Inc.; Institute, Texas A&M Transportation; Arup 2013). Compared are: 1) the base existing schedule (BES) and base new schedule (BNS), 2) TSP no schedule (TnoS) and TSP new schedule (TnewS), and 3) the base existing schedule (BES) and TSP new schedule (TnewS).

The change in total travel time by new schedules is presented in the following Table 4-3.

Table 4-3 Total travel time (min)

Case	*Base: Existing Schedule (BES) VS New Schedule (BNS)*			
	BES	BNS	Diff (min)	% Diff
Schedule- 1	22.0	22.7	0.7	3
Schedule- 2		22.5	0.5	2
Schedule- 3		22.6	0.6	3
Schedule- 4		22.7	0.7	3
Case	*TSP: No Schedule (TnoS) VS New Schedule (TnewS)*			
	TnoS	TnewS	Diff (min)	% Diff
Schedule- 1	18.6	18.7	0.1	1
Schedule- 2		18.8	0.2	1
Schedule- 3		19.0	0.4	2
Schedule- 4		18.9	0.3	2
Case	*Base Existing Schedule (BES) VS TSP New Schedule (TnewS)*			
	BES	TnewS	Diff (min)	% Diff
Schedule- 1	22.0	18.7	-3.3	-15
Schedule- 2		18.8	-3.2	-15
Schedule- 3		19.0	-3	-14
Schedule- 4		18.9	-3.1	-14

Negative values indicate improvement in the travel time performance, and vice versa. Based on Table 4-3, total travel time is increased with slack time in the schedule. Comparison between base existing schedule (BES) and base new schedule (BNS) or TSP no schedule (TnoS) and TSP new schedule (TnewS) confirm this. A maximum of a 3% increase in travel time is observed during the comparison of base existing schedule (BES) and base new schedule (BNS). Under TSP scenario, increase in travel time is lower than base scenario. At timing points, lower slack time is required under TSP condition because TSP itself can reduce variation in travel time. The increment in lateness weighting factor increases slack time as well as the travel time. After comparing base existing schedule (BES) with TSP new schedule (TnewS), an improvement in travel time is observed. About, 15% reduction in travel time is observed. Therefore, implementation of slack time on the study corridor with active TSP can improve performance of Route 1 in terms of travel time.

The change in coefficient of variation (CoV) of segment-based travel time by new schedules is presented in Table 4-4.

Table 4-4 Coefficient of variation (CoV) of segment-based travel time

Segment	A to B				B to C			
Case	*Base: Existing Schedule (BES) VS New Schedule (BNS)*							
	BES	BNS	Diff	% Diff	BES	BNS	Diff	% Diff
Schedule- 1	0.31	0.31	0	0	0.38	0.08	-0.3	-79
Schedule- 2		0.33	0.02	6		0.06	-0.32	-84
Schedule- 3		0.32	0.01	3		0.06	-0.32	-84
Schedule- 4		0.32	0.01	3		0.06	-0.32	-84
Case	*TSP: No Schedule (TnoS) VS New Schedule (TnewS)*							
	TnoS	TnewS	Diff	% Diff	TnoS	TnewS	Diff	% Diff
Schedule- 1	0.14	0.14	0	0	0.09	0.07	-0.02	-22
Schedule- 2		0.15	0.01	7		0.07	-0.02	-22
Schedule- 3		0.14	0	0		0.05	-0.04	-44
Schedule- 4		0.14	0	0		0.06	-0.03	-33
Case	*Base Existing Schedule (BES) VS TSP New Schedule (TnewS)*							
	BES	TnewS	Diff	% Diff	BES	TnewS	Diff	% Diff
Schedule- 1	0.31	0.14	-0.17	-55	0.38	0.07	-0.31	-82
Schedule- 2		0.15	-0.16	-52		0.07	-0.31	-82
Schedule- 3		0.14	-0.17	-55		0.05	-0.33	-87
Schedule- 4		0.14	-0.17	-55		0.06	-0.32	-84

Comparison between base existing schedule (BES) and base new schedule (BNS) or TSP no schedule (TnoS) and TSP new schedule (TnewS) show no improvement in CoV of segment-based travel time along segment AB. While, CoV of segment-based travel time along BC is improved at a significant level, for all new schedules. For segment AB, no slack time is assigned at timing point A. Also, there is no timing point in between stop A and B. Thus, variation is travel time is not absorbed by new strategy. The CoV of segment-based travel time along AB for BES vs BNS and TnoS vs TnewS should be same, but a minor difference is observed. This might be due to randomness in traffic flow in VISSIM. Slack time is assigned at timing point B which helps to absorb variation along AB. Therefore, CoV of segment-based travel time along BC is comparatively lower in both BES vs BNS and TnoS vs TnewS. Implementation of TSP has a significant impact on the variation of travel time. Along segment A,B, the variation in travel time is reduced significantly, up to 55%. Therefore, the comparison between base existing schedule (BES) and TSP new schedule (TnewS) shows satisfactory improvement in CoV of travel time along the entire corridor. The effect of lateness weighting factor on CoV of travel time can explained by the results presented in Table 4-4, and the reduction in CoV is higher with high weighting factor for lateness along segment B,C.

The change in coefficient of variation (CoV) of departure time by new schedules is presented in Table 4-5.

Table 4-5 Coefficient of variation (CoV) of departure time

Bus stop	B				C			
Case	*Base: Existing Schedule (BES) VS New Schedule (BNS)*							
	BES	BNS	Diff	% Diff	BES	BNS	Diff	% Diff
Schedule- 1	0.022	0.014	-0.01	-36	0.022	0.017	-0.01	-23
Schedule- 2		0.011	-0.011	-50		0.014	-0.008	-36
Schedule- 3		0.008	-0.014	-64		0.014	-0.008	-36
Schedule- 4		0.012	-0.01	-45		0.014	-0.008	-36
Case	*TSP: No Schedule (TnoS) VS New Schedule (TnewS)*							
	TnoS	TnewS	Diff	% Diff	TnoS	TnewS	Diff	% Diff
Schedule- 1	0.02	0.01	-0.01	-50	0.02	0.01	-0.01	-50
Schedule- 2		0.009	-0.011	-55		0.01	-0.01	-50
Schedule- 3		0.008	-0.012	-60		0.01	-0.01	-50
Schedule- 4		0.008	-0.012	-60		0.01	-0.01	-50
Case	*Base Existing Schedule (BES) VS TSP New Schedule (TnewS)*							
	BES	TnewS	Diff	% Diff	BES	TnewS	Diff	% Diff
Schedule- 1	0.022	0.01	-0.012	-55	0.022	0.01	-0.012	-55
Schedule- 2		0.009	-0.013	-59		0.01	-0.012	-55
Schedule- 3		0.008	-0.014	-64		0.01	-0.012	-55
Schedule- 4		0.008	-0.014	-64		0.01	-0.012	-55

Reliability of bus route service in terms of variation of departure time is improved with new schedule based on Table 4-5. At both timing points B and C, CoV of departure time is decreased with BNS compared to BES. This indicates that the timing points B and C are working at a satisfactory level. The weighting factor for lateness is higher for schedule 3 than other schedules, and this is reflected in the CoV of departure time. The improvement of CoV of departure time at B and C with schedule 3, is comparatively higher than other schedules. TSP has a clear influence on the CoV of departure time. The improvement on CoV of departure time is higher with TnewS. Between timing points B and C, higher improvement is observed at B. This can be related with the slack time assigned at B.

The change in % earliness by new schedules is presented in the following Table 4-6.

Table 4-6 Percent earliness

Bus stop	B				C			
Case	*Base: Existing Schedule (BES) VS New Schedule (BNS)*							
	BES	BNS	Diff	% Diff	BES	BNS	Diff	% Diff
Schedule- 1	1	0	-1	-100	4	0	-4	-100
Schedule- 2		0	-1	-100		0	-4	-100
Schedule- 3		0	-1	-100		0	-4	-100
Schedule- 4		0	-1	-100		0	-4	-100
Case	*TSP: No Schedule (TnoS) VS New Schedule (TnewS)*							
	TnoS	TnewS	Diff	% Diff	TnoS	TnewS	Diff	% Diff
Schedule- 1	4	0	-4	-100	29	0	-29	-100
Schedule- 2		0	-4	-100		0	-29	-100
Schedule- 3		0	-4	-100		0	-29	-100
Schedule- 4		0	-4	-100		0	-29	-100
Case	*Base Existing Schedule (BES) VS TSP New Schedule (TnewS)*							
	BES	TnewS	Diff	% Diff	BES	TnewS	Diff	% Diff
Schedule- 1	1	0	-1	-100	4	0	-4	-100
Schedule- 2		0	-1	-100		0	-4	-100
Schedule- 3		0	-1	-100		0	-4	-100
Schedule- 4		0	-1	-100		0	-4	-100

From Table 4-6, % earliness is completely removed with all new schedules because schedule-based holding strategy holds early buses to schedule departure time. It is observed earlier that TSP reduces travel time for buses along the corridor. Therefore, the % earliness is increased for TnoS. Especially at C, 29% of buses are departed early, while the value was 4% with BES. Besides earliness, the % lateness is also influenced by the new schedule.

The change in % lateness with new schedules is presented in the following Table 4-7.

Table 4-7 Percent lateness

Bus stop	B				C			
Case	*Base: Existing Schedule (BES) VS New Schedule (BNS)*							
	BES	BNS	Diff	% Diff	BES	BNS	Diff	% Diff
Schedule- 1	84	21	-63	-75	66	9	-57	-86
Schedule- 2		19	-65	-77		6	-60	-91
Schedule- 3		7	-77	-92		9	-57	-86
Schedule- 4		17	-67	-80		9	-57	-86
Case	*TSP: No Schedule (TnoS) VS New Schedule (TnewS)*							
	TnoS	TnewS	Diff	% Diff	TnoS	TnewS	Diff	% Diff
Schedule- 1	45	9	-36	-80	2	12	10	500
Schedule- 2		10	-35	-78		11	9	450
Schedule- 3		4	-41	-91		4	2	100
Schedule- 4		5	-40	-89		8	6	300
Case	*Base Existing Schedule (BES) VS TSP New Schedule (TnewS)*							
	BES	TnewS	Diff	% Diff	BES	TnewS	Diff	% Diff
Schedule- 1	84	9	-75	-89	66	12	-54	-82
Schedule- 2		10	-74	-88		11	-55	-83
Schedule- 3		4	-80	-95		4	-62	-94
Schedule- 4		5	-79	-94		8	-58	-88

% lateness is also reduced with new schedule, and the % reduction is comparatively higher with high weighting factor for lateness than other schedules. It is also observed that reduction in the % lateness at C is comparatively higher than at B. This again indicates that a significant amount of variation in service characteristics is absorbed at B. Thus, a combined strength of both timing points is observed at C. The percentage of lateness is lower with TSP, compared to the BES. A significant reduction is observed at C where the % lateness is reduced from 66% to 2%. This definitely explains the impact of TSP towards reducing delay at signalized intersection. Moreover, TnewS shows better improvement in % earliness than BNS, especially at timing point B. From overall comparison, % lateness is greatly improved with TnewS compared to BES. The on-time departure from timing points and delay reduction at signalized intersection (because of TSP) should have influence on the variation or spread of headway.

The change in CoV of variation of headway by new schedules is presented in the following Table 4-8.

Table 4-8 Coefficient of variation (CoV) of headway

Bus stop	B				C			
Case	*Base: Existing Schedule (BES) VS New Schedule (BNS)*							
	BES	BNS	Diff	% Diff	BES	BNS	Diff	% Diff
Schedule- 1	0.11	0.08	-0.03	-27	0.13	0.08	-0.05	-38
Schedule- 2		0.08	-0.03	-27		0.08	-0.05	-38
Schedule- 3		0.06	-0.05	-45		0.08	-0.05	-38
Schedule- 4		0.07	-0.04	-36		0.09	-0.04	-31
Case	*TSP: No Schedule (TnoS) VS New Schedule (TnewS)*							
	TnoS	TnewS	Diff	% Diff	TnoS	TnewS	Diff	% Diff
Schedule- 1	0.07	0.06	-0.01	-14	0.09	0.07	-0.02	-22
Schedule- 2		0.05	-0.02	-29		0.07	-0.02	-22
Schedule- 3		0.05	-0.02	-29		0.07	-0.02	-22
Schedule- 4		0.06	-0.01	-14		0.08	-0.01	-11
Case	*Base Existing Schedule (BES) VS TSP New Schedule (TnewS)*							
	BES	TnewS	Diff	% Diff	BES	TnewS	Diff	% Diff
Schedule- 1	0.11	0.06	-0.05	-45	0.14	0.07	-0.07	-50
Schedule- 2		0.05	-0.06	-55		0.07	-0.07	-50
Schedule- 3		0.05	-0.06	-55		0.07	-0.07	-50
Schedule- 4		0.06	-0.05	-45		0.08	-0.06	-43

Along with other reliability measures, variation of headway is also reduced by using schedule-based holding strategy. By comparing BES and TnoS, variation in headway is reduced at both timing points with TSP along the corridor. However, the reduction in CoV is same at those stops. More than 50% of CoV of headway is reduced with TnewS compared to BES. Improvement in CoV of headway is higher with schedule 3 (high weighting factor for lateness) than other schedules.

The advantage of a schedule with slack time towards reliability of Route 1 is observed from the analysis of all simulation results. Implementation of new schedules in base VISSIM model results improvement in reliability, but travel time of Route 1 along the eastbound direction of the corridor is increased. All reliability-based performance measures indicate improvement in service with BNS compared to BES, except the CoV of segment-based travel time. Similar pattern is observed with TnoS and TnewS. The absence of timing point in between A and B can explain this pattern. During comparison of TnoS and TnewS, it is observed that travel time is reduced with TSP compared to existing situation. Not only travel time but also reliability is improved with TSP. This statement completely matched with the study conducted by Chang, et al (2003). After inspiring with this phenomenon, schedule-based holding strategy is applied on the study corridor with active TSP, and satisfactory performance of Route 1 is obtained. Under TnewS, both reliability and efficiency are improved compared to BES.

4.5 Summary

Reliability of a bus route service can be improved by implementing a new schedule with slack times on a transit signal priority (TSP) corridor. This has been demonstrated through a framework of determining and implementing slack time. The framework includes two major modeling processes: 1) slack time optimization model, and 2) VISSIM simulation model. Schedules of a route are developed from the optimization model, where travel time inputs are come from VISSIM model. After testing new schedules in VISSIM model, results of various performance measures are compared. The analysis indicated that a reliable system can be achieved with schedule-based holding strategy for a bus route running along a corridor with active TSP. However, implementation of schedule-based holding strategy without TSP can also improve reliability to a great extent but an increase in total travel time.

CHAPTER 5. CONCLUSION AND RECOMMENDATION

Service reliability is an important indicator of bus operational performance, and has been the subject of much attention in both the research and practice. This chapter discusses the major findings of this thesis research, and presents recommendations for future research.

5.1 Conclusions

The objective of this research is to assess and improve reliability of a bus route. The literature review on the bus service reliability reveals that there has been limited attention given to the development of a comprehensive reliability assessment framework. Previous studies mentioned that reliability can be improved by the schedule-based holding strategy. It is also observed in literature that transit signal priority (TSP) can also improve reliability. However, application of schedule-based holding strategy along the corridor with TSP can influence reliability of bus route(s). Therefore, this study has sought to answer two major questions: 1) How to develop a comprehensive performance assessment framework to evaluate reliability and efficiency? And 2) How to improve reliability of a bus route service with the schedule-based holding strategy?

The comprehensive performance assessment framework is developed through the processes of selection, evaluation, and calculation of measures. 16 appropriate measures were first selected, that were judged to best reflect bus service reliability and efficiency. In order to address reliability and efficiency from different perspectives, the quality of all measures were evaluated based on concern bodies (agency, operator & passenger), application level (stop, segment, direction, route & network) and service type (high & low frequency). Automatic Passenger Counter (APC) data from bus Route 1 of Edmonton Transit System (ETS) was used to calculate these measures. Route 1 runs between the West Edmonton Mall Transit Centre and the Capilano Transit Centre. It was observed that some of the reliability measures indicated Route 1 service to be reliable, while others indicated worse performance. For instance, the coefficient of variation (CoV) of travel time, CoV of departure time, and CoV of headway showed that the variation of travel time, departure time and headway is low. But % lateness and earliness showed weak performance of Route 1, and this results extra wait time for passengers using this route. This situation suggested exploring the possibility of an improved scheduling of Route 1. Moreover, Route 1 reliability is comparatively lower during peak hours than off-peak hours due to higher variation in passenger demand, control delay, and traffic along the route. Therefore, both agency and passengers are required to budget extra time to reach their destination. It was also observed that buses take more time for covering all segments than the scheduled travel time especially during peak hours. This indicates an efficiency loss of Route 1. The increase in travel time was anticipated with high passengers' delay per kilometre. Route 1 is very comfortable for passenger regarding the crowding situation throughout the day. For agency, capacity utilization is lower during the morning than any other periods till early evening.

The reliability assessment framework suggested improving the scheduling of Route 1. Under schedule-based holding strategy, early buses will be held at the timing point, based on slack time. In this study, a stochastic optimization model was developed finding robust slack time at timing points. The model also considered the operator's effort towards absorbing schedule deviation. VISSIM simulation model played an important part in this schedule development process. The study simulated the West TSP corridor in the City of Edmonton. This is called such as it has been identified as a candidate for TSP implementation by ETS. The corridor runs between 156 St. & Stony Plain Rd. and 108 St. & Jasper Ave. The major input of the optimization model is travel time which comes from VISSIM. New schedule was built with slack time, and was tested in VISSIM. With schedule-based holding strategy, the reliability of Route 1 along the eastbound direction improved. The CoV of travel time, CoV of departure time, % earliness, % lateness, and CoV of headway were reduced from the base existing schedule (BES) to base new schedule (BNS). But the total travel was increased by almost 3%. This increase in travel time can be compromised by using the active TSP coded in VISSIM model. The results from the comparison between base existing schedule (BES) and TSP new schedule (TnewS) indicated almost 15% decrease in travel time with the schedule-based holding strategy and active TSP. Not only travel time was improved, but also reliability-based performance measures showed highest improvement with TnewS.

5.2 Recommendations and Future Research

1. This research used APC data for 2 months for assessing performance of the Route 1. It would be better to have higher resolution data during assessment. In future, the assessment process can be extended with APC data for longer period.
2. There are two main reasons for getting lower sampling for APC data such as the penetration rate of APC equipped buses is low and bus stops with no passenger activity. Those problems can be resolved by using Automatic Vehicle Location (AVL) data. Thus, the framework for performance assessment can be updated with APC as well as AVL data.
3. The performance of Route 1 is assessed during the period of July to August 2014. But, cities in Canada can experience long winters with heavy snowfall. So, updating the framework to cover the winter periods can help to assess weather effects on the bus route service reliability and efficiency.
4. The study is solely concentrated on the assessment and improvement of reliability of a single bus route service. Application of the methodology of this study to another major bus corridor(s) or route(s) within the city can be a good way to extend this research.
5. Currently, there is no actual TSP implementation along the West Corridor. Thus, simulation data from VISSIM under TSP scenario is used in optimization model to develop schedule with TSP. The City of Edmonton has a plan to implement active TSP along this corridor in near future. Then, field data with real TSP can be used in the optimization model to verify the developed schedule.

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APPENDIX A

A sample of location reports collected from APC Database of ETS

ETS Automatic Passenger Count
Location Report
Bus Stop: 2301
Location: Capilano WN
Start Date: 6/29/2014
End Date: 8/30/2014

Sort Order	Time Period	Route	Run	Schedule Arrival	Schedule Departure	Observed Arrival	Observed Departure	Adherence Arrival	Adherence Departure	Action	Arrival Status?	Departure Status?	Ons	Offs	Depart Load	Ramp Deployed	Observed Date	Day Of Week	Calendar Events
1	Early Morning (03:00-05:29)	1	102		05:21	05:17:00	05:21:11		0.2				3	1	3		Jul 08, 2014	Tue	
1	Early Morning (03:00-05:29)	1	102		05:21	05:23:08	05:23:54		2.9			Departed Late	2	1	2		Jul 22, 2014	Tue	KDay
1	Early Morning (03:00-05:29)	1	102		05:21	05:20:26	05:22:11		1.2			Departed Late	1	0	2		Jul 25, 2014	Fri	KDay
1	Early Morning (03:00-05:29)	1	102		05:21	05:18:07	05:23:52		2.9			Departed Late	0	0	1		Jul 28, 2014	Mon	
1	Early Morning (03:00-05:29)	1	102		05:21	05:22:26	05:22:54		1.9			Departed Late	1	0	2		Jul 29, 2014	Tue	
1	Early Morning (03:00-05:29)	1	102		05:21	05:17:20	05:22:32		1.5			Departed Late	0	0	1		Jul 31, 2014	Thu	
1	Early Morning (03:00-05:29)	1	102		05:21	05:14:51	05:21:36		0.6				2	0	3		Aug 01, 2014	Fri	
1	Early Morning (03:00-05:29)	1	102		05:21	05:20:00	05:24:40		3.7			Departed Late	1	1	1		Aug 05, 2014	Tue	
1	Early Morning (03:00-05:29)	1	102		05:21	05:18:21	05:22:37		1.6			Departed Late	2	2	1		Aug 07, 2014	Thu	
1	Early Morning (03:00-05:29)	1	102		05:21	05:21:04	05:21:17		0.3				0	0	1		Aug 11, 2014	Mon	
1	Early Morning (03:00-05:29)	1	102		05:21	05:19:56	05:21:59		1				0	0	1		Aug 13, 2014	Wed	
1	Early Morning (03:00-05:29)	1	102		05:21	05:19:50	05:22:06		1.1			Departed Late	1	0	2		Aug 20, 2014	Wed	
1	Early Morning (03:00-05:29)	1	102		05:21	05:19:44	05:21:01		0				1	0	2		Aug 21, 2014	Thu	
1	Early Morning (03:00-05:29)	1	102		05:21	05:13:00	05:22:28		1.5			Departed Late	3	3	1		Aug 25, 2014	Mon	
1	Early Morning (03:00-05:29)	1	102		05:21	05:20:30	05:21:24		0.4				0	0	1		Aug 29, 2014	Fri	
2	AM Peak (05:30-08:59)	1	104		05:51	05:59:46	05:59:57		9			Departed Late	1	0	2		Jul 10, 2014	Thu	
2	AM Peak (05:30-08:59)	1	104		05:51	05:55:56	05:56:05		5.1			Departed Late	1	0	2		Jul 30, 2014	Wed	
2	AM Peak (05:30-08:59)	1	104		05:51	05:45:08	05:53:05		2.1			Departed Late	1	0	2		Aug 08, 2014	Fri	
2	AM Peak (05:30-08:59)	1	104		05:51	05:45:26	05:52:48		1.8			Departed Late	1	0	2		Aug 14, 2014	Thu	
2	AM Peak (05:30-08:59)	1	104		05:51	05:50:27	05:51:46		0.8				2	0	3		Aug 15, 2014	Fri	
2	AM Peak (05:30-08:59)	1	104		05:51	05:39:53	05:50:38		-0.4				3	2	2		Aug 18, 2014	Mon	
2	AM Peak (05:30-08:59)	1	104		05:51	05:42:34	05:51:22		0.4				2	0	2		Aug 28, 2014	Thu	
2	AM Peak (05:30-08:59)	1	3302	05:53		05:49:06	05:50:07	-3.9	-25.9			Left HOT	0	3	1		Jun 30, 2014	Mon	
2	AM Peak (05:30-08:59)	1	3302	05:53		05:48:56	05:50:37	-4.1	-25.4			Left HOT	0	4	1		Jul 02, 2014	Wed	
2	AM Peak (05:30-08:59)	1	3302	05:53		05:49:03	05:50:09	-4	-25.9			Left HOT	0	2	2		Jul 03, 2014	Thu	
2	AM Peak (05:30-08:59)	1	3302	05:53		05:47:31	05:47:47	-5.5	-28.2		Arrived Early	Left HOT	0	3	1		Jul 04, 2014	Fri	

APPENDIX

Descriptive statistics

Time Period	Indicator	
Early Morning (03:00-05:29)	1	"Neg" for negatively skewed distribution, "Neu" for neutral data sample, and "Pos" for positively skewed data sample. "Flat" for flatness of data sample, "Peak" for peakedness of data sample "Norm" for normal distribution
AM Peak (05:30-08:59)	2	
Midday (09:00-14:59)	3	
PM Peak (15:00-17:59)	4	
Early Evening (18:00-21:59)	5	
Late Evening (22:00-00:59)	6	
Owl (1:00-2:59)	7	

Descriptive statistics of segment-based travel time, westbound

Segment	Time period	Distance, km	Number of obs.	Mean, min	Median, min	Mode, min	Kurtosis	Comments
WEM to ML	1	6.9	0					
	2		111	20.5	18.3	16.2	0.6	Pos&Peak
	3		246	17.6	16.9	17.3	1.6	Pos&Peak
	4		124	22.3	20.1	24.4	2.4	Neg&Peak
	5		174	18.2	17	25.1	0.8	Neg&Peak
	6		58	15.3	15.1	15.7	0	Neg&norm
	7		0					
ML to JP	1	3.8	0					
	2		95	13.1	12.9	10.1	1.4	Pos&Peak
	3		106	13.3	13.1	12.6	1.1	Pos&Peak
	4		131	14.2	14	12.2	8.3	Pos&Peak
	5		118	13.1	13.2	11.4	-0.4	Pos&Flat
	6		58	12.3	12.3	12	1	Pos&Peak
	7		0					
JP to 124/102	1	2.8	0					
	2		126	13.9	14	14.2	-0.3	Neg&Flat
	3		260	12.6	12.3	11	0.9	Pos&Peak
	4		128	13.5	13.3	12.4	1.1	Pos&Peak
	5		171	12.9	12.9	11.6	1.2	Pos&Peak
	6		73	12.5	12.8	11.5	-0.4	Pos&Flat
	7		0					
124/102 to 99/102	1	3	0					
	2		111	10.1	9.7	8.5	0.1	Pos&Peak
	3		107	11.9	11.7	10.4	12	Pos&Peak
	4		125	13	12.7	9.4	0.7	Pos&Peak
	5		118	10.4	10.2	8.6	12	Pos&Peak

	6		73	9.8	9.8	8.6	0.2	Pos&Peak
	7		6	8.8	8.7	8.7	0	Pos&Peak
99/102 to 79/106	1	2.3	0					
	2		120	6	5.7	5.1	8	Pos&Peak
	3		106	6.2	6	5.9	1.9	Pos&Peak
	4		123	6.8	6.4	5.6	4.3	Pos&Peak
	5		131	6.7	6	5.7	0.7	Pos&Peak
	6		84	5.6	5.6	4.6	-0.7	Pos&Flat
	7		6	4.1	4.2		1.2	Uniform
79/106 to Cap	1	2	0					
	2		113	5.7	5.7	5.2	4.4	Pos&Peak
	3		106	6.2	5.8	4.9	5.9	Pos&Peak
	4		117	6.2	5.8	5.2	5.2	Pos&Peak
	5		131	5.9	5.5	5.7	5.3	Pos&Peak
	6		73	4.9	4.8	4.3	8.1	Pos&Peak
	7		21	4.3	4	8	3.1	Neg&Peak

Descriptive statistics of segment-based travel time, eastbound

Segment	Time period	Distance, km	Number of obs.	Mean, min	Median, min	Mode, min	Kurtosis	Comments
Cap to 79/106	1	2	41	5.3	5	4.8	14.2	Pos&Peak
	2		138	8	6.9	5.6	-0.7	Pos&Flat
	3		246	7.5	6.7	6.1	-0.2	Pos&Flat
	4		133	7.3	7.1	6.1	0	Pos&Norm
	5		193	6.5	6.4	6.2	0.3	Pos&Peak
	6		65	5.1	5	4	-0.3	Pos&Flat
	7		15	4.3	4.3		0	Uniform
79/106to 101/JA	1	2.3	26	4.7	4.5	4.5	2.2	Pos&Peak
	2		119	6.3	6	4.8	0.3	Pos&Peak
	3		223	6.5	6.3	8.1	10.8	Neg&Peak
	4		43	7.4	6.8		4.2	Uniform
	5		0					
	6		0					
	7		0					
101/JA to 122/102	1	4.3	26	8.9	8.7	7.8	-0.3	Pos&Flat
	2		133	12.3	12	12	0.6	Pos&Peak
	3		236	12	11.9	10.5	22.2	Pos&Peak
	4		124	12.7	12.5	11.1	2.8	Pos&Peak
	5		182	11.1	10.6	9.4	8.9	Pos&Peak
	6		77	9.7	9.3	9.5	0.6	Pos&Peak
	7		6	9.2	8.9		-1.2	Uniform

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122/102to JP	1		27	15	15.2		-1.1	Pos&Flat
	2		124	15.4	15.3	14.1	-0.3	Pos&Flat
	3		239	16.5	16.4	15.8	0.5	Pos&Peak
	4	3.4	120	17.5	17.7	13.8	-0.1	Pos&Flat
	5		196	15.5	15.4	15.1	1.8	Pos&Peak
	6		58	13.6	13.7	15	-0.8	Neg&Flat
	7		7	13	13		1.5	Uniform
JP to ML	1		0					
	2		125	8.5	8.2	10.4	2	Neg&Peak
	3		251	8.1	7.8	7	31.3	Pos&Peak
	4	3.1	135	9.2	9.1	8	10.8	Pos&Peak
	5		178	8.1	8	7.8	0.8	Pos&Peak
	6		58	8.4	8.2	7.2	-0.7	Pos&Flat
	7		0					
ML to WEM	1		0					
	2		137	15.5	15.2	13.4	1.7	Pos&Peak
	3		107	15.8	15.4	14.2	6	Pos&Peak
	4	6.9	107	20.6	18.1	15.6	0.3	Pos&Peak
	5		131	15.2	14.7	12.4	6.4	Pos&Peak
	6		58	14.9	15.1	13.8	0.3	Pos&Peak
	7		0					

Descriptive statistics of schedule adherence, westbound

Bus Stop	Time period	Number of observations	Mean, min	Median, min	Mode, min	Kurtosis	Comment
WEM	1	15	1.4	1.2		-0.1	Uniform
	2	127	-2.1	0	-9.5	-0.8	Pos&Flat
	3	265	0	0.2	-0.2	27	Pos&Peak
	4	142	-4.7	-2	-4.7	2	Pos&Peak
	5	180	-1.4	0.3	0.2	0.2	Pos&Peak
	6	58	2.1	1.6	4.4	0.6	Neg&Peak
	7	0					
ML	1	0					
	2	126	0.7	0.3	-0.2	4.7	Pos&Peak
	3	174	2.9	2	0.8	41	Pos&Peak
	4	141	1.4	0.9	-0.9	7.5	Pos&Peak
	5	191	0.9	0.4	-0.3	4.6	Pos&Peak
	6	64	1.7	0.8	-1.5	0.5	Pos&Peak
	7	0					
JP	1	8	1.7	1.2		-1	Uniform

	2	126	-2.4	-2.8	-4.3	6.6	Pos&Peak
	3	268	1	0.1	-2	20.1	Pos&Peak
	4	140	1.7	1.1	-0.8	10.1	Pos&Peak
	5	184	-0.2	-0.2	-0.8	2.4	Pos&Peak
	6	79	-0.7	-0.8	0.8	-0.3	Neg&Flat
	7	0					
124/102	1	0					
	2	133	0.8	0.3	0.1	14.7	Pos&Peak
	3	260	2.7	1.9	0.2	7.9	Pos&Peak
	4	137	2.9	2	0.2	6.4	Pos&Peak
	5	184	1.6	1	0.1	1.5	Pos&Peak
	6	88	0.9	0.5	-0.6	1.5	Pos&Peak
	7	6	1.8	1.6		-1.8	Uniform
99/102	1	10	-0.2	0.2		3.5	Uniform
	2	127	0.7	0.4	0.2	9.1	Pos&Peak
	3	259	2	0.8	-0.4	6.3	Pos&Peak
	4	139	1.6	0.7	0.3	5.4	Pos&Peak
	5	185	0.1	0.3	-0.1	15.3	Pos&Peak
	6	98	1.2	0.4	0.2	0.9	Pos&Peak
	7	5	0.7	0		-3.1	Uniform
79/106	1	0					
	2	137	1	0.9	0.1	15.6	Pos&Peak
	3	258	2.8	1.6	0.6	7.2	Pos&Peak
	4	123	3.3	2.3	0.3	7.7	Pos&Peak
	5	195	2.4	2.2	1.8	16.5	Pos&Peak
	6	91	2.6	2.3	2	1	Pos&Peak
	7	21	3.3	3.2		-1.1	Uniform
Cap	1	41	0.6	0.7	0.6	10.9	Pos&Peak
	2	148	-1.4	-0.4	-6	-0.7	Pos&Flat
	3	252	0.2	0.4	-3.6	6.9	Pos&Peak
	4	135	1	1.1	-2.3	4.9	Pos&Peak
	5	201	0.8	0.9	0.9	16.3	Ne&Peak
	6	65	0.6	0.4	-0.2	6.6	Pos&Peak
	7	15	1.9	2.1		0.4	Uniform

Descriptive statistics of schedule adherence, eastbound

Bus Stop	Time period	Number of observations	Mean, min	Median , min	Mode, min	Kurtosis	Comment
Cap	1	41	0.6	0.7	0.6	10.9	Pos&Peak
	2	148	-1.4	-0.4	-6	-0.7	Pos&Flat
	3	253	0.2	0.4	-3.6	6.9	Pos&Peak

	4	135	1	1.1	-2.3	4.9	Pos&Peak
	5	198	0.8	0.9	0.9	16	Ne&Peak
	6	65	0.6	0.4	-0.2	6.6	Pos&Peak
	7	15	1.9	2.1		0.4	Uniform
79/106	1	40	-0.01	0.04	-0.02	1.94	Pos&Peak
	2	138	0.2	0.1	-0.4	1.6	Pos&Peak
	3	253	1.4	0.8	-0.4	20.4	Pos&Peak
	4	140	2.9	2.8	1.1	10.6	Pos&Peak
	5	193	1.6	1.6	1.6	28.2	Neu&Peak
	6	71	0.4	0.1	0	0.4	Pos&Peak
	7	15	0.3	0.1	0.1	-1.5	Pos&Flat
101/JA	1	27	0	-0.1	-0.1	4.3	Pos&Peak
	2	142	0.1	0	-0.7	2.2	Pos&Peak
	3	255	0.4	0.2	0.2	51.4	Pos&Peak
	4	147	1.2	0.6	-0.1	12.6	Pos&Peak
	5	190	0.4	0.3	0.2	35.2	Pos&Peak
	6	83	0.7	0.3	0.8	2.9	Neg&Peak
	7	7	0.7	0.7		0.3	Uniform
122/102	1	26	0.1	-0.3	-0.6	0.8	Pos&Peak
	2	143	0.3	0.4	-4.5	0.3	Pos&Peak
	3	255	3.6	3.2	1.9	22.7	Pos&Peak
	4	131	5.1	4.4	3.3	3	Pos&Peak
	5	206	2.6	2.3	3.8	8.2	Neg&Peak
	6	81	1.6	1	-0.7	-0.2	Pos&Flat
	7	7	1.1	0.8		-1	Uniform
JP	1	27	-1.7	-1.4	0.7	-0.5	Neg&Flat
	2	123	-0.7	-0.5	-1.3	1.4	Pos&Peak
	3	259	4.8	4.4	-0.1	6.2	Pos&Peak
	4	135	6.7	6.3	0.2	1	Pos&Peak
	5	191	3.9	3.3	-0.6	2.9	Pos&Peak
	6	58	1.5	2.2	2.4	-0.2	Neg&Flat
	7	0					
ML	1	0					
	2	150	-0.3	-0.3	0	10.1	Neg&Peak
	3	251	4.2	3.6	-0.4	14.1	Pos&Peak
	4	142	7.1	6.7	1.3	0.6	Pos&Peak
	5	175	3.5	2.4	0.8	1.5	Pos&Peak
	6	71	1.3	0.5	-1	3.3	Pos&Peak
	7	0					
WEM	1	15	1.4	1.2		-0.1	Uniform

	2	127	-2.1	0	-9.5	-0.8	Pos&Flat
	3	264	0	0.2	-0.2	26.9	Pos&Peak
	4	142	-4.7	-2	-4.7	2	Pos&Peak
	5	180	-1.4	0.3	0.2	0.2	Pos&Peak
	6	57	2.2	1.6	4.4	0.6	Neg&Peak
	7	0					

Descriptive statistics of headway, westbound

Bus Stop	Time period	Number of observations	Mean, min	Median , min	Mode, min	Kurtosis	Comment
WEM	1	0					
	2	28	14.5	14.9		0.6	Uniform
	3	61	15.5	15.2	14.3	1	Pos&Peak
	4	37	18.3	17.1		0.6	Uniform
	5	58	14.6	15		-0.4	Uniform
	6	9	29.7	30.5		0.3	Uniform
	7	0					
ML	1	0					
	2	24	17	15.3		2.8	Uniform
	3	61	15.1	15.1	15.1	3.9	Neg&Peak
	4	35	13.5	14		2.2	Uniform
	5	60	15.5	15.5	15.4	1	Pos&Peak
	6	12	29.2	29.5		0.2	Uniform
	7	0					
JP	1	0					
	2	24	14.6	14.8		-0.9	Uniform
	3	65	15	15.1	15	0.5	Pos&Peak
	4	38	14.6	14.8	14.8	0.8	Neg&Peak
	5	59	15.6	15.6	13.2	3.4	Pos&Peak
	6	14	26.5	28.6		2.7	Uniform
	7	0					
124/102	1	0					
	2	25	15.6	14.9		12.6	Uniform
	3	63	14.9	15.7		0.1	Uniform
	4	36	14.3	15		0.1	Uniform
	5	55	15.3	15.2	15.8	4	Neg&Peak
	6	20	22.7	27.8	28.3	-1.6	Neg&Flat
	7	0					
99/102	1	0					
	2	31	15.8	15.2		7.9	Uniform

	3	62	15.1	15.1	11.1	1.3	Pos&Peak
	4	37	13.8	14.3	13.7	1.1	Pos&Peak
	5	58	15.7	15.6		3.1	Uniform
	6	26	22	19.1		-1.9	Uniform
	7	0					
79/106	1	0					
	2	31	15.2	15.1		10.2	Uniform
	3	62	15.4	15.5	13.4	1.6	Pos&Peak
	4	34	13.9	14.3	15.6	1.9	Neg&Peak
	5	55	15.6	15.4	15.1	2.4	Pos&Peak
	6	27	21.9	19.6		-1.7	Uniform
	7	0					
Cap	1	10	29.4	29.9		0.5	Uniform
	2	33	15	15.4	15.7	0.1	Neg&Peak
	3	58	15.4	14.9		-0.2	Uniform
	4	37	14.5	14.7		0.4	Uniform
	5	58	15.8	15.5	15.1	1.9	Pos&Peak
	6	12	30.1	30.1		4.7	Uniform
	7	0					

Descriptive statistics of headway along Eastbound

Bus Stop	Time period	Number of observations	Mean, min	Median, min	Mode, min	Kurtosis	Comment
Cap	1	10	29.4	29.9		0.5	Uniform
	2	33	15	15.4	15.7	0.1	Neg&Peak
	3	58	15.4	14.9		-0.2	Uniform
	4	37	14.5	14.7		0.4	Uniform
	5	58	15.8	15.5	15.1	1.9	Pos&Peak
	6	12	30.1	30.1		4.7	Uniform
	7	0					
79/106	1	8	29.4	29		3.5	Uniform
	2	30	14.6	15	15.1	3.3	Neg&Peak
	3	60	15.2	15.4	16.1	2	Neg&Peak
	4	41	15.2	15	12.4	1.3	Pos&Peak
	5	54	15.6	15.2		3.2	Uniform
	6	16	26.6	30.1		-0.5	Uniform
	7	0					
101/JA	1	0					
	2	32	15.9	15.1	15.2	10.3	Pos&Peak
	3	59	15.2	14.9	13.4	1.9	Pos&Peak

	4	40	14.4	15		2.2	Uniform
	5	51	15.3	15		1.7	Uniform
	6	17	22.1	26		-2.1	Uniform
	7	0					
122/102	1	0					
	2	32	14.9	13.6		4.3	Uniform
	3	59	15.2	15	13	-0.4	Pos&Flat
	4	34	14.8	14.9	17.7	1.4	Neg&Peak
	5	57	15.6	15.8	15	2.3	Pos&Peak
	6	17	22.2	24.3		-1.9	Uniform
	7	0					
JP	1	0					
	2	28	16.3	15.8	19.2	4.6	Neg&Peak
	3	61	14.6	15.1		0.4	Uniform
	4	35	13.9	13.5		2.2	Uniform
	5	55	16.6	16.7		1	Uniform
	6	6	27.9	28.7		0.2	Uniform
	7	0					
ML	1	0					
	2	38	19.2	15.5		-1.3	Uniform
	3	57	15	15.2	16.8	2.6	Neg&Peak
	4	35	13.8	13.5		2.7	Uniform
	5	52	15.8	16.6		0.9	Uniform
	6	0					
	7	0					
WEM	1	0					
	2	28	14.5	14.9		0.6	Uniform
	3	61	15.5	15.2	14.3	1	Pos&Peak
	4	37	18.3	17.1		0.6	Uniform
	5	58	14.6	15		-0.4	Uniform
	6	9	29.7	30.5		0.3	Uniform
	7	0					

APPENDIX B

VISSIM Simulation Model Development: West TSP corridor

The West TSP corridor was chosen in the phase-I project for evaluating performance under Transit Signal Priority (TSP), which was conducted using a microscopic traffic simulation tool, VISSIM, with ASC/3 module (Han, et al. 2013). This study considers similar approach for evaluation. Therefore, the developed West TSP corridor model of Phase-I project is used in this study. The traffic network is built using VISSIM 5.4 containing the ASC/3 module, a full-scale signal emulator in VISSIM. The modeling consists of several sequential steps: 1) Drawing roadway networks, 2) inputting traffic volumes, 3) configuring traffic signal, 4) setting up transit routes and 5) defining driving behaviors. Each of these steps requires specific information which was collected from both Edmonton Transit System (ETS) and operation branch of the City of Edmonton (CoE). The data include:

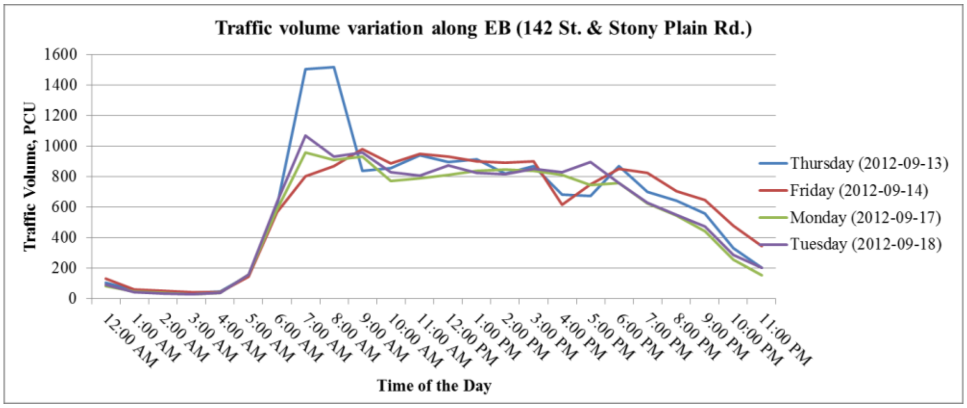
- Traffic turning movement counts at signalized intersection (5 minutes resolution)
- Signal timing plan at signalized intersection
- Citywide speed profile
- Sep12 sign-up bus service schedule
- Bus station location and stop length
- Automatic Passenger Counter (APC) data

Other data sources include the field observation, City of Edmonton website, Google map and street view. After gathering all those information, the VISSIM simulation model of West TSP corridor was started.

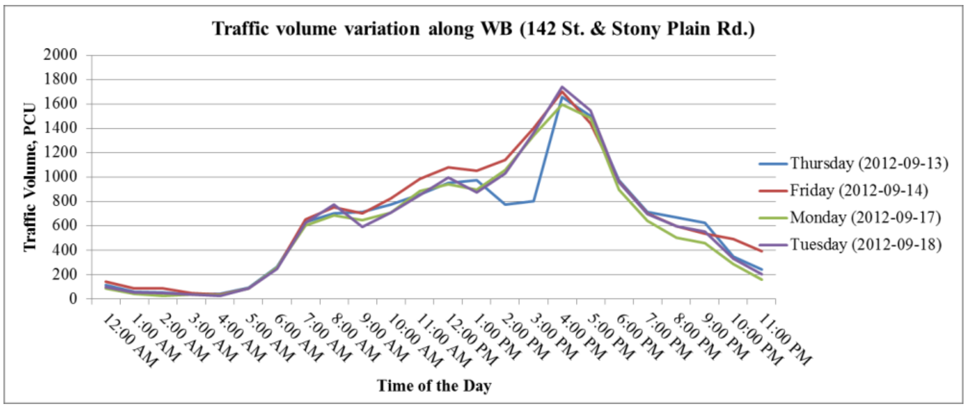
Traffic and pedestrian volume input

For this study, traffic counts at 5-minute intervals from key intersections were provided by the City of Edmonton. Data was collected at some intersections for 12 or 18 hours, while at other intersections data was collected only for the morning and evening peak hours. Following figures show the variation in hourly traffic volume along eastbound (eastbound) and westbound (westbound) respectively, close to 142 St. & Stony Plain Rd.

APPENDIX



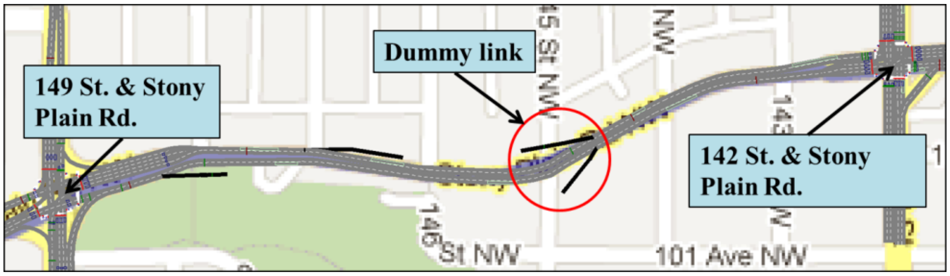
Traffic volume variation along eastbound



Traffic volume variation along westbound

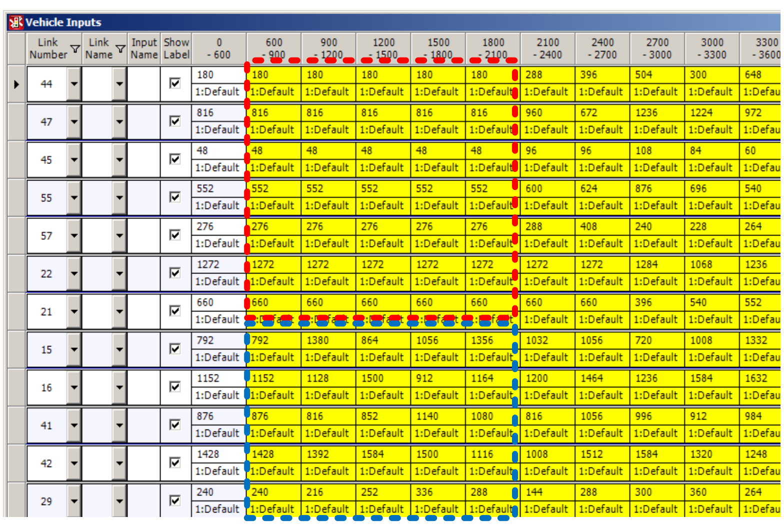
Along eastbound, the traffic volume is higher during AM peak compared to other times of the day. The opposite pattern is observed along westbound. The westbound traffic volume shows a distinguished peak during PM peak. The process of inputting traffic volume in VISSIM has two steps: 1) inputting volume at the access point of the extreme-end links and 2) setting route decisions (left, through and right). The traffic volume and route decision are set with same time interval which is five minutes. Before starting that process, it is necessary to check the volume balance of the traffic count data.

Traffic volume balance is checked by comparing outbound traffic from an upstream intersection with the inbound traffic of a downstream intersection. Both of those volume data should be same if three conditions are prevailed. First, volumes are counted during same time period. Second, there are no access or egress points (driveway) in between the two intersections. Finally, the collected volume is free of error(s). The traffic count data of CoE was collected during different time periods and on different days. This might cause volume imbalance which is required to be solved. In the VISSIM simulation model, traffic is balanced between intersections by introducing or withdrawing virtual vehicles via intermediate driveways (dummy link). The volume balancing process is showing in the following figure.



Balancing traffic volume between intersections

There was a compatibility issue existed between traffic count and passenger count. Although the intersection traffic counts were taken at 5-minute intervals, pedestrian volume was given in 15-minute intervals. Therefore, 15-minute pedestrian count was evenly divided into three 5-minute intervals. Another issue was experience with the data given by the CoE. Traffic count data is not always consistent with the transit peak hours identified by ETS. Especially, early AM peak hour data was not given. Then, the traffic volume of the first 5 minutes is extended to the beginning of the transit peak hour. The volume input table in VISSIM is shown in the following figure.



Vehicle Inputs

Link Number	Link Name	Input Name	Show Label	0 - 600	600 - 900	900 - 1200	1200 - 1500	1500 - 1800	1800 - 2100	2100 - 2400	2400 - 2700	2700 - 3000	3000 - 3300	3300 - 3600
44			☑	180 1:Default	180 1:Default	180 1:Default	180 1:Default	180 1:Default	180 1:Default	288 1:Default	396 1:Default	504 1:Default	300 1:Default	648 1:Defau
47			☑	816 1:Default	816 1:Default	816 1:Default	816 1:Default	816 1:Default	816 1:Default	960 1:Default	672 1:Default	1236 1:Default	1224 1:Default	972 1:Defau
45			☑	48 1:Default	48 1:Default	48 1:Default	48 1:Default	48 1:Default	48 1:Default	96 1:Default	96 1:Default	108 1:Default	84 1:Default	60 1:Defau
55			☑	552 1:Default	552 1:Default	552 1:Default	552 1:Default	552 1:Default	552 1:Default	600 1:Default	624 1:Default	876 1:Default	696 1:Default	540 1:Defau
57			☑	276 1:Default	276 1:Default	276 1:Default	276 1:Default	276 1:Default	276 1:Default	288 1:Default	408 1:Default	240 1:Default	228 1:Default	264 1:Defau
22			☑	1272 1:Default	1272 1:Default	1272 1:Default	1272 1:Default	1272 1:Default	1272 1:Default	1272 1:Default	1272 1:Default	1284 1:Default	1068 1:Default	1236 1:Defau
21			☑	660 1:Default	660 1:Default	660 1:Default	660 1:Default	660 1:Default	660 1:Default	660 1:Default	660 1:Default	396 1:Default	540 1:Default	552 1:Defau
15			☑	792 1:Default	792 1:Default	1380 1:Default	864 1:Default	1056 1:Default	1356 1:Default	1032 1:Default	1056 1:Default	720 1:Default	1008 1:Default	1332 1:Defau
16			☑	1152 1:Default	1152 1:Default	1128 1:Default	1500 1:Default	912 1:Default	1164 1:Default	1200 1:Default	1464 1:Default	1236 1:Default	1584 1:Default	1632 1:Defau
41			☑	876 1:Default	876 1:Default	816 1:Default	852 1:Default	1140 1:Default	1080 1:Default	816 1:Default	1056 1:Default	996 1:Default	912 1:Default	984 1:Defau
42			☑	1428 1:Default	1428 1:Default	1392 1:Default	1584 1:Default	1500 1:Default	1116 1:Default	1008 1:Default	1512 1:Default	1584 1:Default	1320 1:Default	1248 1:Defau
29			☑	240 1:Default	240 1:Default	216 1:Default	252 1:Default	336 1:Default	288 1:Default	144 1:Default	288 1:Default	300 1:Default	360 1:Default	264 1:Defau

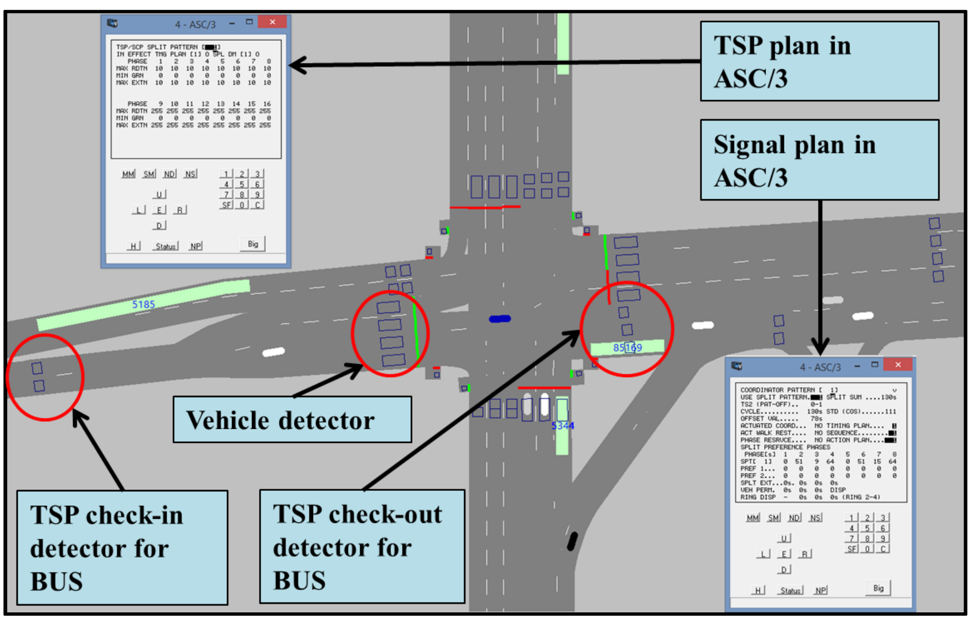
The 5-minute vehicle and pedestrian volumes over time in vissim

As demonstrated in above figure, the traffic counts within the red rectangle were not available until 1,800 seconds, and the missing traffic counts were replaced with the earliest available traffic counts (from 1,800 seconds to 2,100 seconds). The traffic counts within the blue rectangle were available throughout the study periods.

Configuring signal controllers

The signal timing plan of sixteen signalized intersections is implemented in VISSIM by using the ASC/3 signal emulator. Besides signal plan, information related to detector is important during the configuration of signal controller. Information related to signal timing and detector were provided by the City of Edmonton's traffic operations branch.

TSP activation in VISSIM requires three major steps: 1) configuring the bus-only detectors in VISSIM to place TSP requests, 2) developing the corresponding TSP plans in VISSIM and 3) mapping the bus-only detectors in VISSIM with the TSP check-in/check-out detectors in the ASC/3 emulator. The placement of bus-only check-in and check-out detectors are shown in the following figure.

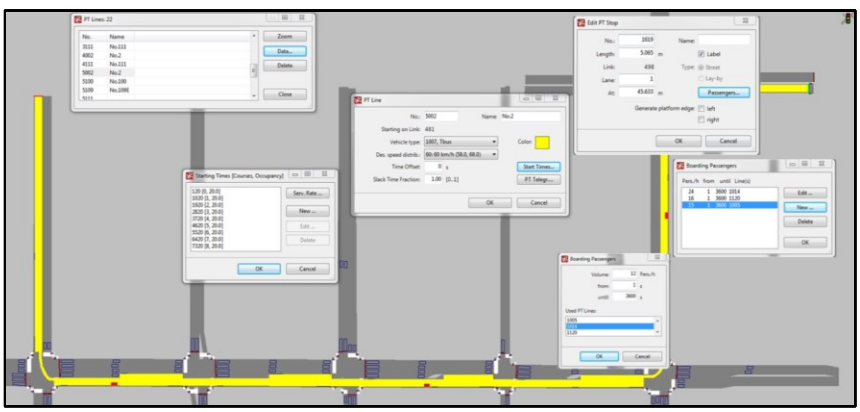


Signal and TSP Settings in VISSIM

The TSP check-in and check-out detectors can send a pulse signal to the signal controller when a bus passes. Once a pulse signal is received by the ASC/3 controller, the signal controller replaces the current timing with the corresponding TSP plan. For each TSP plan, two types of parameters need to be configured: 1) MAX RDTN and 2) MAX EXTN. The MAX RDTN defines the maximum green reduction of a non-TSP phase when a TSP request is granted. The MAX EXTN defines the maximum green extension of a TSP phase when a TSP request is granted.

Configuring public transit routes & stops

According to PTV Vission (2012), bus stops should be configured before bus route, and this is done here too. The proper dimension and location of bus stops are maintained during the modelling. The dimension and location of bus stops are provided by the City of Edmonton's traffic operations branch. After setting bus stops, bus routes and schedules are configured. Route and schedule information related to AM peak period was extracted and summarized from the schedule documents and route maps provided by ETS. A graphical illustration of the process of setting bus route and frequency is given in the following figure.

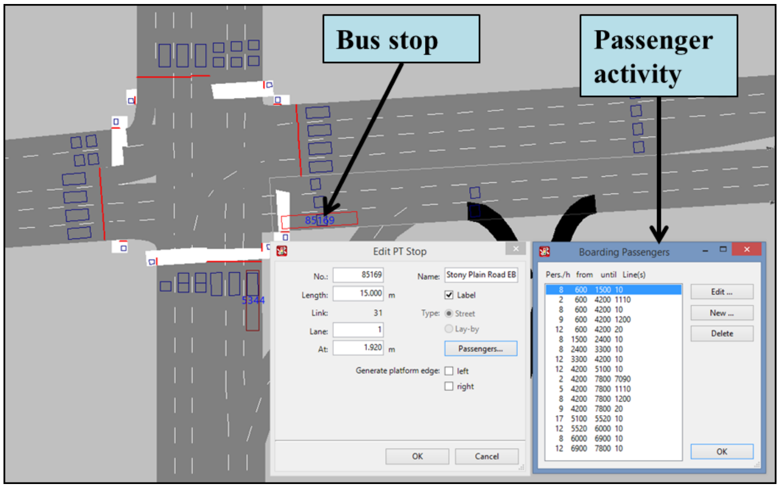


Bus Routes and Stations in VISSIM

Based on the route maps, bus routes are placed along the specific links of the road network. Then, the frequency of those bus routes are configured at the starting time window given in VISSIM. During frequency setting, the September-12-sign-up (September 2 to December 1) document of ETS was used.

Bus Dwell Times at Bus Stops

The bus dwell time can be configured in VISSIM in two ways: 1) using default bus dwell time distributions; and 2) using empirical bus dwell time calculation according to the number of boarding passengers. In this study, method 2 was adopted. The number of boarding is configured at bus stops, based on the information collected from the APC database. The configuration of passenger activity at bus stop is illustrated in the following figure.



Bus Boarding Passengers' Configuration in VISSIM

This method will recreate bus dwell times in the VISSIM models that are more reflective of those in reality, while reducing the amount of calibration required for accurate modelling.

VISSIM Model Calibration

Calibration of Link Traffic Volume

The calibration process of a micro-simulation model can be defined as the repeated numerical comparison of field data to the output of the simulation model (Park and Won 2006). Mid-block traffic volumes are a widely-used benchmark for VISSIM calibrations (Park and Won 2006). This process of balancing volume (dummy link) can be considered as the calibration process. The link traffic volume is estimated by coding traffic counter at mid-block section of each link. The collected mid-block volumes from simulation model are compared with the field data provided by the CoE.

Calibration results are evaluated with R^2, the coefficient of determination. The coefficient indicates the fitness of the simulation data compared to the field data. R^2 value ranges between one and zero. The value of one indicates the perfect fitness and vice versa. The mathematical expression of R^2 is shown in the following equation:

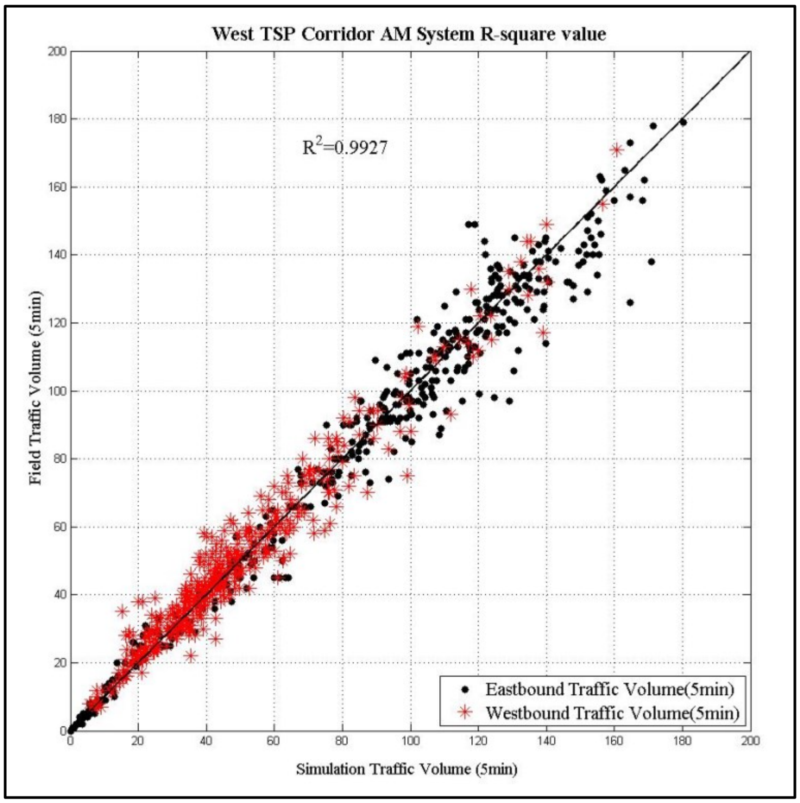
APPENDIX

$$R^2 = 1 - \frac{\sum_i (v_i - f_i)^2}{\sum_i \left(v_i - \frac{1}{n}\sum_{i=1}^{n} v_i\right)^2}$$

Where:

- v_i is the 5-minute traffic volumes from the VISSIM simulation
- f_i is the 5-minute empirical traffic volumes (received from the City of Edmonton)

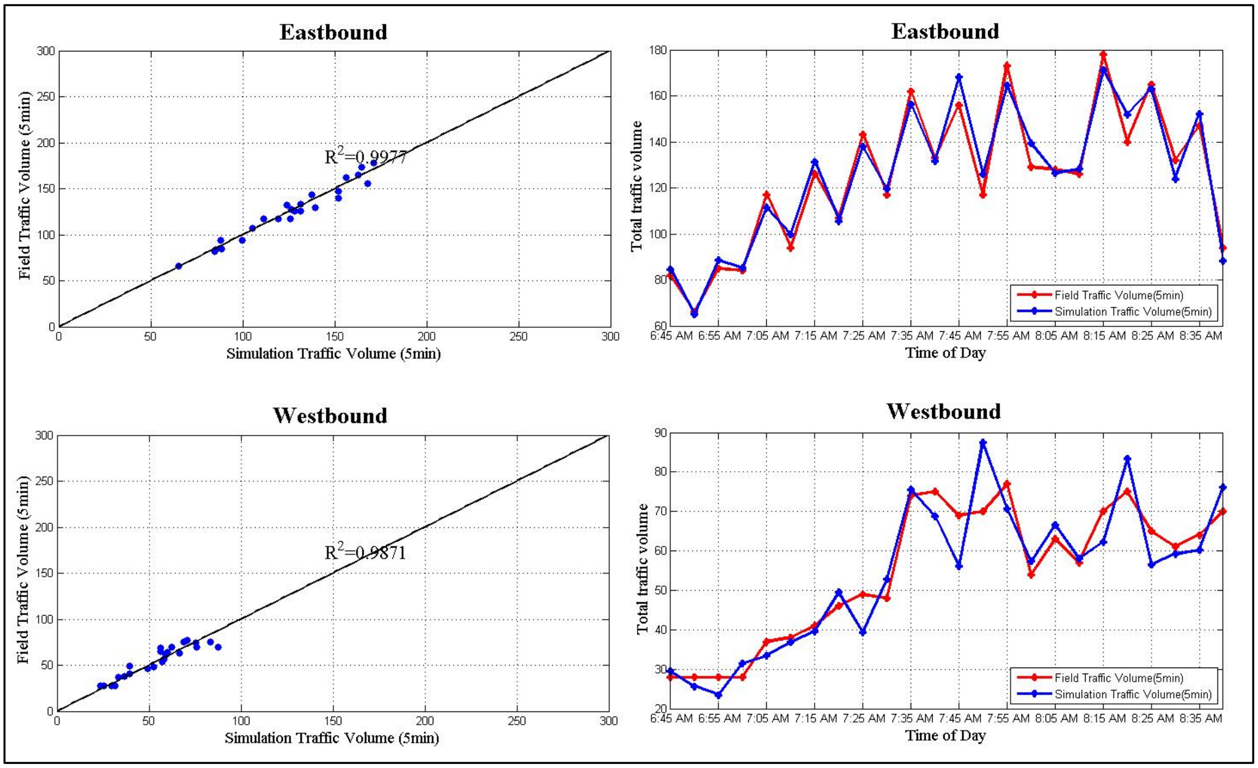
A system R^2 value is used to show the overall calibration results of study corridor. In system R^2, all the observed data points and simulated data points along the entire corridor are plotted on a two-dimensional graph shown in the following figure.



System Traffic Volume Calibration Results of West TSP Corridor

Using the equation 1, the overall coefficient of determination is obtained and shown on above figure. Since the R^2 value of the West TSP corridor is close to one, the VISSIM model represents the reality well. To further investigate the model quality, the segment by segment traffic volume data from field observation and simulation output are compared. The following figure shows an example of segment traffic volume data comparison.

APPENDIX

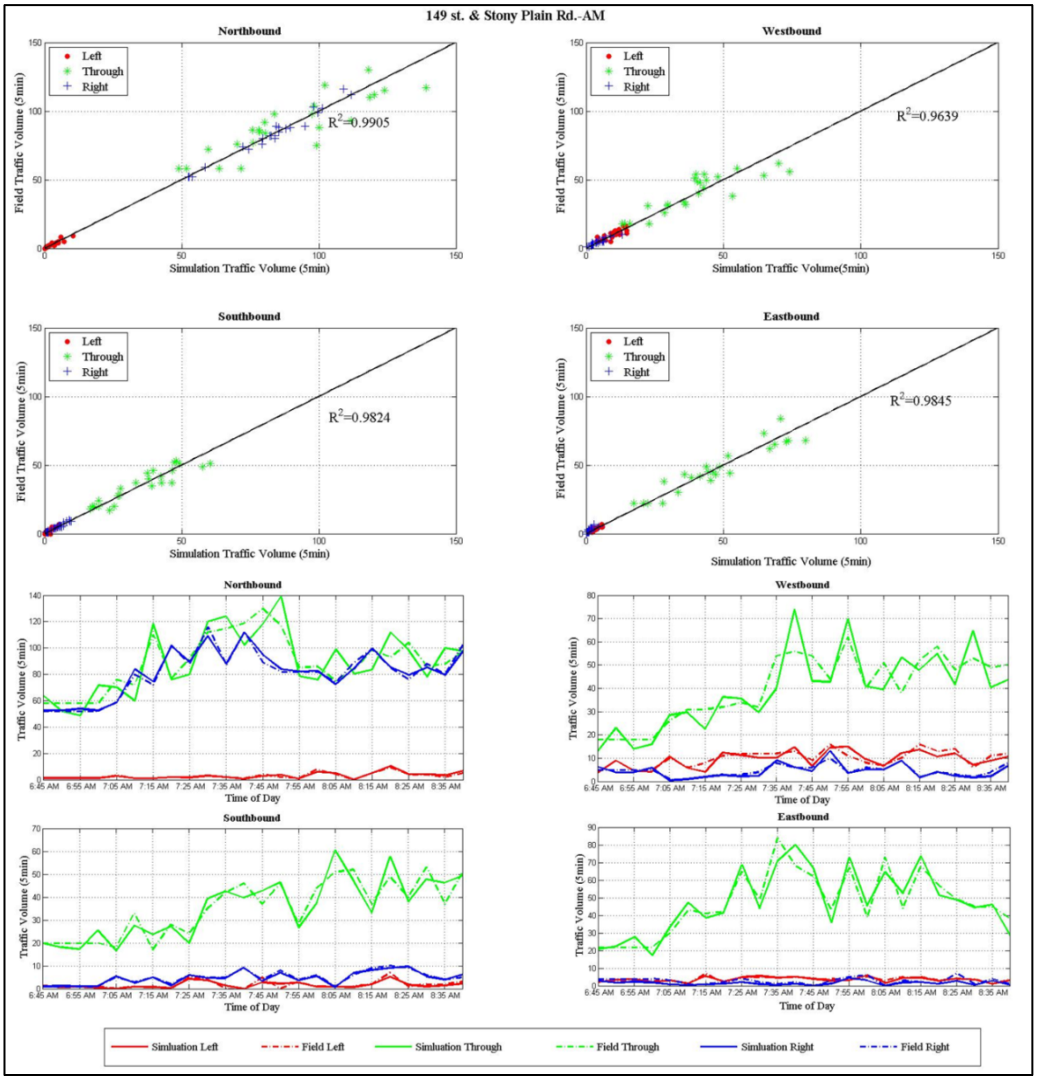


Comparison of traffic volume between 149 St. & Stony Plain Rd. and 142 St. & Stony Plain Rd. during AM Peak

Based on the results shown in the above figure, R^2 values of the comparison between the actual and VISSIM modeled traffic volumes for both eastbound and westbound during AM peak hours are nearly 1, indicating that the VISSIM traffic volumes are statistically the same as those observed in the field.

Calibration of turning movement counts at signalized intersections

The turning movement count is an important indicator for model calibration for an arterial corridor. Thus, a comparison study on turning movements is conducted at each signalized intersection. A volume counter is placed at each lane of the connector to count the turning volume of each approach at five minutes interval. Then, the simulated tuning volume is compared to the field turning volume to find the R^2 value. The results of calibration of turning movement counts are shown in the following figure.



Turning Movement Calibration Result

Four R^2 values are presented on figure, and value related to westbound turning movement is lower than others. Lower value can be explained by the comparative variation in turning movement along westbound, presented in the bottom last (right) figure.

Calibration of Bus Travel Time

The simulation bus travel time was calibrated with field observations. There are several factors that affect bus travel time along the whole corridor such as the bus speed, dwell time and stop skipping phenomenon. Bus usually skips stop when there is no passenger activity. All these three factors are adjusted during the calibration process. In simulation, the desired bus speed distribution was adjusted according to the field-observed speed limits. Besides that, the dwell time of bus can be calibrated by changing the public transit parameters: 1) allowable boarding, 2) allowable alighting time per passenger and 3) clearance time per bus at a single stop. The stop skipping action of bus is activated by adjusting default option in VISSIM. After calibration and adjustments, the travel times of buses closely match the field observations (within a 10% relative error in most cases). The calibration results of the Route-1 are shown in the following table.

Bus travel time calibration results

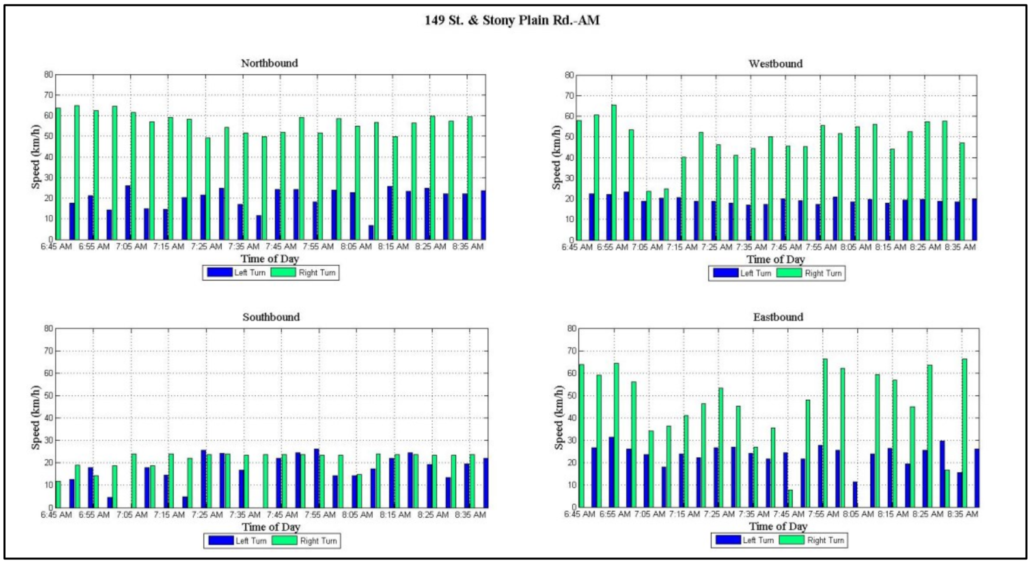
Route 1	AM (min)	
	eastbound (SD)	westbound (SD)
Scheduled	17	18
Field Observation	16.53 (2.71)	15.32 (2.02)
Simulation	15.29 (5.71)	14.20 (2.01)
Relative Error	-7.5%	-7.3%

The scheduled travel time of the Route-1 was retrieved from the ETS trip planner. The observed (field) travel time data was retrieved from the APC database. Simulated travel time of bus is estimated by coding the travel time collector in VISSIM. Here, the travel time collector covers the whole corridor to find the total travel time. Based on the results shown in the above table, all relative errors are lower than 10% which is considered as a satisfactory condition in terms of the calibration. The values in the bracket are presenting the standard deviation of travel time.

Calibration of Traffic Turning Speeds at Intersections

The turning speeds of right or left turning traffic are calibrated based on the speed data provided by the CoE. According to the CoE, conditions are to set speed between 15 km/h to 25 km/h for tight right turns and 25 km/h to 35 km/h for wide right turns and left turns. For left turns and right turns at intersections with an island, vehicles only slow down near the obstructive points. The calibration results of left and right turning speeds are shown in the following figure.

APPENDIX



Example of Traffic Turning Speed

The intersection 149 St. and Stony Plain Rd. has only one sharp right turn which is southbound right turn. Other three right turns are accommodated with island. The calibration results explain that clearly, based on the above figure. Only, SB right turning speed is lower than 30 kph. The left turning speed along all directions follows the speed limit provided by the CoE.

APPENDIX C

Optimal number of runs in VISSIM

The statistical significance is tested with the Chebyshev's inequality formula. According to this formula, for any population with mean μ, standard deviation σ, and the number of standard deviation $k > 1$, the following percentage of observation should lie within the interval of $(\mu \pm k\sigma)$ (Washington, Karlaftis and Mannering 2003, Newbold, Carlson and Thorne 2013):

$$100 * \left[1 - \left(\frac{1}{k^2}\right)\right] \%$$

Optimization results with different combinations of weighting factor

$\gamma_{1,A,B}$	$\gamma_{2,A,B}$	$\gamma_{1,B,C}$	$\gamma_{2,B,C}$	λ	Base with new schedule				TSP with new schedule			
					τ_{A-B}	τ_{B-C}	GSD	F	τ_{A-B}	τ_{B-C}	GSD	F
1	1	1	1	1	-2.8	0.1	139	237	-2.4	-0.3	119	202
1	1	1	1	1.5	-1.1	-0.3	139	286	-2.0	0.4	119	243
1	1	1	1	2	-0.8	-0.1	139	335	-0.7	0.0	119	285
1	1	1	1	2.5	-0.2	0.2	139	384	-0.2	0.0	119	326
1	1	1	1	3	0.1	0.2	139	433	-0.4	0.0	119	368
1	1.5	1	1	1	18.2	-9.7	159	257	14.0	-7.3	136	219
1	1.5	1	1	1.5	14.3	-7.1	159	306	12.4	-7.0	135	260
1	1.5	1	1	2	14.5	-7.6	159	355	11.0	-6.4	136	302
1	1.5	1	1	2.5	11.9	-6.0	159	404	9.1	-5.2	136	343
1	1.5	1	1	3	10.9	-5.2	159	453	8.6	-5.1	136	385
1	2	1	1	1	33.6	-15.7	173	273	26.2	-12.5	148	232
1	2	1	1	1.5	29.6	-14.7	174	322	23.7	-12.4	149	274
1	2	1	1	2	27.1	-14.2	174	372	21.0	-11.2	149	316
1	2	1	1	2.5	23.8	-12.3	175	422	19.5	-10.4	149	358
1	2	1	1	3	21.4	-11.4	176	471	18.0	-10.4	151	400
1	2.5	1	1	1	45.5	-20.1	184	286	37.6	-17.4	161	243
1	2.5	1	1	1.5	40.6	-19.2	186	337	33.6	-17.2	158	286
1	2.5	1	1	2	36.3	-17.9	187	387	30.1	-15.7	160	329
1	2.5	1	1	2.5	33.8	-17.9	188	437	27.1	-14.6	160	371
1	2.5	1	1	3	30.8	-17.3	190	487	24.7	-13.7	161	413
1	3	1	1	1	56.7	-23.9	194	297	47.2	-20.8	165	252
1	3	1	1	1.5	51.1	-24.2	196	348	42.8	-20.5	166	296
1	3	1	1	2	46.8	-22.1	197	400	38.5	-19.7	168	340
1	3	1	1	2.5	42.2	-22.2	199	451	34.5	-18.4	170	383
1	3	1	1	3	39.2	-21.0	201	501	31.8	-17.4	172	425