Metro Transit Service Reliability Measures Assessment

Final Report

Prepared for

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Executive Summary

Transit agencies have installed automatic data collection systems to improve operation management and provide real-time information to the public. Various methodologies have been developed to measure system performance and capture the impacts of deployed strategies on improving service reliability. This paper aims to identify transit service reliability measures that may be applicable to bus and light rail services and how they might be used most effectively by Metro Transit in the Twin Cities metro area. Metro Transit is the transportation resource for the Twin Cities, offering an integrated network of bus, light rail and commuter train services. In 2015[1], Metro Transit operated 132 routes and provided nearly 86 million rides with 72% of those rides served by bus and the other 28% by rail.

The objectives of this project are to expand the definitions of transit service reliability, determine which ones are applicable to Metro Transit's services, and provide a proof of concept of how these measures could be applied using available operations data. We first reviewed common service reliability measures that are used for bus and light rail services both in the United States and internationally. We identified 18 common service reliability measures and categorized them into four groups (see Appendix A). Four service reliability measures, On-Time Performance (OTP), Excess Wait Time (EWT), Gap Assessment (GA), and the 90th percentile of lateness (LA90), were finalized for further evaluation. We applied the finalized service reliability measure on 13 high frequency routes (route 2, 4, 5, 6, 10, 17, 18, 19, 21, 54, 64, 84, and 515) and 2 LRT lines (901-blue and 902 - green lines) using transit operations data from Jan. 2014 to Apr. 2016.

The following selection criteria are applied to evaluate how the 4 selected measures are applicable to transit services and how they might be used most effectively by Metro Transit.

1. Is the service reliability measure easy to interpret?
2. Is data available for both historical reporting and real-time applications?
3. Can the metric provide a different perspective as compared to current OTP?
4. Can the metric support best operational practices?

OTP is the current key performance index used by the Metro Transit. It will continue to be used as a baseline measure for service reliability. In addition to OTP, GA, and LA90 were selected for implementation. GA is a customer focused headway adherence measure. It could be easily implemented based on existing transit operations data. In addition to the OTP, the LA90 measure describes the typical late range of a transit service. It indicates 'how badly' the transit services are not meeting the OTP threshold. The excess wait time (EWT) is not recommended for implementation because it is difficult to interpret and the computed results are unable to provide a clear indication of operations performance.

This study demonstrates how the identified measures could be applied using available operations data currently collected by Metro Transit to improve quality of service.

[1] Metro Transit Facts 2015, https://www.metrotransit.org/Data/Sites/1/media/about/facts/2015/2015_metrotransit_facts.pdf

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1. Introduction

Service reliability measures can be defined as the availability and stability of transit service attributes at certain locations, affecting riders and operators' decision-making. In the literature, various service reliability measures have been identified by researchers from both passengers' and transit agencies' perspectives (Diab et al., 2015; Government Technology, 2015; Cats 2016). These measures range from minimizing running time delays and riders' wait time to achieving on-time performance (OTP) using either historical or real-time data (Reddy, 2014; Tribone et al. 2016). The Transit Capacity and Quality of Service Manual (TCQSM) describes several service reliability measures that transit agencies can implement improvement strategies to improve transit service operations and reduce operating costs (TCRP Report 165).

Metro Transit currently use one measure of service reliability for all bus routes. Buses within 1 minute early to 5 minutes late are deemed to be "on-time". Transit services outside the "on-time" range are identified as either "early" or "late". Metro Transit has an overall goal that bus service will be on-time 87.6 percent of the time. A separate service reliability measure is used for light rail service. Light rail transit (LRT) within 1 minute early to 4 minutes late are considered as "on-time". Metro Transit has goals of 95 percent and 90 percent on-time for the Blue Line and Green Line services, respectively.

In addition to OTP measure, there are several other measures of service reliability used by transit agencies in the industry. Some examples are excess wait time (Cramer et al., 2010) and headway variation (Kamrul et al. 2015). These measures are often used on high frequency services as a measure of how customers experience the service as they wait for the next bus or train. The objective of this study is to explore different measures of transit service reliability used by other transit agencies or in the literature, determine which ones are applicable to Metro Transit's services, and provide a proof of concept of how these measures could be applied using available Metro Transit operations data.

This research aims to identify measures of transit service reliability that are applicable to Metro Transit bus and light rail services and how they might be used most effectively by Metro Transit. We reviewed 18 service reliability measures used in the transit industry or found in the literature and divided them into four categories, i.e., (A) schedule adherence, (B) travel time reliability / delay, (C) headway, and (D) others. After discussions with Metro Transit staff, 8 metrics from the 18 service reliability measures were selected with examples to better understand the purpose and effectiveness of these measures based on the availability of existing operations data.

After several meetings and discussions with Metro Transit, the following four service reliability measures, On-Time Performance (OTP), Excess Wait Time (EWT), Gap Assessment (GA), and 90th percentile of lateness (LA90), were finalized for reliability analysis on high-frequency routes. These performance metrics were initially analyzed on 3 bus routes (5, 18 & 84) and 2 LRT lines (901 & 902) using 1 month (January, 2016) of transit operations data. Service reliability measures were divided and analyzed in 5 time periods, early morning (12AM-6AM), AM peak (6-9AM), mid-day (9AM-3PM), PM peak (3-6:30PM), and late evening (6:30PM-12AM).

- On-Time Performance (OTP) - The OTP is defined as the difference between actual and scheduled times of arrival or departures times, usually expressed in minutes. The measured result

is highly dependent on how the "on-time" is defined. The OTP measures how often buses are approximately on-time. It describes the proportion of departures considered on-time and gives riders an overview of system performance. However, it is difficult to apply to specific rider needs.

- Excess Wait Time (EWT) - EWT measure for high frequency services describes how much longer than half the headway riders should expect to wait for a trip they regularly ride. Riders may expect a larger excess wait time to indicate later buses, but really it may be related to gaps and bunching.
- Gap Assessment (GA) - Gap assessment measures the frequency of gaps in services. It categorizes gaps in headways by gap size. Different thresholds are used for rail and bus services. In order to better determine the appropriate gap size for gap assessment, we picked two thresholds, 20% and 40% of scheduled headway, for our analysis.
- 90^{th} Percentile of Lateness (LA90) – This metric computes the 90^{th} percentile of late time in minutes for transit services that are late at time point level. This measure is different from the OTP which relies on a selected "on-time" threshold. The purpose of LA90 is to measure the spread of the adherence.

This project included the analysis of the 4 service reliability measure on 13 high frequency services (route 2, 4, 5, 6, 10, 17, 18, 19, 21, 54, 64, 84, and 515) and 2 LRT lines (901-blue and 902 - green lines) using transit data provided by Metro Transit from January 2014 to April 2016.

2. Identify Common Service Reliability Measures

From literature review and practices in the transit industry, we searched common service reliability measures that are used for bus and light rail services both in the United States and internationally. 18 common service reliability measures were identified and categorized into four groups: (A) schedule adherence, (B) travel time reliability / delay, (C) headway, and (D) others. A TAP meeting was held on 4/25/2016 with Metro Transit staff to discuss the identified measures.

2.1. Schedule Adherence

This section describes on time performance and excess wait time measures.

2.1,1 On-time Performance (OTP) from operator's perspective

The OTP is one of the several different measures of reliability used by transit operators (Table 2-1). It is most widely used reliability measure in the North American transit industry (Benn, 1995; CUTA, 2001). The OTP measures how often buses are approximately on-time. It describes the proportion of departures considered on-time and gives riders an overview of system performance. However, it is difficult to apply to specific rider needs. The OTP is defined as the difference between actual and scheduled times of arrival or departures times, usually expressed in minutes. One drawback of the OTP measure is that the measured result is highly dependent on how the "on-time" is defined. According to Transit Capacity and Quality of Service Manual (TCQSM), many transit agencies in the US use an "on-time" window as less than 1 min early and up to 5 min late. The OTP measure is calculated as number of transit services that are on time divided by the total number of services (Eq. 2-1).

$$OTP = \frac{Number\ of\ services\ "on-time"}{Total\ number\ of\ services} \times 100\% \quad (2\text{-}1)$$

Table 2-1 On-time Definition Used by Transit Agencies

On Time Performance (OTP) Measures by Transit Agency		
Agency	**OTP Range (early/late)**	**Reference**
Denver Regional Transportation District (RTD), Denver, CO	-1 minute / +5 minutes	City of Denver 2008, RTD 2012
King County Metro Transit, Seattle, WA	-1 minute / +5 minutes (2013 target 80%, 77.5% in 2012, PM peak 65%)	King County Metro Transit 2013
Maryland Transit Administration (MTA), MD	(target 90%, local bus 82%, subway 97%, LRT 97% in 2013)	Maryland DOT, Angeline Baker
Massachusetts Bay Transportation (MBTA), Boston, MA	**Headway >=10 min** (start: 0 min/+3 min, mid: 0 min/+7 min; end: -3/+7 min), **Headway < 10 min** (OTP within 1.5x of scheduled headway and OTP at end within 20% of run time)	MBTA 2009, MassDOT 2013
Miami-Dade Transit, Miami, FL	-2 minutes / +5 minutes (target 80% in 2012)	Miami-Dade Transit 2012
New Jersey Transit, NJ	- 59 sec / +5 minutes (94% in 2010)	NJ Transit 2012

San Francisco Municipal Transportation Agency (SFMTA), San Francisco, CA	-1 minute / +4 minute	SFMTA 2013
Southeastern Pennsylvania Transportation Authority (SEPTA), Philadelphia, PA	-59 sec / +4 minutes (target 78%)	SEPTA 2013
WMATA, Washington, DC	- 2 minutes / +7 minutes (target 78%, 77.5% in 2012)	WMATA 2012
OC Transpo, Ottawa, Canada	0 minute / +5 minutes	OC Transpo, 2012
Société de transport de Montréal (STM), Montréal, Canada	-1 minute / +3 minutes (target 83%)	STM, 2011
South Coast Columbia Transportation Authority, Vancouver, Canada	0 minute / +3 minutes	TransLink, 2012

2.1.2 OTP from rider's perspective

Tribone et al. (2014) from Massachusetts Bay Transportation Authority (MBTA) proposed to capture passengers' waiting time by incorporating a passenger arrival model at each stop or time point (TP). The measure the passenger waiting time in 3 groups such as the percentage of passengers who waited: (1) less than published headway, (2) shorter than a big gap (the lesser of 1.5 times or 3 min greater than the published headway, and (3) less than twice the published headway. The disadvantage of this measure is that it requires the development of a passenger arrival model at each stop or TP. However, this measure was able to reflect riders' experiences.

2.1.3 Excess Wait Time (EWT)

Excess Wait Time (EWT) is defined as the actual departure time minus the scheduled departure time (positive values only). It represents the extra wait time that passengers experience at stop or TP as compared to the schedule.

2.1.3.1 EWT Based on TCQSM

For transit services with shorter headways (approximately 10 min or shorter), passengers arrive randomly (TCQSM). The average passenger wait time is computed as shown in Eq. (2-2).

$$t_w = 0.5h_0(1 + c_{vh}^2) \quad (2\text{-}2)$$

Where,

t_w is the average wait time (min),
h_0 is the average observed headway (min), and
c_{vh} is the coefficient of variation of headways.

Therefore, the excess wait time (EWT), $0.5h_0c_{vh}^2$, is the average wait time (AWT), t_w, minus the scheduled wait time (SWT), $0.5h_0$.

EWT measure for high frequency services describes how much longer than half the headway riders should expect to wait for a trip they regularly ride. Riders may expect a larger excess wait time to indicate later buses, but really it means more variable, more gaps and more bunching.

2.1.3.2 EWT from CLIP UK

The Central Local Information Partnership (CLIP) in the UK suggested a weighted EWT method for bus punctuality monitoring. The average passenger wait time is weighted by the headway for higher frequency services (headway less than 10 min). For example, Table 2-2 shows a sample observation of a bus service at a stop with a scheduled frequency of 6 buses per hour. Column A lists the actual bus departure time and the actual bus headway is computed in column B. The average wait time (column C) is defined as half of the headway. The weighted average wait time (column D) is computed by multiplying the headway (column B) with the average wait time (column C). Dividing the sum of the weighted average wait time (sum of column D, 1070.0 from Table 2-2) by the sum of the headway (sum of column B, 176 min from Table 2-2), the AWT can be computed as (1070.0/176.0) 6.08 min according to the example in Table 2-2. The SWT is 5.0 min (0.5 x 10 min). Therefore, the EWT can be calculated as 1.08 (6.08 – 5.0) min.

Table 2-2 Sample Observations of a Bus Service at a Stop

Bus departure Time	**Headway (min)**	**Average wait time (min)**	**Weighted average wait time**
(A)	**(B)**	**(C) = (B) / 2**	**(D) = (B) x (C)**
8:02			
8:11	9.0	4.5	40.5
8:19	8.0	4.0	32.0
8:30	11.0	5.5	60.5
8:50	20.0	10.0	200.0
9:00	10.0	5.0	50.0
9:13	13.0	6.5	84.5
9:18	5.0	2.5	12.5
9:30	12.0	6.0	72.0
9:41	11.0	5.5	60.5
9:50	9.0	4.5	40.5
10:00	10.0	5.0	50.0
10:19	19.0	9.5	180.5
10:20	1.0	0.5	0.5
10:30	10.0	5.0	50.0
10:38	8.0	4.0	32.0
10:50	12.0	6.0	72.0
10:58	8.0	4.0	32.0

2.2 Travel Time Reliability / Delay

Travel time reliability measures such as passenger travel time delay, journey time, run time variation and run time deviation are described as follow.

2.2.1 Passenger Travel Time Delay

The passenger travel time delay compares the actual travel time with the median trip time. This measure, as suggested by Tribone et al. (2014), requires passenger entry and exit information. MBTA reports passenger travel time measure in 2 groups (delay less than 3 and 6 min).

2.2.2 Journey Time

The London underground transit system uses journey time measure to calculate customers' travel time from entering and leaving the transit system. The tap-in and tap-out time from the Oyster card allows the transit agency to compute the journey time from an origin to a destination. The journey time will be difficult to infer for bus services without capturing both boarding and alighting times.

2.2.3 Run Time Variation

Diab & El-Geneidy (2013) used the coefficient of variation (CV), i.e., dividing run time variance by the average run time, to evaluate the impact of bus run time variation. This measure is often used as one of the parameters for transit modeling. It does not necessary reflect the performance of a trip.

2.2.4 Run Time Deviation

Similar to the run time variation measure, the run time deviation is computed by dividing the actual run time over the scheduled run time. It's a simple metric that reflects the deviation of the actual run time from the scheduled run time.

2.3 Headway

Headway related measures such as headway deviation, wait analysis, bunching or gap, and headway adherence, are discussed as follow.

2.3.1 Headway Deviation

The headway deviation is defined as the actual headway measured at the end of a segment divided by the scheduled headway at the end of the same segment. This measure describes how headways are skewed towards short or long intervals. It offers headway reliability analysis and evaluates potential bunching. However, it is not appropriate for less frequent services (Strathman & Kimpel, 2003; Sharma et al., 2015).

2.3.2 Wait Analysis

To evaluate bunching and significant gap in service at route level, New York City Transit (NYCT) used a percent based wait assessment (WA) to capture a snapshot of the daily performance on a route level (Cramer et al., 2010). Three WA criteria are used for subway and bus services based their wait assessment matching algorithm (DiNapoli, 2014).

- Normal Gaps – Subway: less than 25% above scheduled headway, Bus: less than 3 min (peak) or 5 min (off-peak) above schedule headway;
- Minor Gaps – 25-50% above scheduled headway;
- Medium Gaps – 50-100% above scheduled headway;
- Major Gaps – 100% above scheduled headway.

NYCT sets a baseline of the WA for each route for the 4 groups described above to monitor the trend and performance of bus service in a week as compared to the corresponding baseline targets.

2.3.3 Bunching or Gap

A bus service is considered as bunching when the actual headway is less than 25% of the scheduled headway, (NYCT and SFMTA). A bunching measure is derived by computing the % of bus trips that are bunched as compared to the total number of trips by route direction and time period.

Gap assessment measures the frequency of gaps in services. It categorizes gaps in headways by gap size. Different thresholds are used for rail and bus services.

2.3.4 Headway Adherence

Headway adherence is suggested in TCQSM to measure the bunching effect of a transit service. It measure the variation of headways and describes the regularity of transit vehicle arrivals with respect to the scheduled headway. The headway adherence is computed as the coefficient of variation of headways, i.e., the standard deviation of headways divided by the average headway as shown in Eq. (2-3). The headway adherence measure may be difficult to explain to stakeholders. Table 2-3 relates the HA to passenger or operator's perspective.

$$Headway\ Adherence\ (HA) = \frac{STDEV.\ of\ Headway}{Average\ Headway} \quad (2\text{-}3)$$

Table 2-3 Interpretation of HA (source: TCQSM)

Headway Adherence (HA)	**Passenger & Operator Perspective**
0.00 - 0.21	Service provided like clockwork
0.22 - 0.30	Vehicles slightly off headway
0.31 - 0.39	Vehicles often off headway
0.40 - 0.52	Irregular headways, with some bunching
0.53 - 0.74	Frequent bunching
0.75 or greater	Most vehicles bunched

2.4 Others

2.4.1 Dwell at Time Point (TP)

NYCT measures dwell time at TP to evaluate the median dwell time variation. The dwell time is computed as the departure time at TP minus the arrival time at TP. The use the % of dwell time change as compared to a baseline at a TP to monitor the trend of dwell time performance at a TP.

2.4.2 Holding Time at TP

When a transit vehicle is ahead of its schedule, it stays at a TP to kill the excess scheduled time in order to maintain its service within the OTP criteria. The holding time can ideally be computed by comparing the scheduled departure time and the time when the door was closed.

2.4.3 Missed Trips

Missed trips is a measure suggested in TCQSM by measuring the number of missed trips. The percent of missed trips as compared to scheduled trip in a route is then used as a performance measure to monitor service reliability.

2.4.4 Percent of Scheduled Trips in Operation

Similar to D.3 (missed trips), the percent of scheduled trip in operation is discussed in TCQSM as one of the performance measures to monitor service reliability.

2.4.5 Distance Traveled between Mechanical Breakdowns

Another measure from TCQSM is the distance traveled between mechanical breakdowns. This measure focuses on the vehicle reliability that affects the service performance.

2.4.6 Earliness and Width Index

Earliness Index (EI) and Width Index (WI) are three new performance measures developed by Saberi et al. (2013) for bus service reliability. Each of these measures is defined as illustrated in Figure 2-1 & 2-2, respectively.

The Earliness Index (EI) measures the percent of trips are early. It is defined as the percentile rank of delay/headway deviation of zero. The percentile rank of a particular delay/headway deviation is the percentage of delay/headway deviations in its frequency distribution that are lower or equal to it. Figure 2-1 is a is a graphical representation of EI on an empirical cumulative distribution function of bus departure tie at a TP. EI ranges between 0 and 1. For frequent services, an EI of 0 represents that all services are late or behind schedule, and an EI of 1 represents that all services are early or ahead of schedule.

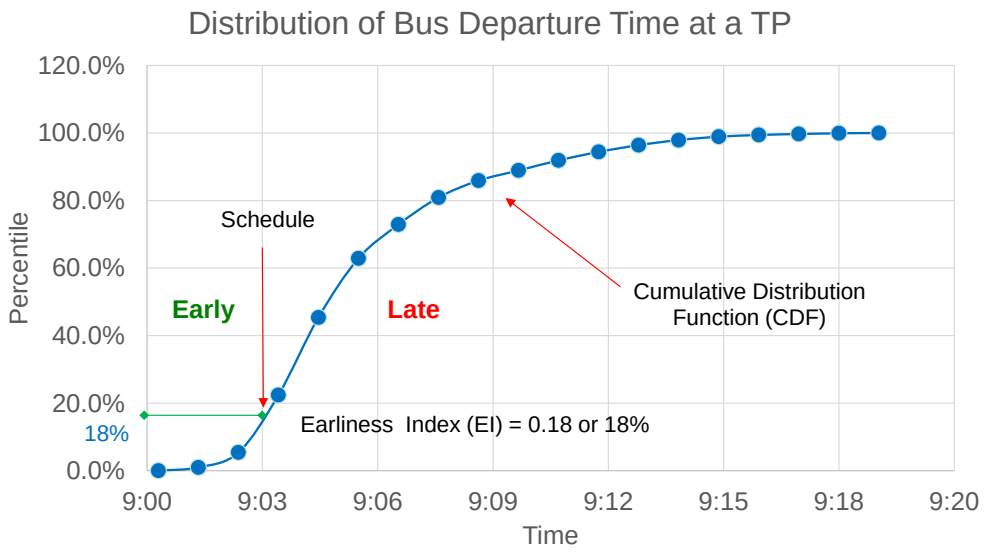


Figure 2-1 Earliness Index (EI)

The Width Index (WI) is defined as the 95th percentile of headway deviations minus the 5th percentile of headway deviations divided by the average scheduled headway as shown in Eq. (2-4).

$$Width\ Index\ (WI) = \frac{F^{-1}(0.95) - F^{-1}(0.05)}{Average\ Headway} \quad (2\text{-}4)$$

Where,

$F^{-1}(x)$ is the inverse of the cumulative distribution function.

Figure 2-2 is a graphical representation of WI on an empirical cumulative distribution function of a bus departure time at a TP. As shown in Figure 2-2, the 95th bus departure time is 9:11:30 and the 5th bus departure time is 9:02:00. The WI can be computed as 9.5 min / 10 min (headway) = 0.95. The ideal width of the distribution of delays/headway deviations is zero (WI = 0) when the 95th percentile and the 5th percentile are equal.

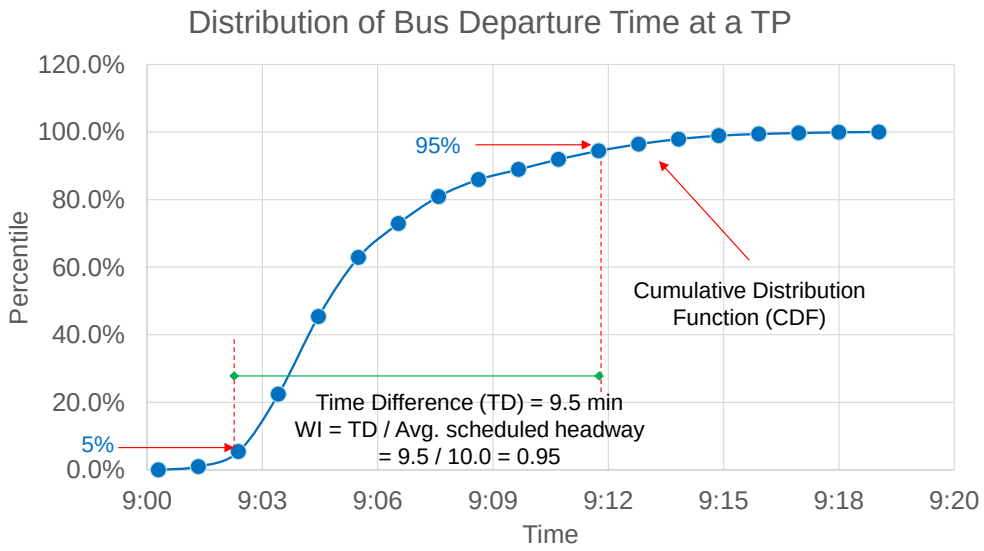


Figure 2-2 Width Index (WI)

A full list of service reliability measures from our literature review is summarized in Appendix A. Further evaluation and discussion of selected measures were included in the following section.

3. Evaluate Selected Measures

We met with Metro Transit staff to refine the list of service reliability measures as discussed in previous chapter and discussed how specifically each measure can be applied to Metro Transit services based on existing data. The following eight metrics from Table A-1 in Appendix A were selected with examples for further discussion.

- A.1 On-Time Performance (OTP)
- A.3.1 Excess Wait Time (EWT) – TCQSM
- A.3.2 Excess Wait Time (EWT) – CLIP UK
- C.1 Headway Deviation (HD)
- C.2&3 Gap Assessment (GA)
- C.4 Headway Adherence (HA)
- D.6a Earliness Index (EI)
- D.6b Width Index (WI)

3.1 Definitions

Metric: A metric is a quantifiable indicator of performance or condition

Measure: A measure is an expression based on a metric, used to establish targets and to assess progress towards achieving the established target.

Target: A target is a quantifiable level of performance or condition, as a value for a measure, to be achieved within a time period required by an agency.

3.2 On-Time Performance (OTP)

Figure 3-1 illustrates the distribution of a bus schedule adherence at a time point (TP). The on-time performance (OTP) threshold for OTP is selected as a bus departing a time point less than 1-minute early and no more than 5-minute late. The schedule adherence distribution shown in Figure 3-1 indicates that 84% of buses depart at this time point "on-time". The OTP measure at TP level can also be calculated at route level or the entire transit network. For example, 275 bus trips are on-time out of 312 total bus trips. The OTP is 88.1% (275/312 = 88.1%).

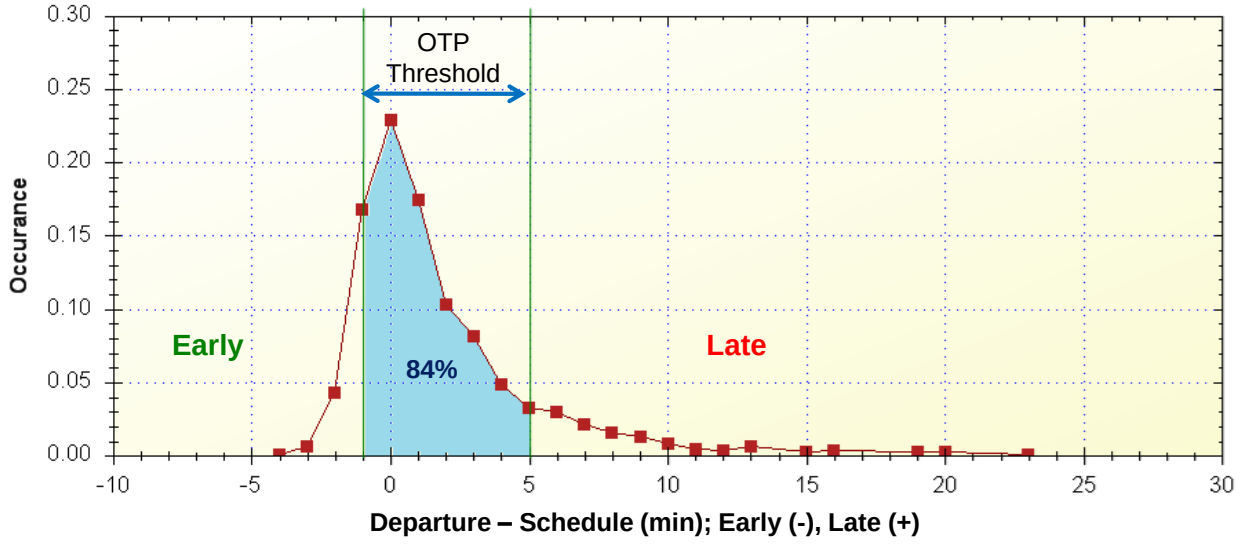


Figure 3-1 A sample Histogram of Bus Schedule Adherence

3.3 Excess Wait Time (EWT)

Transit Capacity and Quality of Service Manual (TCQSM) approach

The EWT based on the recommendation from the TCQSM can be computed as follows.

(i) For scheduled headway 10 minutes or less, the EWT is calculated using Eq. (3-1).

$$t_w = 0.5h_0(1 + c_{vh}^2) \quad (3\text{-}1)$$

Where,

t_w is the average wait time (min),
h_0 is the average observed headway (min), and
c_{vh} is the coefficient of variation of headways.

The excess wait time (EWT), $0.5h_0c_{vh}^2$, is the average wait time (AWT), t_w, minus the scheduled wait time (SWT), $0.5h_0$. For example, Table 3-1 lists the departure time of a bus at a TP with 10 minutes scheduled headway. The observed bus headway is calculated in column (B). The average headway (h_0), 10.4 min., can be calculated by taking the average of column (B) from Table 3-1. The standard deviation of headway (column B) is 4.46. Therefore, the coefficient of variation (CV), defined as the ratio of the standard deviation to the mean, is computed as 4.46/10.4 = 0.43. The average wait time (t_w) can be found by applying Eq. (3-1),

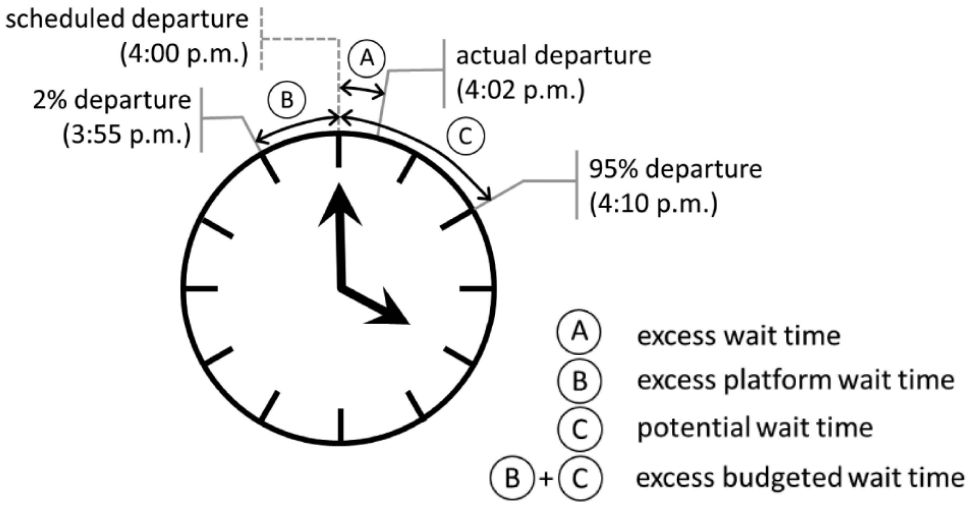
$$t_w = 0.5 \times 10.4 \times (1 + 0.43^2) = 6.14 \quad (3\text{-}2)$$

The scheduled wait time is define as half the scheduled headway, $0.5h_0 = 5\ min$. Therefore, the excess wait time (EWT), can be determined by taking the average wait time ($t_w = 6.14$) minus the scheduled wait time (5.0). In the example, a passenger should expect to wait 1.14 minutes longer than half the headway for a regular trip at this TP.

Table 3-1 Departure Times and Headways at a TP

Bus departure Time	**Headway (min)**
(A)	**(B)**
8:02 am	
8:11 am	9.0
8:19 am	8.0
8:30 am	11.0
8:50 am	20.0
9:00 am	10.0
9:13 am	13.0
9:18 am	5.0
9:30 am	12.0
9:41 am	11.0
9:50 am	9.0
10:00 am	10.0
10:19 am	19.0
10:20 am	1.0
10:30 am	10.0
10:38 am	8.0
10:50 am	12.0
10:58 am	8.0

(ii) For scheduled headway 15 minutes or greater, the EWT is calculated as the difference between the actual and scheduled departure times for all late buses. Figure 3-2 from TCRP report 113 illustrates the excess wait time, excess platform wait time, potential wait time, and excess budgeted wait time.



Source: Derived from *TCRP Report 113* (*25*).

Figure 3-2 Illustration of Passenger Wait Time

Figure 3-3 displays the distribution of bus departure time at a TP where the bus is scheduled at 9:04 AM. The 2 and 95 percentile bus departure times are 9:02 and 9:12, respectively. According to the definition from Figure 3-2, the potential wait time is 8 minutes (9:12 - 9:04). The excess platform wait time is 2 minutes (9:04 – 9:02). The EWT of a bus departing at 9:06 is 2 minutes (9:06 – 9:04).

CLIP UK approach

The CLIP UK uses a different method to compute the EWT. For example, Table 3-2 lists the bus departure times (column A) at a TP with scheduled headway of 10 minutes. The observed headways are calculated and listed in column (B). The average wait time for the passengers is defined as half the headway in column (C). The CLIP UK approach computes the weighted wait time by multiplying the headway (column B) with the average wait time (column C). The average wait time (AWT), 6.08, is computed by dividing the sum of column (D), 1070, over the sum of column (B), 176. Therefore, the EWT, 1.08, is calculated as the AWT (6.08) minus the scheduled wait time (10/2 = 5 minutes). In the example, a passenger should expect to wait 1.08 minutes longer than half the headway for a regular trip at this TP.

Note: The bus departure times in this example are the same as the departure times listed in Table 3-1. The TCQSM approach has a EWT of 1.14 minutes. However, the CLIP UK approach has a EWT of 1.08 minutes.

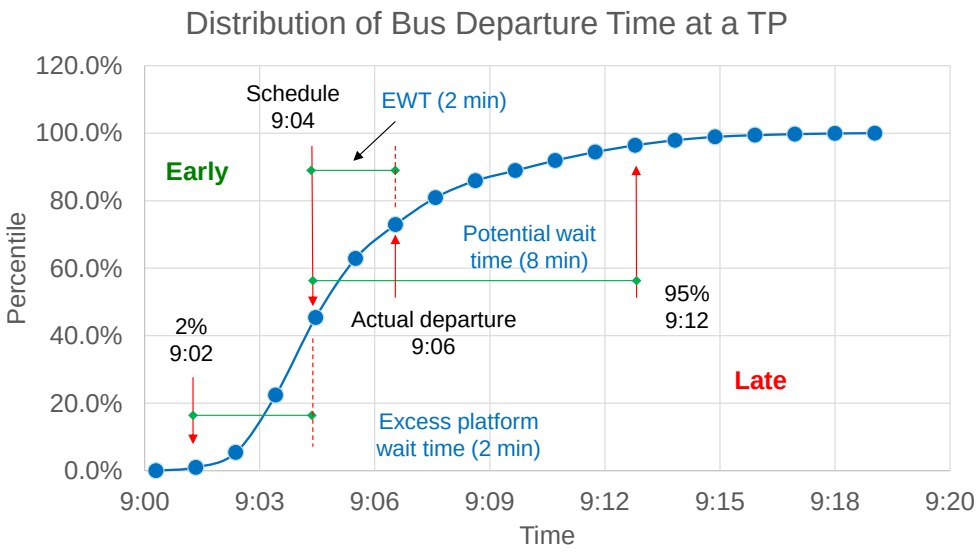


Figure 3-3 Distribution of a Bus Arrival Time at a TP

Table 3-2 Departure Times, Headways, and Weighted Wait Times at a TP

Bus departure Time	Headway (min)	Average wait time (min)	Weighted average wait time
(A)	(B)	(C) = (B) / 2	(D) = (B) x (C)
8:02			
8:11	9.0	4.5	40.5
8:19	8.0	4.0	32.0
8:30	11.0	5.5	60.5
8:50	20.0	10.0	200.0
9:00	10.0	5.0	50.0
9:13	13.0	6.5	84.5
9:18	5.0	2.5	12.5
9:30	12.0	6.0	72.0
9:41	11.0	5.5	60.5
9:50	9.0	4.5	40.5
10:00	10.0	5.0	50.0
10:19	19.0	9.5	180.5
10:20	1.0	0.5	0.5
10:30	10.0	5.0	50.0
10:38	8.0	4.0	32.0
10:50	12.0	6.0	72.0
10:58	8.0	4.0	32.0

3.4 Headway Deviation (HD)

The headway deviation metric is defined as the average headway divided by the scheduled headway. Using the observed headways in Table 3-2 as an example, the average observed headway (average of column B) is 10.4 minutes. The headway deviation (HD) can be computed as 1.04 by dividing 10.4 (average headway) over 10 (scheduled headway).

For example, a transit agency sets a HD threshold ranging from 0.8 to 1.2. There are 312 TPs in the entire transit network, 255 TPs have HD within the threshold. The HD performance measure is (255/312) 81.7%.

3.5 Gap Assessment (GA)

New York City Transit (NYCT) used percentage based wait assessment to capture a snapshot of the daily performance on a route level. They categorize gaps in headways by gap size. Gap assessment criteria are used for subway and bus services as shown in Table 3-3 & 3-4.

Table 3-3 NYCT Gap Assessment Criteria for Bus

Group	Gap Assessment Criteria
Peak	Headway less than scheduled headway + 3 min
Off-peak	Headway less than scheduled headway + 5 min

Table 3-4 NYCT Gap Assessment Criteria for Subway

Group	Gap Assessment Criteria
Meet standard	Headway less than 1.25 x scheduled headway
Minor Gap	Headway is 25% - 50% above scheduled headway
Medium Gap	Headway is 50% - 100% above scheduled headway
Large Gap	Headway is 100% above scheduled headway

For example, Table 3-5 lists the train departure times at a subway station. The headway deviations are computed and listed in column (C). According to the gap assessment criteria as listed in Table 3-4, 8 trains (66.7%) meet the standard, 2 trains (16.7%) have a minor gap, 1 train (8.3%) has a medium gap, and 1 train (8.3%) has a large gap. The purpose of this approach is to determine the frequencies of gaps in service at TP level, route level, or entire transit network.

Table 3-5 Headway of Trains at a Subways Station

Actual Headway (A)	Scheduled Headway (B)	Headway Deviation (C) = (A) / (B)	Meet Standard (C) < 1.25x(B)	Minor Gap 1.25x(B) <= (C) < 1.5x(B)	Medium Gap 1.5x(B) <= (C) < 2x(B)	Large Gap (C) >= 2x(B)
9	10	0.9	1	0	0	0
10	10	1	1	0	0	0
16	10	1.6	0	0	1	0
12	10	1.2	1	0	0	0
13	10	1.3	0	1	0	0
14	10	1.4	0	1	0	0
21	10	2.1	0	0	0	1
11	10	1.1	1	0	0	0
10	10	1	1	0	0	0
12	10	1.2	1	0	0	0
11	10	1.1	1	0	0	0
10	10	1	1	0	0	0
		Count	8	2	1	1
		Percentage	66.7%	16.7%	8.3%	8.3%

3.6 Headway Adherence (HA)

Headway adherence, as described in TCQSM, measures the bunching effect of a transit service. It describes the regularity of transit vehicle arrivals with respect to the scheduled headway. The headway adherence is computed as the coefficient of variation of headways, i.e., the standard deviation of headways divided by the average headway. For example, the average headway from column (B) in Table 3-1 is 10.4 minutes. The standard deviation of the observed headway is 4.46 minutes. The headway adherence (HA) or the coefficient of variation (CV) of headways is 0.43 (4.46/10.4). Based on the interpretation of HA from TCQSM, passengers riding on a bus service with a HA ranging between 0.40 and 0.52 will experience irregular headway services and gaps.

3.7 Earliness Index (EI)

The Earliness Index (EI) is defined as the percentile rank of delay/headway deviation of zero. The percentile rank of a particular delay/headway deviation is the percentage of delay/headway deviations in its frequency distribution that are lower or equal to it. For example, Figure 3-4 is a graphical representation of EI on an empirical cumulative distribution function of bus departure time at a TP. 18% of buses at this time point leave earlier than the scheduled departure time. The value of EI ranges between 0 and 1. For frequent services, an EI of 0 represents that all services are late or behind schedule, and an EI of 1 represents that all services are early or ahead of schedule.

For example, based on an EI performance measure threshold of 0.2 (or 20%), the EI performance at TP level can be computed by divining the number of TP with EI less than the threshold (0.2) over the total number of TPs.

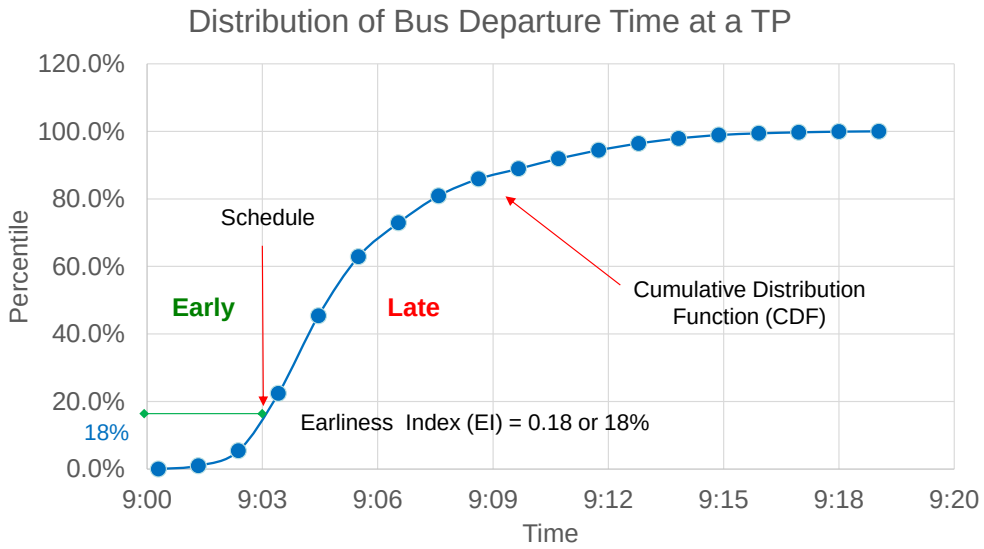


Figure 3-4 Illustration of an Earliness Index (EI)

3.8 Width Index (WI)

The Width Index (WI) is defined as the 95th percentile of headway deviations minus the 5th percentile of headway deviations divided by the average scheduled headway as shown in Eq. (3-3).

$$Width\ Index\ (WI) = \frac{F^{-1}(0.95) - F^{-1}(0.05)}{Average\ Headway} \quad (3\text{-}3)$$

Where,

$F^{-1}(x)$ is the inverse of the cumulative distribution function.

Figure 3-5 is a graphical representation of WI on an empirical cumulative distribution function of a bus departure time at a TP. As shown in Figure 3-5, the 95th bus departure time is 9:11:30 and the 5th bus departure time is 9:02:00. The WI can be computed as 9.5 min / 10 min (headway) = 0.95. The ideal width of the distribution of delays/headway deviations is zero (WI = 0) when the 95th percentile and the 5th percentile are equal.

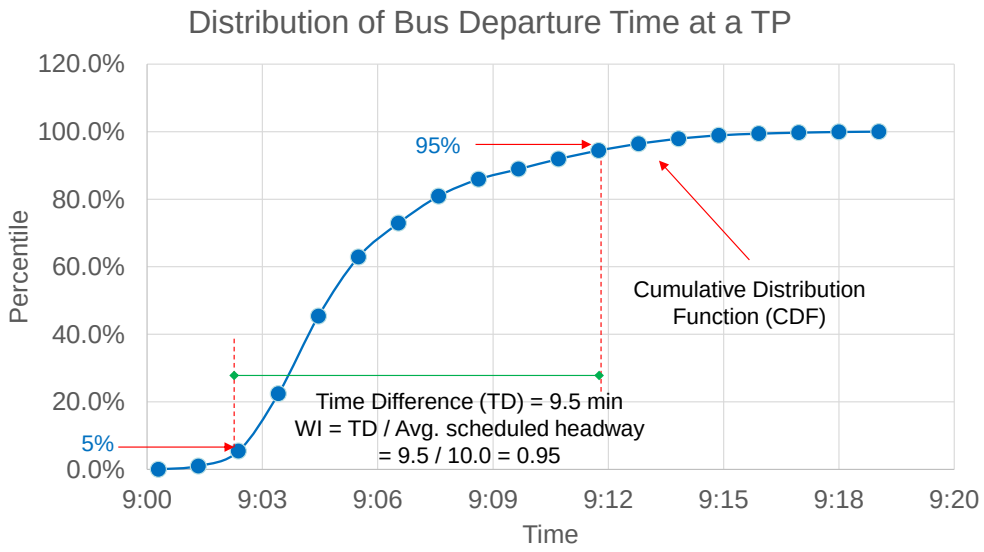


Figure 3-5 Illustration of a Width Index (WI)

Similar to the EI performance measure, using a WI performance measure threshold of 0.5 (or 50%), the WI performance at TP level can be computed by divining the number of TP with WI less than the threshold (0.5) over the total number of TPs.

Three service reliability metrics, (A1) on-time performance, (A3.1a) excess wait time, and (C2&3) gap assessment, were initially selected for preliminary analyses. Plots of service reliability measures at time point level for three high frequency routes (#5, #18, and #84) are included in Appendix B.

Later, a 90th percentile of lateness (LA90) was included to measure the spread of schedule adherence in our analysis. We then computed these selected metrics on the 3 selected routes using transit data from January 2016 provided by Metro Transit. Analysis results of these measures are presented in the following section.

3.9 Summary of Evaluated Metrics

Table 3-6 lists the set of metrics that were analyzed along with the reasoning provided by Metro Transit on whether to advance the metric for the final analysis/selection pool. Although we didn't advance all the metrics for analysis, it didn't necessarily reflect the inherent value of the metric. The selection of the

metric was more often related to Metro Transit's operating environment (e.g. travel times might be a better metric for measuring reliability of a journey).

Table 3-6 Summary of Evaluated Metrics

List of Metrics Selected for Further Discussion	**Rationale for Advancement or Abandonment for Analysis**
On-Time Performance (OTP) [section 3.2]	Advance – current standard metric, helpful for providing context and comparison. This is the most well-understood reliability metric at Metro Transit.
Excess Wait Time (EWT) TCQSM approach [section 3.3]	Abandon – difficult to interpret the metrics because the computed results are based on ratios or coefficients that are not as easily understood as "good" or "poor" and the operations staff is not as confident what an appropriate threshold might be that can be aligned clearly with customer expectations or promises.
Excess Wait Time (EWT) CLIP UK approach [section 3.3]	
Headway Deviation (HD) [section 3.4]	
Gap Assessment (GA) [section 3.5]	Advance – a simple measure to assess percentage of service that operates within a specific gap threshold that is aligned with existing operations standards for acceptable headway performance. Allows business to set a different gap threshold by service type, time of day, etc. It is particularly applicable for light rail and bus rapid transit service.
Headway Adherence (HA) [section 3.6]	Abandon – the coefficient of headway variations is difficult to interpret and communicate meaning to operations staff
Earliness Index (EI) [section 3.7]	Abandon – early departures are well managed and depending on the route and time of year, it is difficult to determine the point when the EI becomes unfavorable
Width Index (WI) [section 3.8]	Abandon – difficult to understand and communicate. It is not easy to explain in plain language why the ideal width of distribution of delays/headway deviations is zero (WI=0) and how that is linked to a better customer experience.
90 Percentile Lateness (LA90) [later described in section 4.4]	Advance – is a simple measure that helps staff understand 'how late is late?' for those observations that do not meet the standard 'on-time' threshold

4. Analyze Service Reliability Measures

After further discussion with Metro Transit, four service reliability measures, On-Time Performance (OTP), Excess Wait Time (EWT), Gap Assessment (GA), and 90th percentile of lateness (LA90), were finalized for analysis. These performance metrics were initially analyzed on 3 bus routes (5, 18 & 84) and 2 LRT lines (901 & 902) using 1 month of transit data (January, 2016). Service reliability measures were divided and analyzed in 5 time periods, early morning (12AM-6AM), AM peak (6-9AM), mid-day (9AM-3PM), PM peak (3-6:30PM), and late evening (6:30PM-12AM).

We applied a threshold of 1 minute early to 5 minutes late for OTP analysis at time point (TP) level for buses. The OTP threshold for LRT is 1 minute early to 4 minutes late. We analyzed EWT on high frequency services with headway less than 15 minutes. Table 4-1 summarizes the percent of trips with 15 minutes or less of headway for route 5, 18, and 84 in January 2016. On average, 80% of the trips on route 5 and 18 have a scheduled headway of 15-minute or less at TP. About 70% of the trips on route 84 have a scheduled headway of 15-minute or less. Overall, 53% of the trips in the entire network in January 2016 have 15-minute or less scheduled headways.

Table 4-1 Percent of High Frequency Bus Serves

Route	Dir	Number of scheduled intervals 15-min or less (A)	Number of all intervals (B)	Percentage A X 100% / B
5	NB	29,904	36,604	81.70%
	SB	27,403	34,949	78.41%
18	NB	25,354	32,074	79.05%
	SB	21,740	28,311	76.79%
84	NB	11,982	17,035	70.34%
	SB	11,641	16,758	69.47%
Entire Network		624,405	1,166,787	53.51%

4.1 On-Time Performance (OTP)

Table 4-2 lists the analyzed statistics of OTP for 3 bus routes by time period and direction. On average, 86.7% of buses for route 5 at time points in both directions are “on-time”. Similarly, 79.2% and 95% of buses for route 18 and 84, respectively, in both directions are “on-time”.

Table 4-2 On-Time Performance by Direction and Time Period for Buses

Route	Dir	Early	AM Peak	Mid Day	PM Peak	Late	All Day
5	NB	91.6%	90.2%	91.0%	80.8%	86.9%	87.9%
	SB	87.2%	89.2%	85.3%	79.4%	87.7%	85.5%
	All Dir.	89.4%	89.7%	88.1%	80.1%	87.3%	86.7%
18	NB	91.3%	88.2%	82.6%	78.9%	80.4%	82.7%
	SB	90.7%	72.8%	76.8%	71.9%	77.7%	75.6%
	All Dir.	91.0%	80.5%	79.7%	75.4%	79.0%	79.2%
84	NB	98.7%	96.0%	95.0%	90.0%	96.8%	94.7%
	SB	99.6%	97.0%	95.8%	94.0%	93.4%	95.3%
	All Dir.	99.2%	96.5%	95.4%	92.0%	95.1%	95.0%

Table 4-3 lists the analyzed statistics of OTP for LRT by time period and direction. On average, the blue line LRT (#901) has OTP of 89% and 80% in NB and SB, respectively. The green line LRT in January 2016 has average OTP of 76% and 88% in EB and SB, respectively. Note: LRT uses a smaller OTP threshold.

Table 4-3 On-Time Performance by Direction and Time Period for LRT

Route	Dir	Early	AM Peak	Mid Day	PM Peak	Late	All Day
901	NB	93.4%	92.7%	91.6%	87.1%	84.1%	89.1%
	SB	92.9%	81.2%	87.5%	74.0%	69.2%	80.2%
	All Dir.	93.1%	87.1%	89.6%	80.7%	77.5%	84.9%
902	EB	86.7%	74.2%	83.2%	64.8%	75.5%	76.1%
	WB	95.3%	89.9%	87.0%	84.5%	86.7%	87.6%
	All Dir.	92.7%	82.6%	85.2%	74.9%	80.7%	82.0%

4.2 Excess Wait Time (EWT)

EWT using the TCQSM formula (described in section 3.3) were also analyzed. Transit services with headway greater than 15 minutes were excluded in the analysis. Table 4-4 shows the EWT in minutes for 3 buses by time period and direction. On average, riders on route 5 in January 2016 experienced 1.24 minutes longer than average wait time at time points in both directions. Riders on route 18 experienced an average EWT of 1.18 minutes in all directions. Similarly, riders on route 84 experienced an average EWT of 0.65 minutes at time points in all directions.

Table 4-4 Excess Wait Time in Minutes (Bus)

Route	Dir	Early	AM Peak	Mid Day	PM Peak	Late	All Day
5	NB	0.95	1.06	1.00	1.78	0.82	1.14
	SB	0.22	1.26	1.31	1.89	0.74	1.34
	All Dir.	0.59	1.16	1.15	1.83	0.78	1.24
18	NB	0.50	0.78	1.02	1.53	0.63	1.12
	SB	0.18	1.08	1.06	1.57	0.92	1.25
	All Dir.	0.47	0.94	1.04	1.55	0.78	1.18
84	NB	0.26	0.28	0.35	0.71	0.28	0.42
	SB	NA	0.31	0.24	0.31	7.94	0.88
	All Dir.	0.26	0.30	0.30	0.51	4.11	0.65

Table 4-5 shows the EWT in minutes for 2 LRT lines by time period and direction. On average, riders on blue line (#901) in January 2016 experienced 0.53 minutes longer than average wait time at LRT stations in both directions. Similarly, riders on green line (#902) experienced an average EWT of 0.49 minutes at light rail stations in both directions.

Table 4-5 Excess Wait Time in Minutes (LRT)

Route	Dir	Early	AM Peak	Mid Day	PM Peak	Late	All Day
901	NB	0.36	0.31	0.51	0.20	0.74	0.54
	SB	0.63	0.22	0.67	0.29	0.46	0.51
	All Dir.	0.50	0.27	0.59	0.25	0.58	0.53
902	EB	0.23	0.25	0.45	0.27	0.59	0.43
	WB	0.05	0.24	0.41	0.47	0.85	0.56
	All Dir.	0.21	0.25	0.43	0.37	0.73	0.49

4.3 Gap Assessment (GA)

In order to better determine the appropriate gap size for gap assessment (GA), we picked two thresholds, 20% and 40% of scheduled headway, for initial analysis. For example, for a 10 minute headway, that would be thresholds of 2 and 4 minutes, respectively. For a 15 minute headway, the thresholds would be 3 and 6 minutes, respectively. Both the 20% and 40% gap thresholds apply on all time points all day.

Table 4-6 summarizes the gap assessment using both thresholds for buses. For bus route 5, 91% of service has gaps within 40% of the scheduled headway and 81% of service has gaps within 20% of the scheduled headway in both directions. The NB trips on route 5 have slightly higher percentage of trips with gaps within 20% or 40% of the scheduled headway as compared to the SB trips. For bus route 18, 89% of service has gaps within 40% of the scheduled headway and 78% of service has gaps within 20% of the scheduled headway in both directions. The NB trips on route 18 have slightly higher percentage of trips with gaps within 20% or 40% of the scheduled headway as compared to the SB trips.

Similarly, 97% of bus 84 service has gaps within 40% of the scheduled headway and 88% of service has gaps within 20% of the scheduled headway in both directions. The SB trips on route 84 have slightly higher percentage of trips with gaps within 20% or 40% of the scheduled headway as compared to the NB trips.

Table 4-6 Gap Assessment by Route and Direction (Bus)

Route	Dir	Gap within 20% of scheduled headway	Gap within 40% of scheduled headway
5	NB	83.1%	92.6%
	SB	79.1%	89.1%
	All Dir.	81.1%	90.8%
18	NB	80.4%	90.6%
	SB	74.9%	86.5%
	All Dir.	77.7%	88.6%
84	NB	87.9%	96.4%
	SB	88.3%	97.1%
	All Dir.	88.1%	96.8%

Table 4-7 summarizes the gap assessment using both thresholds for LRT. For LRT blue line (#901), 98% of service has gaps within 40% of the scheduled headway and 91% of service has gaps within 20% of the

scheduled headway in both directions. The NB trips on LRT route 901 have slightly higher percentage of trips with gaps within 20% or 40% of the scheduled headway as compared to the SB trips. Similarly, 97% of LRT green line service (#902) has gaps within 40% of the scheduled headway and 88% of service has gaps within 20% of the scheduled headway in both directions. The WB trips on LRT route 902 have slightly higher percentage of trips with gaps within 20% or 40% of the scheduled headway as compared to the EB trips.

Table 4-7 Gap Assessment by Route and Direction (LRT)

Route	Dir	Gap within 20% of scheduled headway	Gap within 40% of scheduled headway
901	NB	93.3%	98.2%
	SB	89.2%	97.5%
	All Dir.	91.3%	97.8%
902	EB	86.5%	96.2%
	WB	88.2%	97.2%
	All Dir.	87.7%	96.8%

4.4 90% of Lateness (LA90)

We also discussed the need for a measure of the spread of the adherence distribution. We considered the Width Index (WI) previously described in section 3.8, but landed instead on a metric to measure the 90th percentile of late departures in minutes. Figure 4-1 illustrates the on-time performance and the 90th percentile lateness metrics. For example, the OTP of the bus service in Figure 4-1 is 84% based on the 1 minute early and 5 minutes late threshold. The 90th percentile of buses are 10 minutes late.

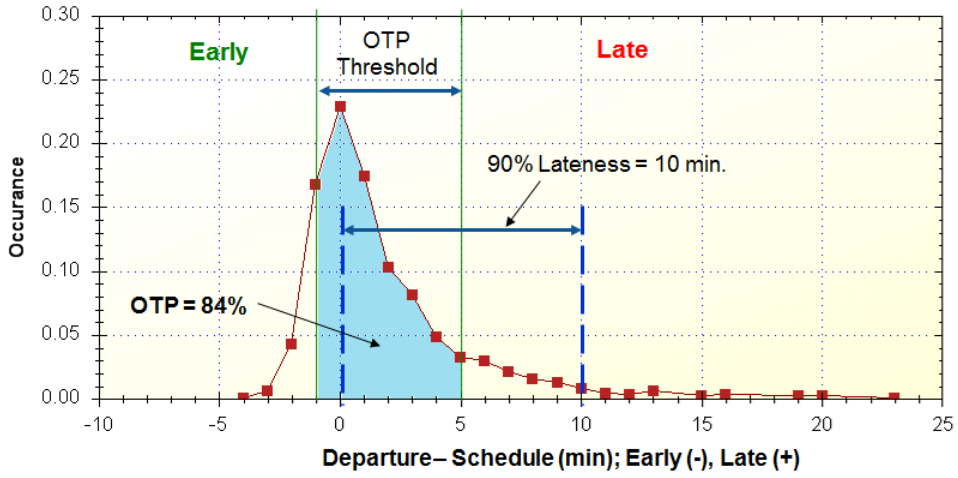


Figure 4-1 Illustration of OTP and 90% Lateness

Table 4-8 lists the 90% lateness of the 3 bus services by route and direction. On average, 90% of route 5 bus service at TP level in NB and SB are less than 5.0 and 5.9 minutes late, respectively. For bus route 18, 90% of service at TP level in NB (SB) is less than 4.7 (7.2) minutes late. Similarly, 90% of route 84 bus service at TP level in NB and SB are averagely less than 3.4 and 3.6 minutes late, respectively.

Table 4-8 Bus 90 Percentile Lateness by Route and Direction

Route	Dir	90 Percentile Late Time (min)
5	NB	5.0
	SB	5.9
	All Dir.	5.5
18	NB	4.7
	SB	7.2
	All Dir.	6.3
84	NB	3.4
	SB	3.6
	All Dir.	3.5

Table 4-9 summarizes the 90% lateness of the LRT services by route and direction. On average, 90% of LRT blue line service (#901) at each station in all directions is less than 4.6 minutes late. Similarly, 90% of LRT green line service (#902) at each station in both directions is less than 5.0 minutes late, averagely.

Table 4-9 LRT 90 Percentile Lateness by Route and Direction

Route	Dir	90 Percentile Late Time (min)
901	NB	4.1
	SB	5.0
	All Dir.	4.6
902	EB	5.7
	WB	4.3
	All Dir.	5.0

4.5 Service Reliability Measures for 10 Other Routes

We further analyzed the OTP, EWT, GA20, and LA90 measure on 10 other bus routes (2, 4, 6, 10, 17, 19, 21, 54, 64, and 515) from January 2014 to April 2016 (28 months). Sample results by month for 3 selected routes (2, 21 & 64) are discussed here. Additional plots are included in Appendix C. Figure 4-2 displays the monthly OTP and GA20 of bus route 2 in both directions. The average OTP and GA20 are respectively around 86.6% and 87.8% for bus route 2 for the 28-month period. Figure 4-3 displays the monthly EWT and LA90 of bus route 2 in both directions. The average EWT and LA90 are respectively around 0.8 and 5.7 minutes for bus route 2.

Figure 4-4 displays the monthly OTP and GA20 of bus route 64 in both directions. The average OTP and GA20 are respectively around 83% and 88% for bus route 64. Figure 4-5 displays the monthly EWT and LA90 of bus route 64 in both directions. The average EWT and LA90 are respectively around 1.2 and 5.4 minutes for bus route 64. Figure 4-6 displays the monthly OTP and GA20 of bus route 21 in both directions. The average OTP and GA20 are respectively around 86% and 82% for bus route 21. Figure 4-7 displays the monthly EWT and LA90 of bus route 21 in both directions. The average EWT and LA90 are respectively around 1.4 and 5.8 minutes for bus route 64.

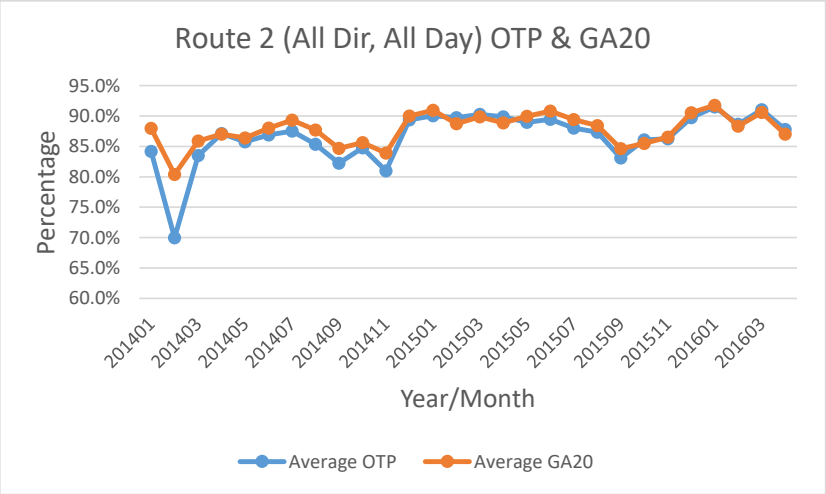


Figure 4-2 Monthly OTP and GA20 of Bus Route 2

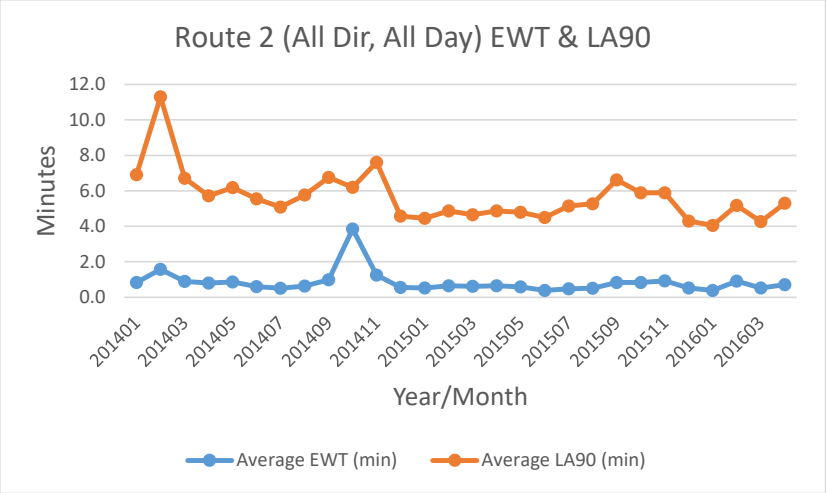


Figure 4-3 Monthly EWT and LA90 of Bus Route 2

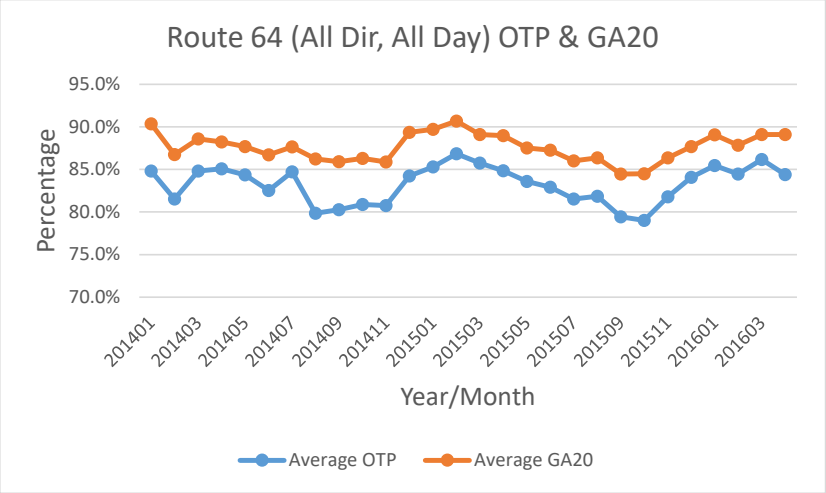


Figure 4-4 Monthly OTP and GA20 of Bus Route 64

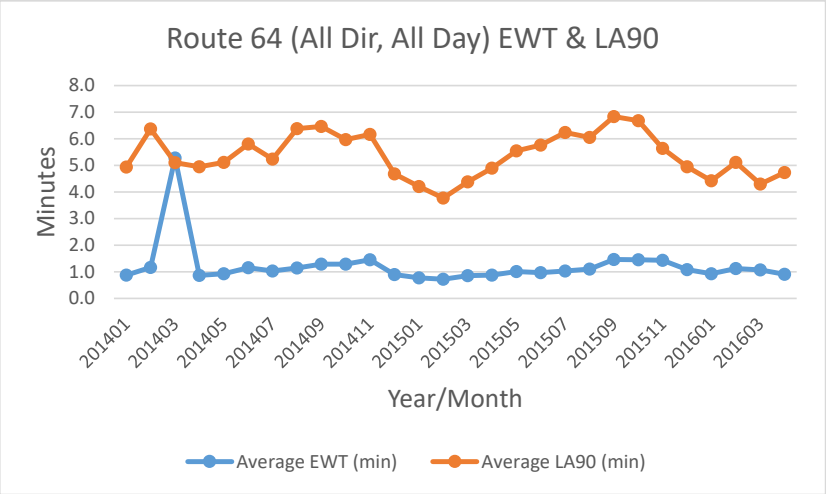


Figure 4-5 Monthly EWT and LA90 of Bus Route 64

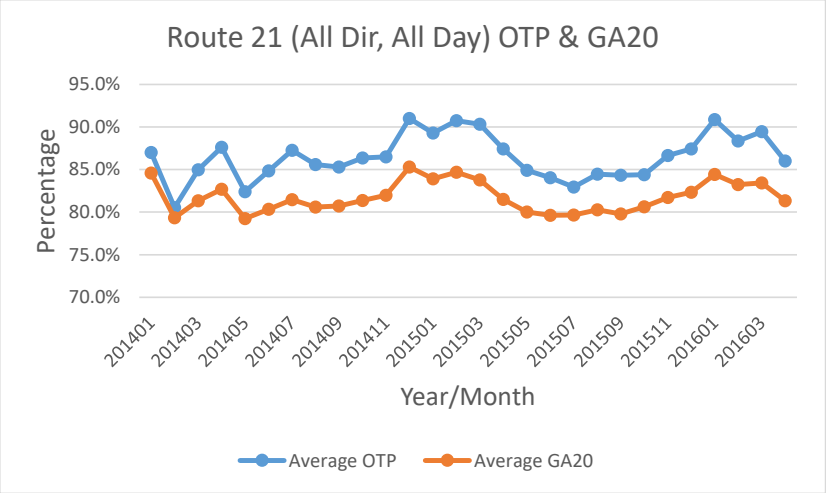


Figure 4-6 Monthly OTP and GA20 of Bus Route 21

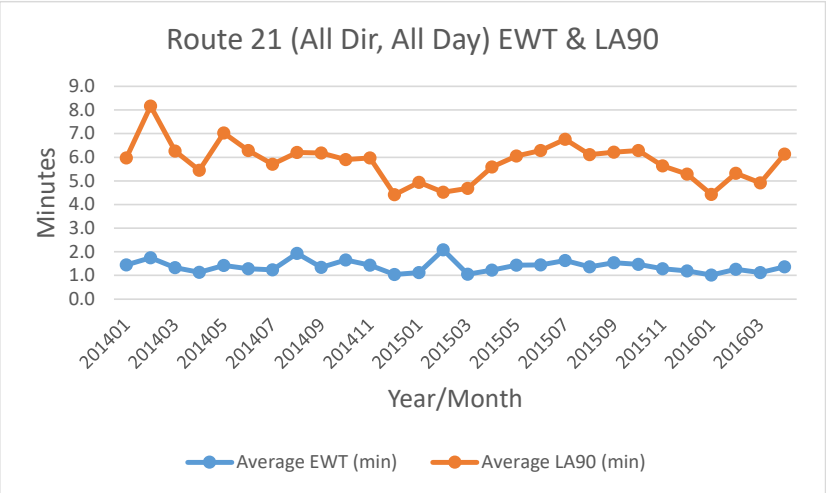


Figure 4-7 Monthly EWT and LA90 of Bus Route 21

4.6 Correlation between Metrics

We further examined the correlation between the service reliability measures. Table 4-10 and 4-11 summarize the 4 service reliability measures for bus and LRT routes, respectively. Table 4-12 and 4-13 list the correlation between two metrics for bus and LRT, respectively. The results indicate that the four metrics are highly correlated. Figure 4-8 and 4-9 respectively display the radar plots of the correlation between two service reliability measures by time period for bus and LRT.

Table 4-10 Summary of Bus Service Reliability Measures

Route	OTP	GA20	EWT	SA90
5 NB	87.90%	83.1%	1.14	5.0
5 SB	85.50%	79.1%	1.34	5.9
18 NB	82.70%	80.4%	1.12	4.7
18 SB	75.60%	74.9%	1.25	7.2
84 NB	94.70%	87.9%	0.42	3.4
84 SB	95.30%	88.3%	0.88	3.6

Table 4-11 Summary of LRT Service Reliability Measures

Route	OTP	GA 20%	EWT	SA 90%
901 NB	89.1%	93.3%	0.54	4.1
901 SB	80.2%	89.2%	0.51	5.0
902 EB	76.1%	86.5%	0.43	5.7
902 WB	87.6%	88.2%	0.56	4.3

Table 4-12 Correlation of Bus Service Reliability Measures

Correlation	OTP	GA20	EWT	LA90
OTP	1.00	-0.98	-0.74	-0.92
GAP20		1.00	0.80	0.96
EWT			1.00	0.80
SA90				1.00

Table 4-13 Correlation of LRT Service Reliability Measures

Correlation	OTP	GA20	EWT	LA90
OTP	1	-0.73	0.91	-0.99
GAP20		1	-0.58	0.76
EWT			1	-0.95
SA90				1

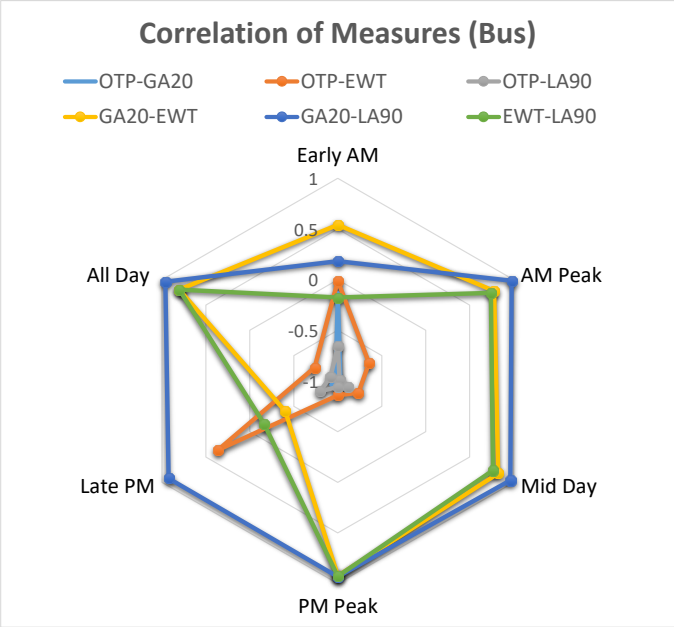


Figure 4-8 Radar Plots of Correlation between Bus Measures

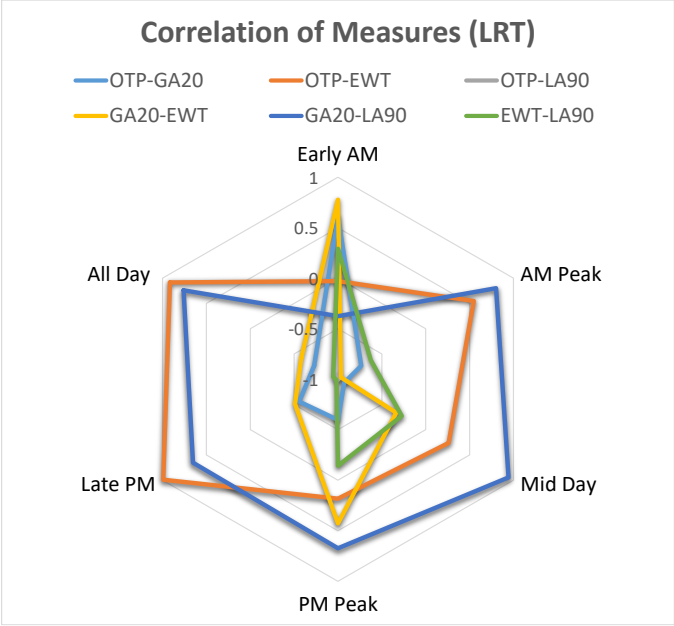


Figure 4-9 Radar Plots of Correlation between LRT Measures

5. Analysis Results

Monthly service reliability measures of on-time performance, gap assessment, and the 90th percentile lateness applied on 13 high frequency routes (route 2, 4, 5, 6, 10, 17, 18, 19, 21, 54, 64, 84, and 515) during a 28 month period (January 2014 to April 2016) are summarized in the following sections.

5.1 Service Reliability Measures in AM Peak Period

The cumulative distribution plot of on-time performance for buses during the AM peak period in all directions is displayed in Figure 5-1. On average, 87.4% of the bus services at time point level is on-time. The worst OTP is 69% in the AM peak period for high-frequency services. The most reliable service among 19 of 20 randomly selected bus routes (95th percentile) with high-frequency bus services in AM peak period will have a probability of 95.5% on-time.

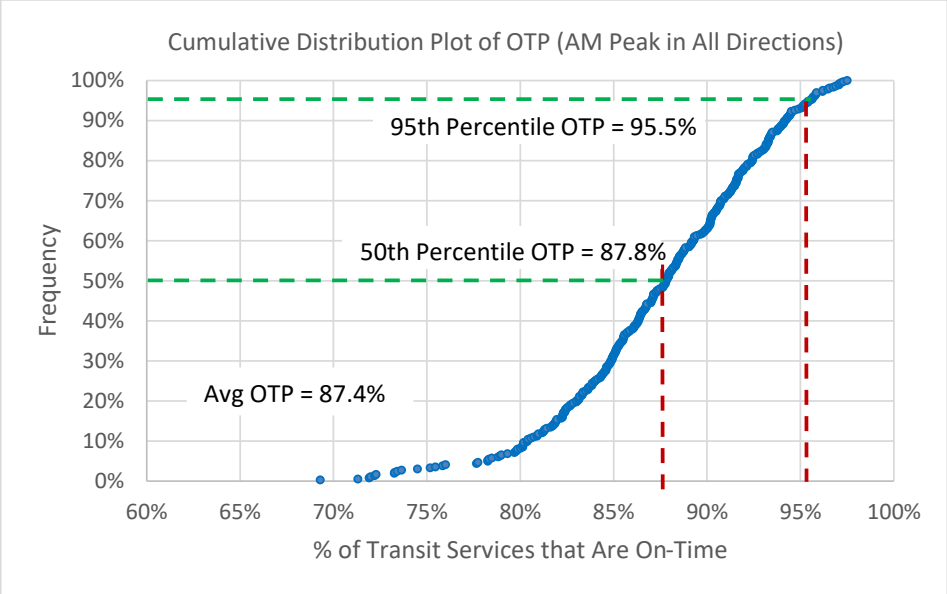


Figure 5-1 CDF Plot of Average OTP in AM Peak Period in All Directions

The cumulative distribution plot of lateness for buses during the AM peak period in all directions is displayed in Figure 5-2. For high-frequency services, the average lateness at time point level is 5.1 min. In the worst case scenario, an unreliable bus service could reach up to 10 min late in the AM peak period. The least reliable service among 19 of 20 randomly selected bus routes (95th percentile) with high-frequency bus services in AM peak period could be 7.9 min late.

The cumulative distribution plot of gap assessment for buses during the AM peak period in all directions is displayed in Figure 5-3.On average, 84% of the bus services at time point level has a gap variation less than or equal to 20% of the scheduled headway. In the least reliable case, only 70% of high-frequency bus services has a gap variation less than or equal to 20% of the scheduled headway in the AM peak period. The most reliable service among 19 of 20 randomly selected bus routes (95th percentile) with high-frequency bus services in AM peak period will have a probability of 93.5% with headway variation less than 20% of the scheduled headway.

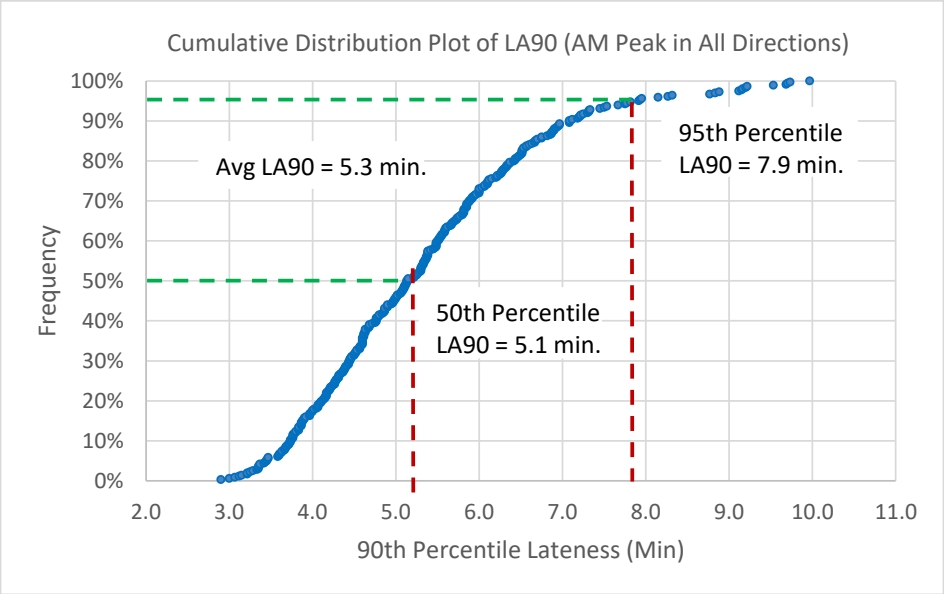


Figure 5-2 CDF Plot of Average 90th Percentile Lateness in AM Peak Period in All Directions

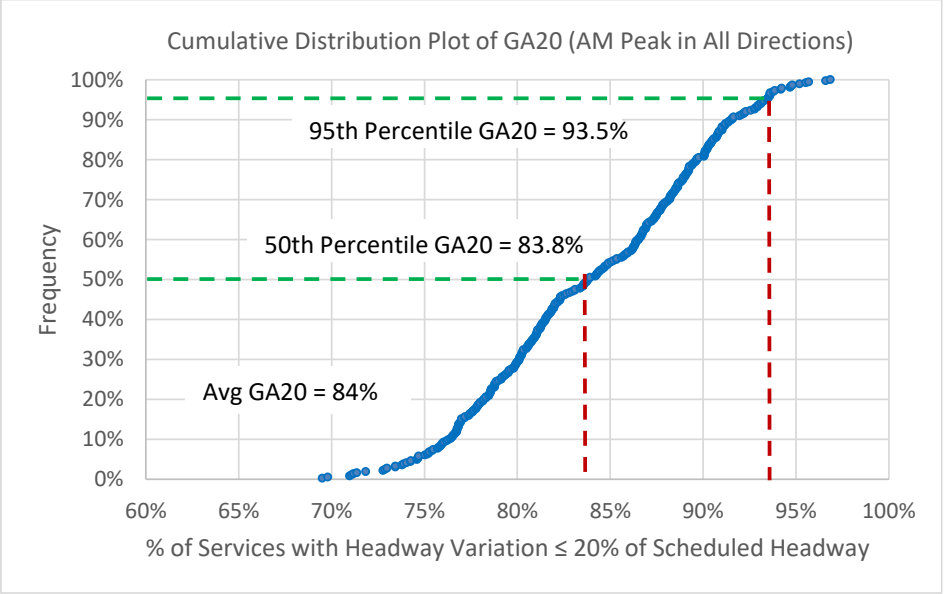


Figure 5-3 CDF Plot of Average Gap Assessment in AM Peak Period in All Directions

5.2 Service Reliability Measures in PM Peak Period

The cumulative distribution plot of on-time performance for buses during the PM peak period in all directions is displayed in Figure 5-4. On average, 76.2% of the bus services at time point level is on-time. The worst OTP is 52% in the PM peak period for high-frequency services. The most reliable service among 19 of 20 randomly selected bus routes (95th percentile) with high-frequency bus services in PM peak period will have a probability of 89.6% on-time.

The cumulative distribution plot of lateness for buses during the PM peak period in all directions is displayed in Figure 5-5. For high-frequency services, the average lateness at time point level is 8.0 min.

In the worst case scenario, an unreliable bus service could reach up to 17 min late in the AM peak period. The least reliable service among 19 of 20 randomly selected bus routes (95th percentile) with high-frequency bus services in PM peak period could be 11.7 min late.

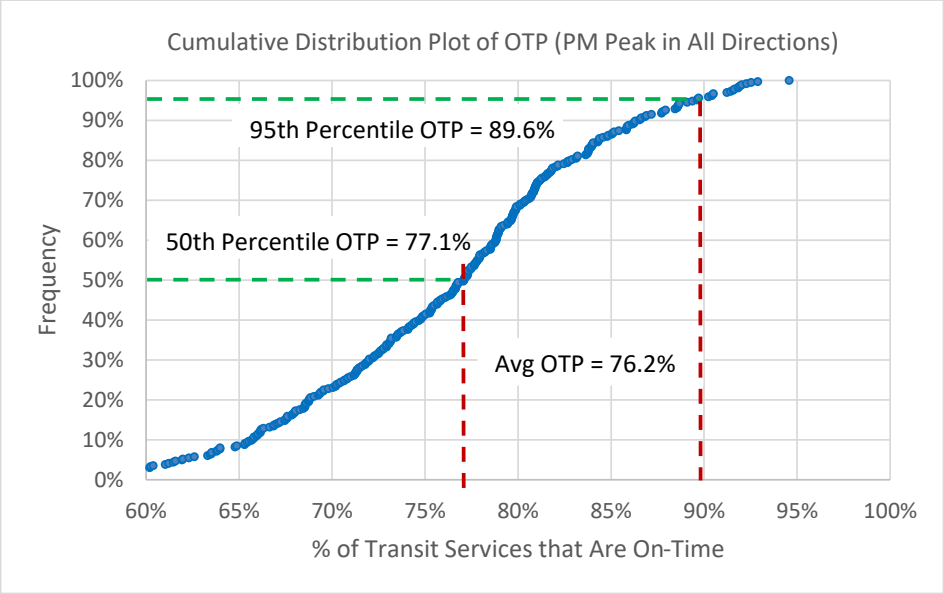


Figure 5-4 CDF Plot of Average OTP in PM Peak Period in All Directions

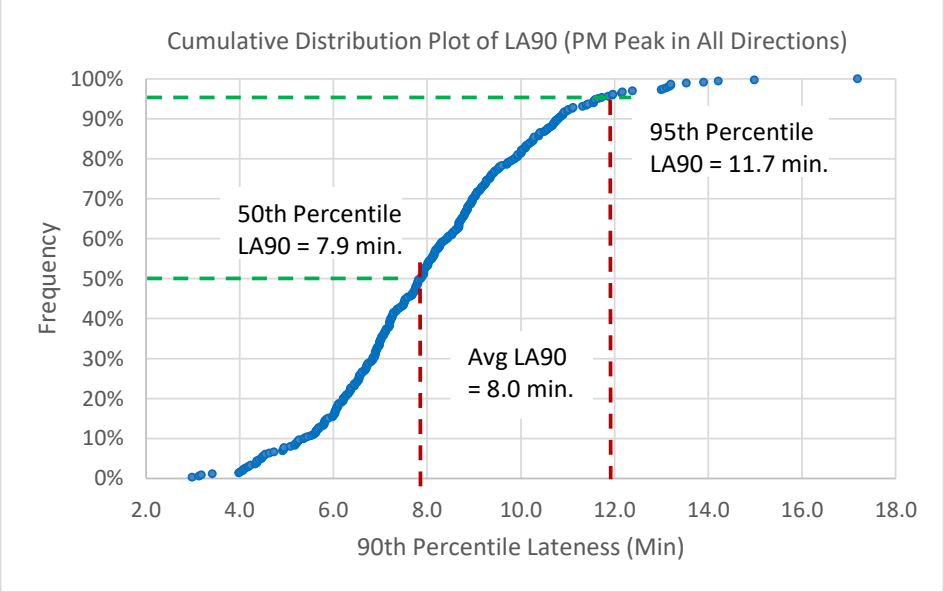


Figure 5-5 CDF Plot of Average 90th Percentile Lateness in PM Peak Period in All Directions

The cumulative distribution plot of gap assessment for buses during the PM peak period in all directions is displayed in Figure 5-6.On average, 76.4% of the bus services at time point level has a gap variation less than or equal to 20% of the scheduled headway. In the least reliable case, only 65% of high-frequency bus services has a gap variation less than or equal to 20% of the scheduled headway in the PM peak period. The most reliable service among 19 of 20 randomly selected bus routes (95th percentile) with

high-frequency bus services in PM peak period will have a probability of 90.2% with headway variation less than 20% of the scheduled headway.

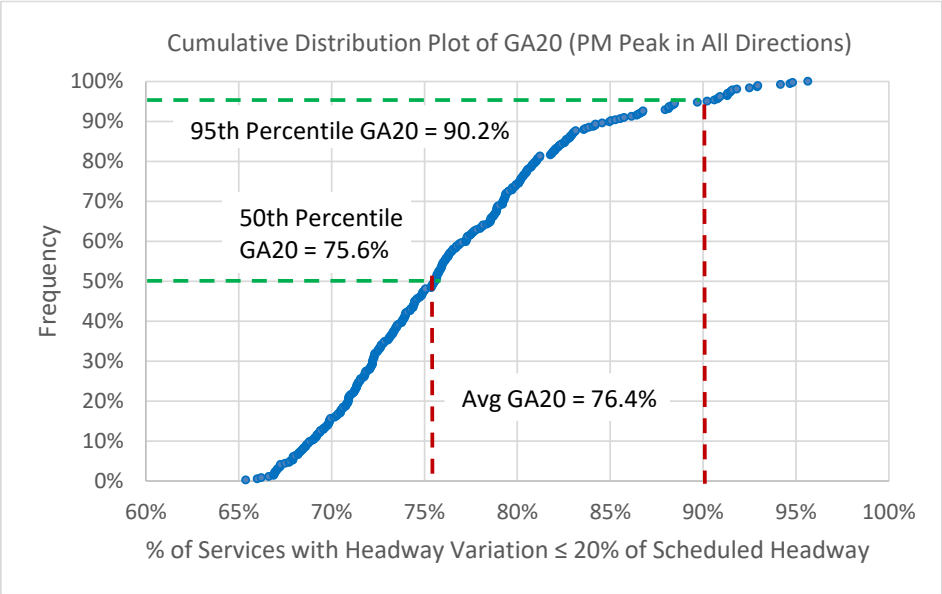


Figure 5-6 CDF Plot of Average Gap Assessment in PM Peak Period in All Directions

5.3 Service Reliability Measures in a Day

The cumulative distribution plot of on-time performance for buses during a day in all directions is displayed in Figure 5-7. On average, 85.3 % of the bus services at time point level is on-time. The worst OTP is 52.1% in a day for high-frequency services. The most reliable service among 19 of 20 randomly selected bus routes (95th percentile) with high-frequency bus services in a day will have a probability of 96% on-time.

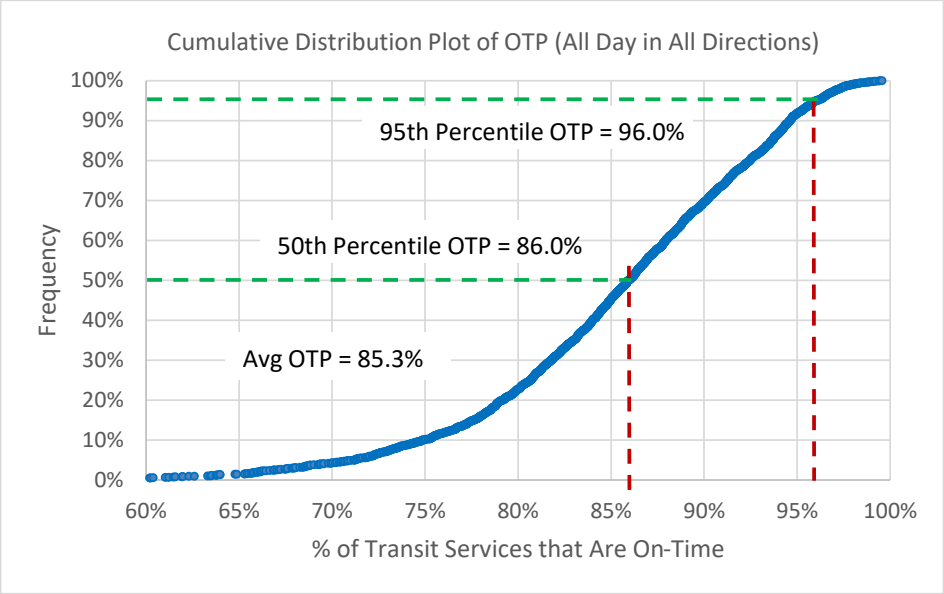


Figure 5-7 CDF Plot of Average OTP in a Day in All Directions

The cumulative distribution plot of lateness for buses in a day in all directions is displayed in Figure 5-8. For high-frequency services, the average lateness at time point level is 5.7 min. In the worst case scenario, an unreliable bus service could reach up to 17 min late in a day. The least reliable service among 19 of 20 randomly selected bus routes (95th percentile) with high-frequency bus services in a day could be 9.5 min late.

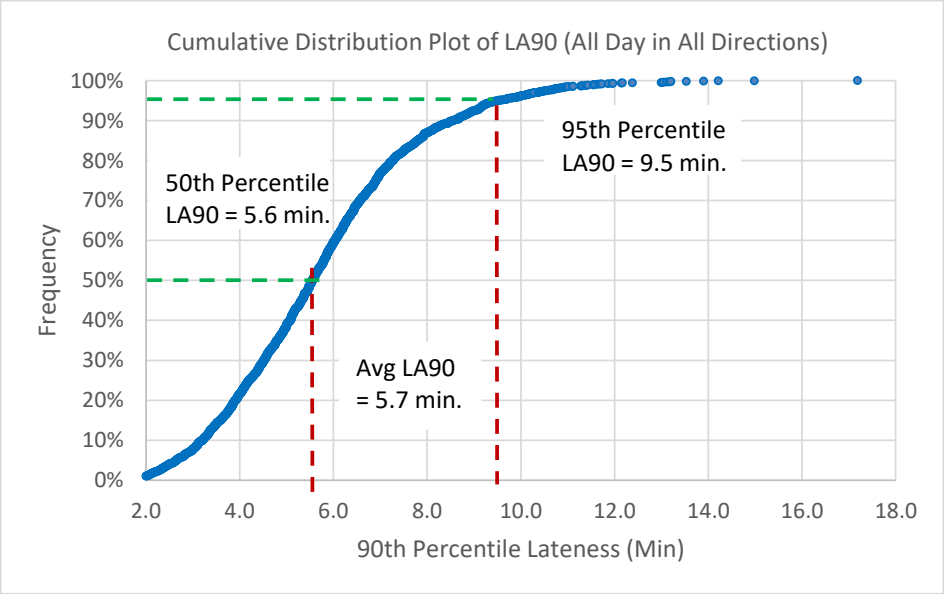


Figure 5-8 CDF Plot of Average 90th Percentile Lateness in a Day in All Directions

The cumulative distribution plot of gap assessment for buses in a day in all directions is displayed in Figure 5-9. On average, 80.5% of the bus services at time point level has a gap variation less than or equal to 20% of the scheduled headway. In the least reliable case, only 65% of high-frequency bus services has a gap variation less than or equal to 20% of the scheduled headway in a day. The most reliable service among 19 of 20 randomly selected bus routes (95th percentile) with high-frequency bus services in a day will have a probability of 98.6% with headway variation less than 20% of the scheduled headway.

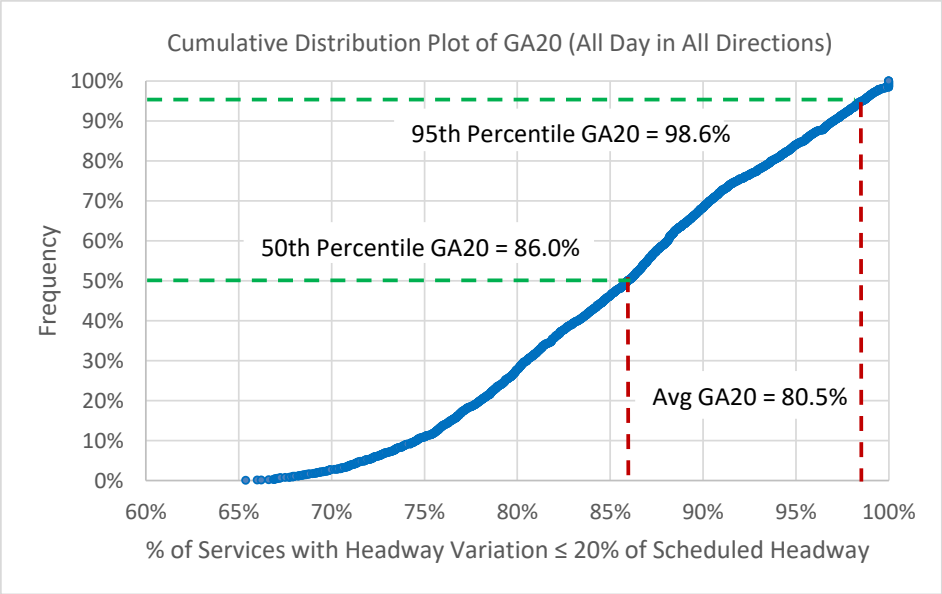


Figure 5-9 CDF Plot of Average Gap Assessment in a Day in All Directions

5.4 Summarized Reliability Measures by Time Period

Figure 5-10 displays the OTP, GA20, and LA90 service reliability measures by time period for high-frequency bus services. Bus services are more reliable in early morning and late evening periods. The PM peak period has the worst performance with 76.2% of on-time performance and 76.4% of gap variation less than 20% of scheduled headway. The high-frequency bus services that are late at time point level will have an average late time of 8-min based on the 90th percentile lateness measure in PM peak period.

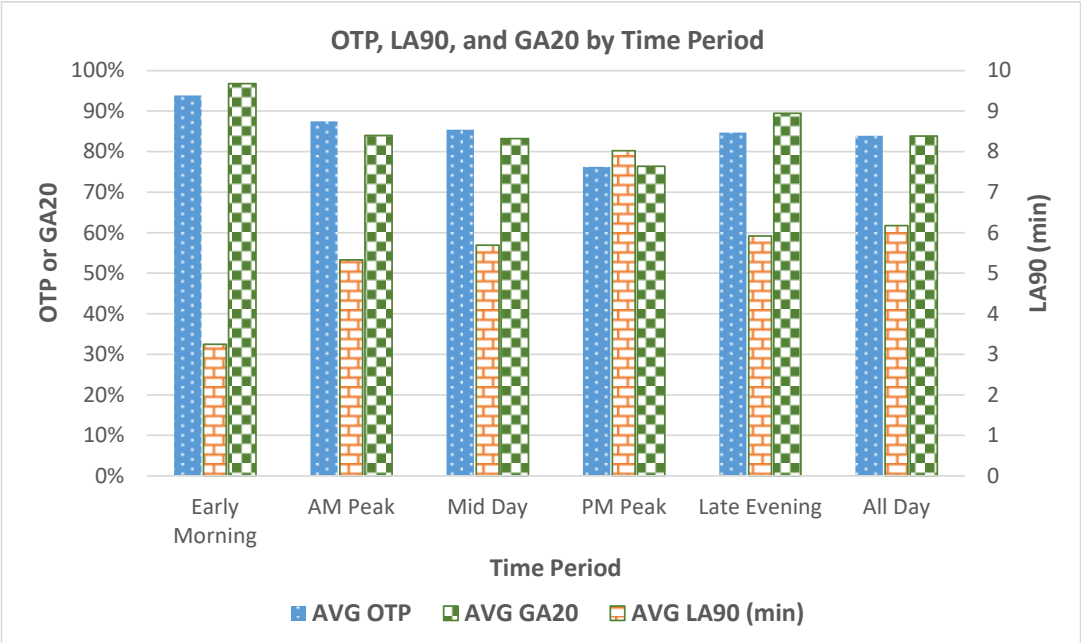


Figure 5-10 Service Reliability Measures by Time Period in All Directions

6. Summary and Discussion

The Transit Capacity and Quality of Service Manual (TCQSM) describes several performance measures for evaluating transit quality of service. Several different measures of service reliability are used by transit operators. The most common of these used in the transit industry are on-time performance, headway variation, and excess wait time. These measures are often used on high frequency services as a measure of how customers experience the service as they wait for the next bus or train.

Metro Transit currently use one measure of service reliability for all bus routes. Buses within 1 minute early to 5 minutes late are deemed to be "on-time". Light rail transit (LRT) within 1 minute early to 4 minutes late are considered as "on-time". Transit services outside the "on-time" range are identified as either "early" or "late". Metro Transit has an overall goal that bus service will be on-time 87.6 percent of the time. The on-time performance goals for the Blue Line and Green Line services are 95% and 90% on-time, respectively.

The purpose of this research is to identify measures of transit service reliability that may be applicable to Metro Transit bus and light rail services and how they might be used most effectively by Metro Transit. The objective is to explore different measures of transit service reliability, determine which ones are applicable to Metro Transit's services, and provide a proof of concept of how these measures could be applied using available Metro Transit operations data.

We first reviewed common service reliability measures that are used for bus and light rail services both in the United States and internationally. We identified 18 common service reliability measures and categorized them into four groups: (A) schedule adherence, (B) travel time reliability / delay, (C) headway, and (D) others. Four service reliability measures, On-Time Performance (OTP), Excess Wait Time (EWT), Gap Assessment (GA), and 90th percentile of lateness (LA90), were finalized for further investigation and evaluation. We applied the finalized service reliability measure on 13 high frequency routes and 2 LRT lines using transit operations data from January 2014 to April 2016.

The following selection criteria are applied to evaluate how the 4 selected measures are applicable to transit services and how they might be used most effectively by Metro Transit.

1. Is the service reliability measure easy to interpret?
2. Is data available for both historical reporting and real-time applications?
3. Can the metric provide a different perspective as compared to current OTP?
4. Can the metric support best operational practices?

On-time performance (OTP), gap assessment (GA), and 90th percentile of lateness (LA90) are selected by Metro Transit to implement. OTP is the current key performance index used by the Metro Transit. It will continue to be used as a baseline measure for service reliability. GA is a customer focused headway adherence measure. It could be easily implemented based on existing transit operations data. In addition to the OTP, the LA90 measure describes the typical late range of a transit service. It indicates 'how badly' the transit services are not meeting the OTP threshold. The excess wait time (EWT) is not recommended because it is difficult to interpret and the computed results are unable to provide a clear indication of operations performance.

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Appendix A: Common Service Reliability Measures

Service reliability measures from the literature review are summarized and listed in Table A-1 as follows.

Table A-1 Summary of Service Reliability Measures

Category	#	Service reliability measures	Referemces	Purpose	Methodology / Definition	Pros	Cons	What types of service		Used at which level			Which time period		Examples	Other notes
								Bus	LRT	System level (S)	Route level (R)	Timepoint level (TP)	Historical data (H)	Real-time data (RT)		
A. Schedule Adherence	A1	On-time performance (OTP) from operator's perspective	TCQSM	Measure the quality of service	Difference between real time and scheduled times of arrival or departures times, usually expressed in minutes. On-time definition: 1 min early and up to 5 min late (TCRP Report 100). On time Performance = (Services on time) * 100% / (Total Services)	Simple measure; better for longer header headway (> 10 min)	Insufficient information to effectively maintain transit quality, it cannot identify trends, detect problems with individual routes or trips (brunching). The measured result is highly dependent on how "on time" is defined.	X	X			X	X	X	90% of service was on-time, based on analysis at the timepoint level, with on-time defined as between 1 minute early to 5 minutes late.	
	A2	OTP from riders' perspective	MBTA (Tribone et al. 2014)	Inlcude passengers experiences	1. Percentage of passengers waited less than published headway.	Measur from a customer's perspective; capture passengers wait time	Need to include passenger arrival model at each stop or TP	X	X	X	X	X	X		1. 89% of passengers waited less than published headway (goal 90%).	
					2. Percentage of passengers waited shorter than a big gap, defined as (Minimum[1.5xheadway, headway+3 min]).										2. 98% of passengers waited shorter than a big gap which is defined as the minimum of 1.5xheadway or headway+3 min.	
					3. Percentage of passengers waited shorter than 2x headway										3. 100% of passengers waited shorter than twice the headway	
	A3	Excess wait time (EWT)	TCQSM	Measure rider's excess waiting time and bus punctuality	EWT = departure_time - schedule_time (for all non-negative values)	Measure passenger's waiting experience at time points	Does not consider headway. Need to include passenger arrival info to better assess the impact	X	X			X	X		Excess wait time for passengers is 2 min on average at TP X in AM peak	
			CLIP UK		Excess wait time (EWT) = Average wait time (AWT) - Scheduled Wait Time (SWT)		Suitable for high frequency buses (headway less than 10-min)								Excess wait time for passengers is 1.19 min on average at TP Y in PM peak	http://clip.local.gov.uk/lgv/core/page.do?pageId=36703
B. Travel Time Reliability / Delay	B1	Passenger travel time	MBTA (Tribone et al. 2014)	Measure passenger's trip delay	Compare actual travel time with median trip time	Measur from a customer's perspective	Need passenger O-D info (entry & exit validation)	X	X	X	X		H		96% of passengers experienced delay less than 3 min and/or 99% of passengers experienced delay less than 6 min	
	B2	Journey time	London Underground	Calculate customer's travel time beween entering and leaving the system	Compute time difference between tap-in and tap-out	Capture customer's experience	Require both entry and exit validation	Subway or other transit systems that captures boarding and		X			X	X	90% of passengers experienced no journey delay or delay less than 5 min	
	B3	Run time variation	Diab & El-Geneidy (2013)	Evaluate the impact of bus running time variation	Run time variance / average run time, or coefficient of variation (CV)	Evaluate the impact of TSP/BRT strategies, useful for transit modeling	It does not reflect passenger's experience and transit performance within a trip. The CV is not strongly associated with the normal distribution. It is most pertinent for the lognormal or gamma distribution.	X		X	X		X			
	B4	Run time deviation	Diab & El-Geneidy (2013)	Evaluate the impact of bus running time deviation	Actual run time divided by the scheduled run time	Evaluate the impact of TSP/BRT strategies, useful for transit modeling	It does not reflect passenger's experience and transit performance within a trip. It's difficult to visualize the reliability performance based on the number	X		X	X		X			

Table A-1 Summary of Service Reliability Measures (Cont.)

Category	#	Service reliability measures	Referemces	Purpose	Methodology / Definition	Pros	Cons	What types of service		Used at which level			Which time period		Examples	Other notes
								Bus	LRT	System level (S)	Route level (R)	Timepoint level (TP)	Historical data (H)	Real-time data (RT)		
C. Headway	C1	Headway deviation	Strathman & Kimpel (2003); Sharma et al. (2015)	Evaluate the impact of headway deviation on passenger load or other service reliability measures	Actual headway measured at the end of a segment divided by scheduled headway at the end of the segment, headway_actual / headway_scheduled	Offer headway reliability analysis and evaluate potential bunching	It does not incude passengers' waiting at TPs or stops. Not appropriate for less-frequent services. It's difficult to visualize the reliability performance based on the number	X	X			X		X	Headway deviation for bus route X in off-peak in NB is 0.2	Use percentage by comparing to a baseline
	C2	Headway Analysis - Wait Assessment (WA)	NYCT	Evaluat bunching and significant gap in service at route level	Percentage of scheduled intervals passing the WA criteria defined as follows. Subway +25%, Bus +3 min (peak), +5 min (off-peak). **Minor gaps** - 25-50% above scheduled headway; **Medium gaps** - 50-100% above scheduled headway; **Major gaps** - 100% above scheduled headway; wait assessment matching algorithm	A simple measure to assess the daily performance of a route		X	X		X		X			65% of buses on route X operates within (headway+3 min) in AM peak and 70% of buses on route X operates within (headway+5 min) in off-peak period	
	C3	Bunching and Gap	NYCT, SFMTA	Measure bunching or gaps between transit vehicles	% of bus trips are bunched as compared to the total number of trips by route direction and time period (actual headway < 25% of scheduled headway is considered bunched)	A summarized measure to assess bunching at a route or system level for frequency transit services	Does not consider passengers' waiting time	X		X	X		X	X	5% of buses on route X is bunched in AM peak in NB direction	http://sfgov.org/scorecards/transit-trips-bunching-or-gaps-between-vehicles
	C4	Headway adherence	TCQSM	Evaluate headway variations	Standard deviation of headway deviations / mean scheduled headway	A normalized measure to measure head adherence	It's difficult to visualize the reliability performance based on the adherence number (coefficient of variation)	X	X	X	X	X	X		Headway ahderence for bus route X in PM peak in EB is 0.3	Use percentage by comparing to a baseline
D. Others	D1	Dwell at TP	NYCT	Evaluate median dwell time variation	Dwell = Departure time at TP - arrival time at TP. % of dwell change as compared to a baseline at a TP	Assess dwell variation at a time point	Does not reflect dwell causes such passenger demand	X	X		X	X	X		1.0% of dwell time increase at TP X in AM peak in SB this week	
	D2	Holding time at TP		Measure excess scheduled TT	Schedule time - last door close time	Evaluate excess scheduled time	May include signal delay at near-side TP	X	X		X	X	X		66 sec of average holding time at TP X in off peak in SB	
	D3	Missed trips	TCQSM	Compute # of missed trips	Percentage of missed trips as compared to scheduled trips in a route			X	X	X	X		X		0.5% of missed trips for route X in WB	
	D4	Percent of scheduled time in operation	TCQSM	Measure % of transit vehicles in operation				X	X	X	X		X			
	D5	Distance traveled between mechanical breakdowns	TCQSM	Measure vehicle failure rate				X	X	X	X		X			
	D6	Earliness, Delay Index & Width Index	Saberi (PSU)	Identify possible delay sources	Distribution of buses arrive early or late			X	X	X		X	X			

Appendix B: Service Reliability Measures by Time Point

Plots of selected service reliability measures by time point are included as follows.

B.1 On-Time Performance (OTP)

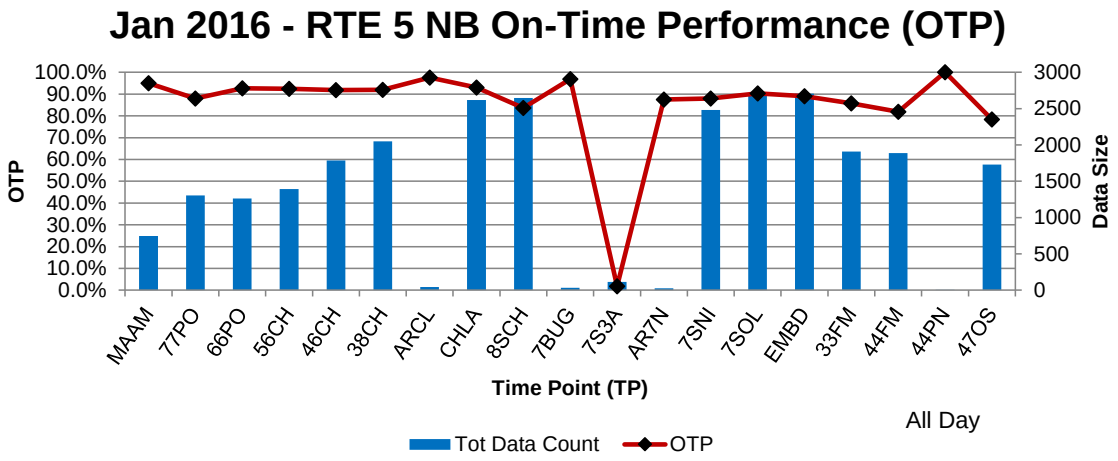

Figure B-1 Bus Route 5 NB OTP by TP

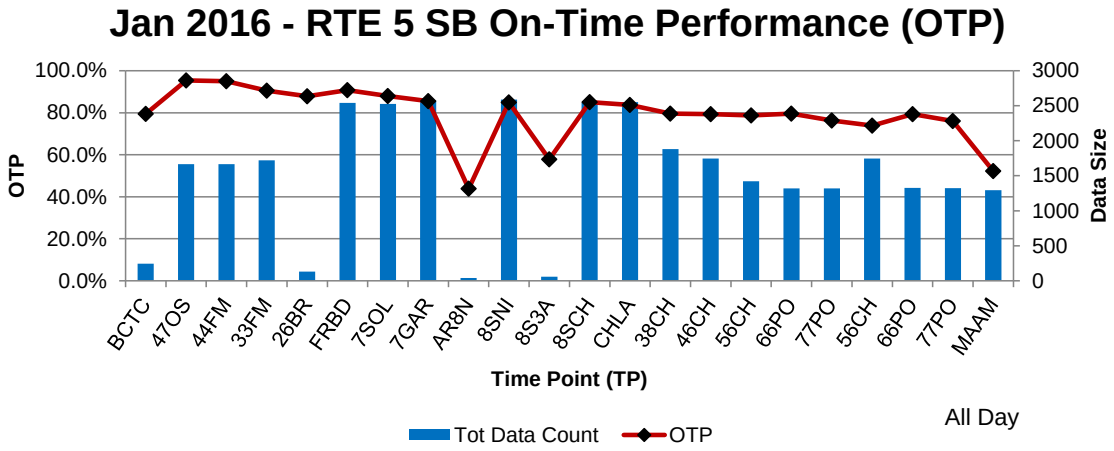

Figure B-2 Bus Route 5 SB OTP by TP

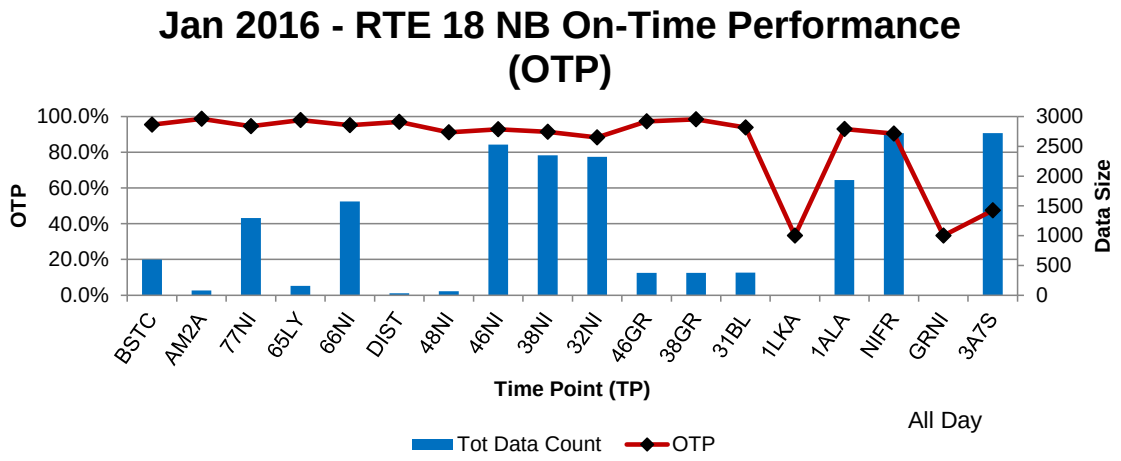

Figure B-3 Bus Route 18 NB OTP by TP

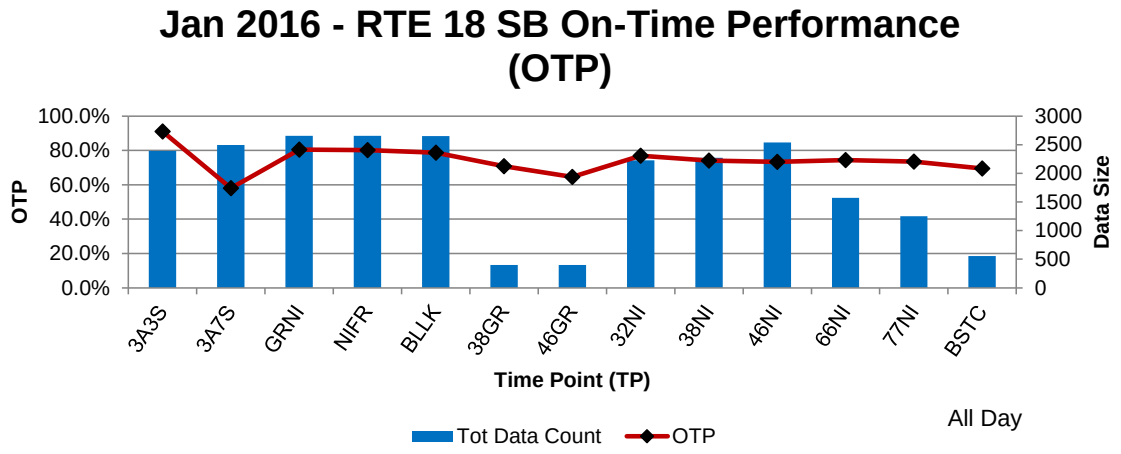

Figure B-4 Bus Route 18 SB OTP by TP

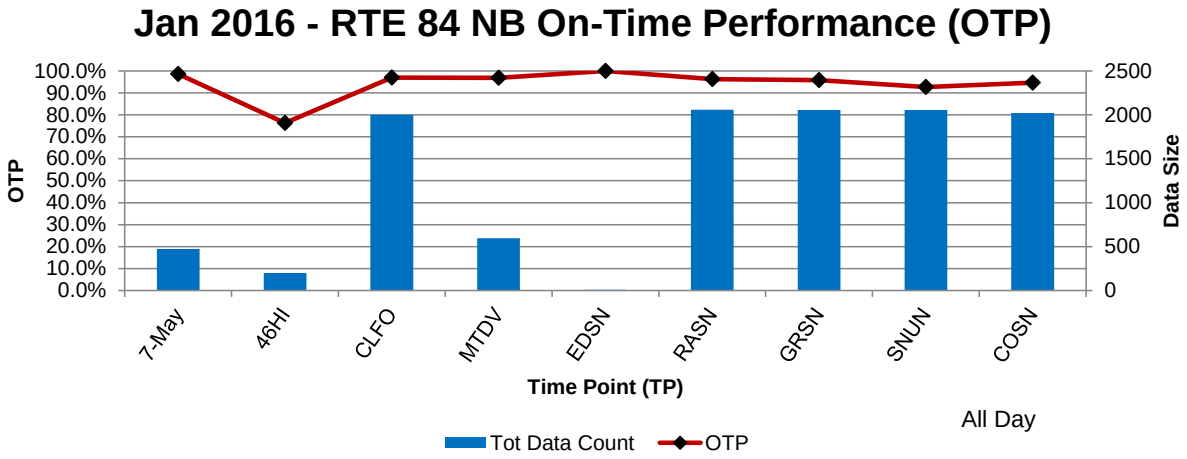

Figure B-5 Bus Route 84 NB OTP by TP

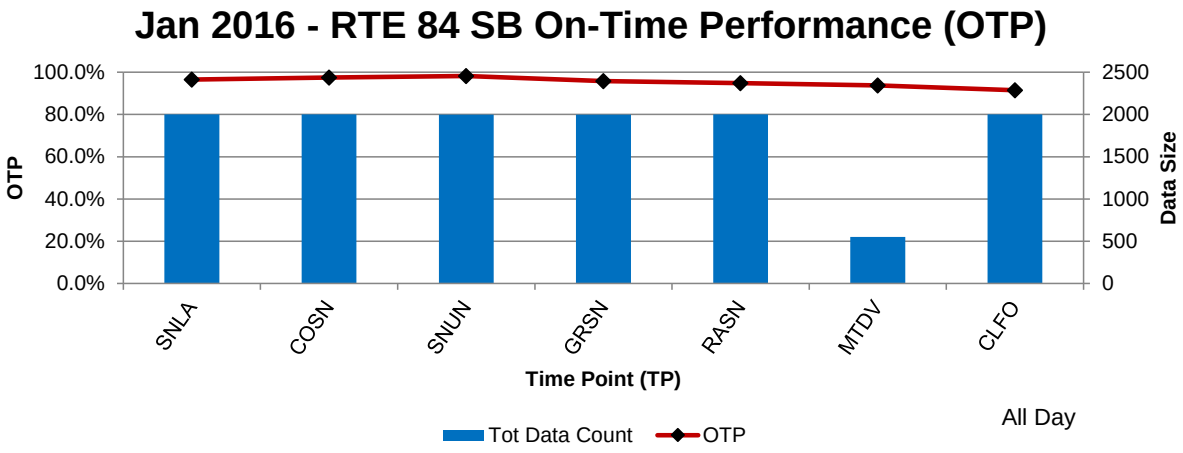

Figure B-6 Bus Route 84 NB OTP by TP

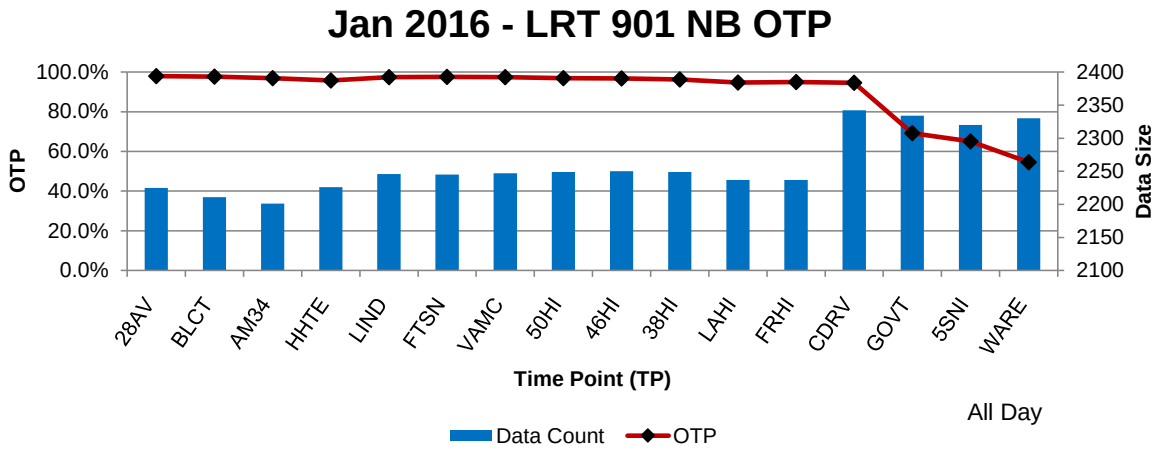

Figure B-7 LRT Blue Line NB OTP by TP

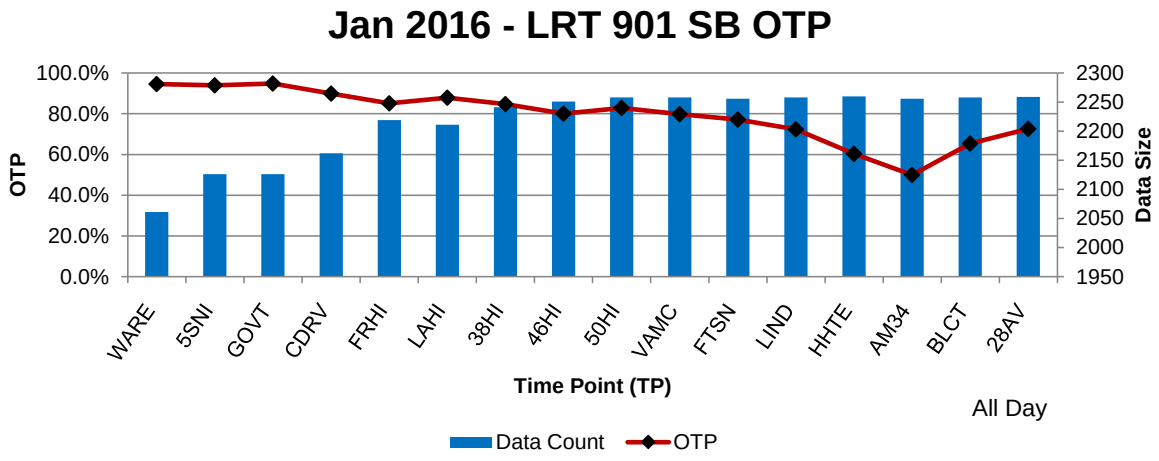

Figure B-8 LRT Blue Line SB OTP by TP

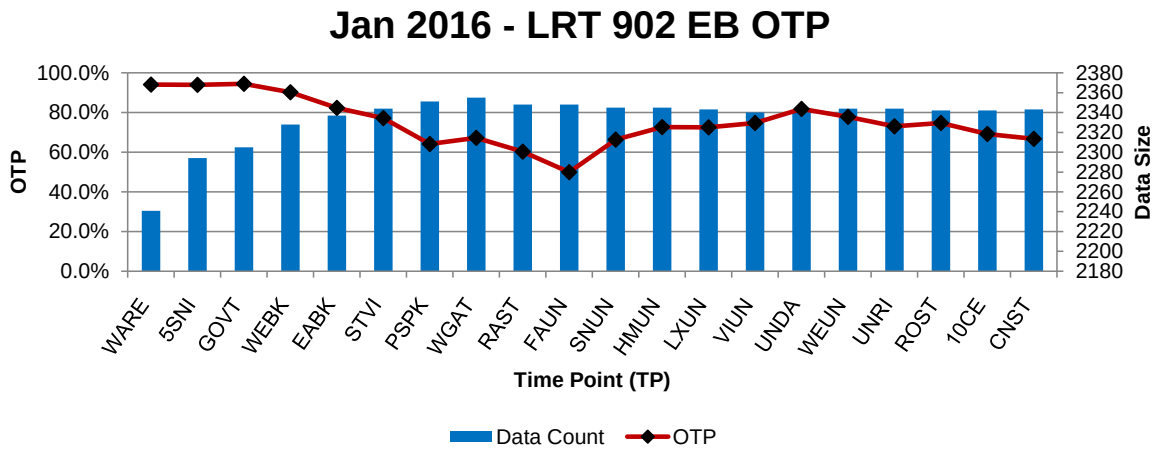

Figure B-9 LRT Green Line EB OTP by TP

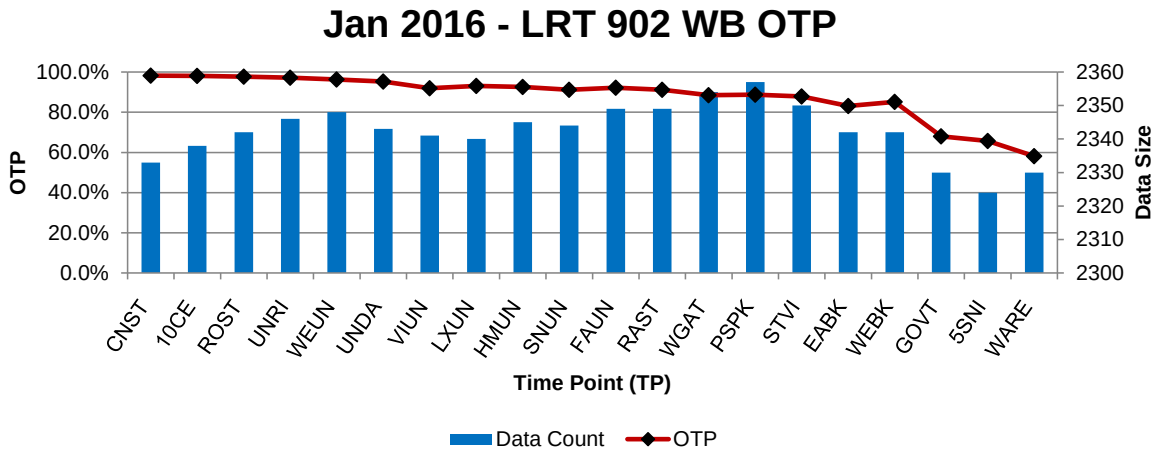

Figure B-10 LRT Green Line WB OTP by TP

B.2 Excess Wait Time (EWT)

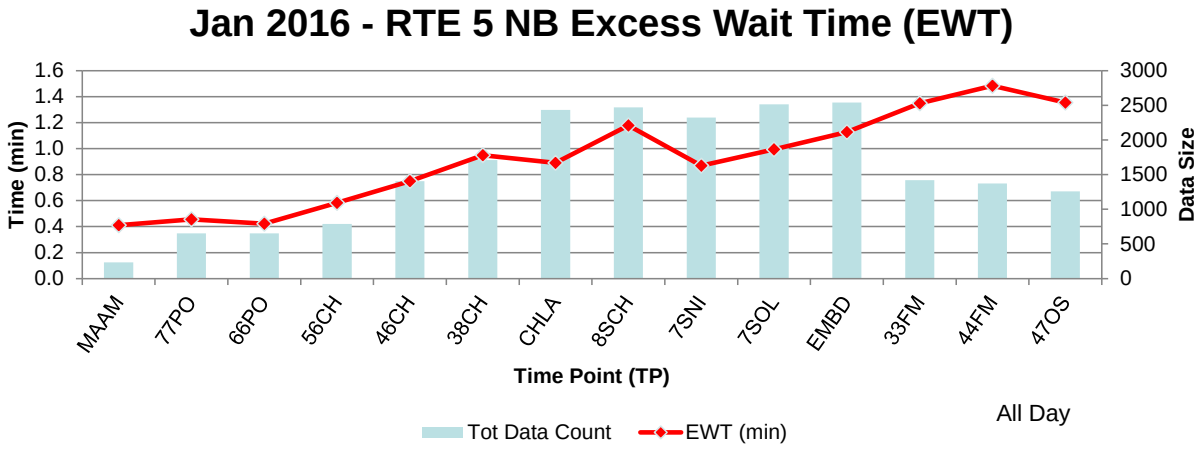

Figure B-11 Bus Route 5 NB EWT by TP

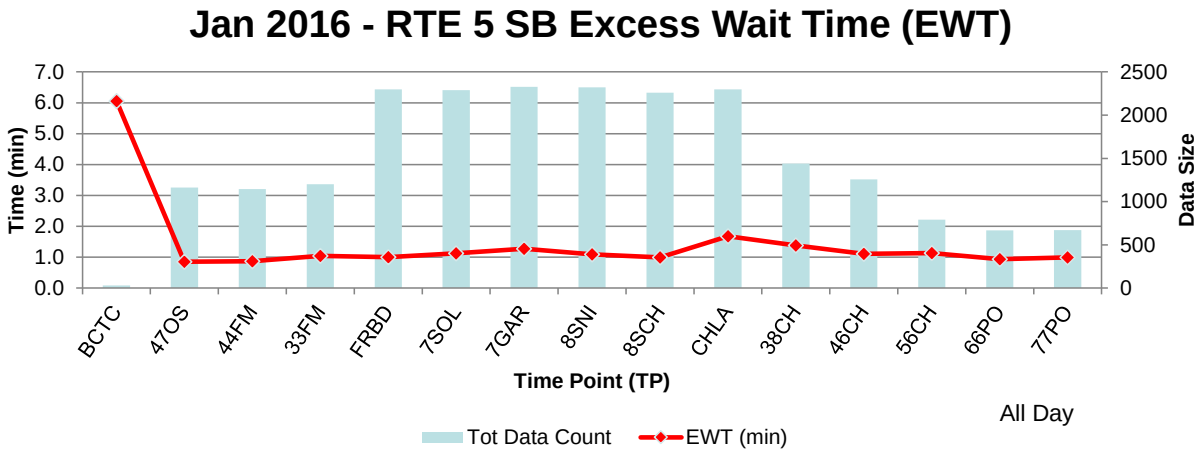

Figure B-12 Bus Route 5 SB EWT by TP

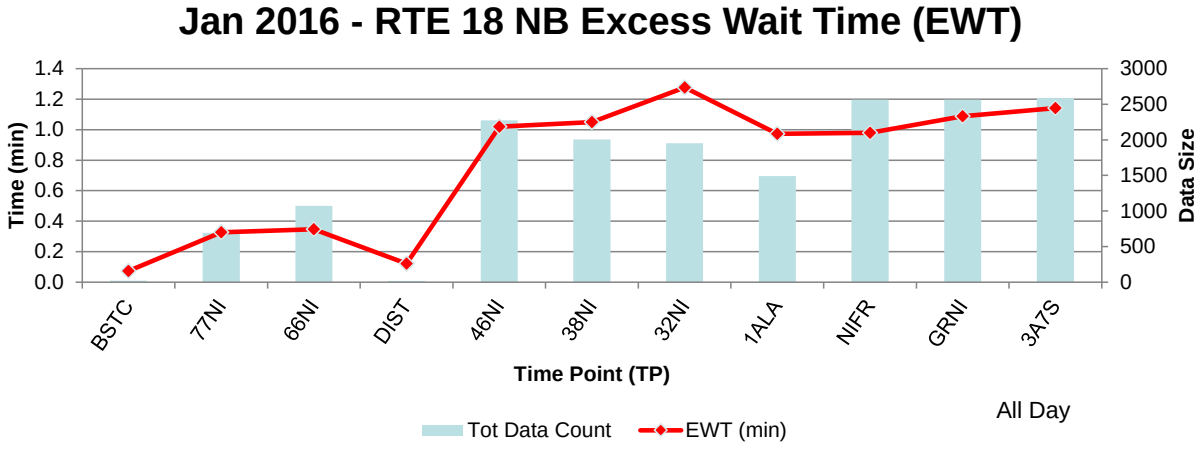

Figure B-13 Bus Route 18 NB EWT by TP

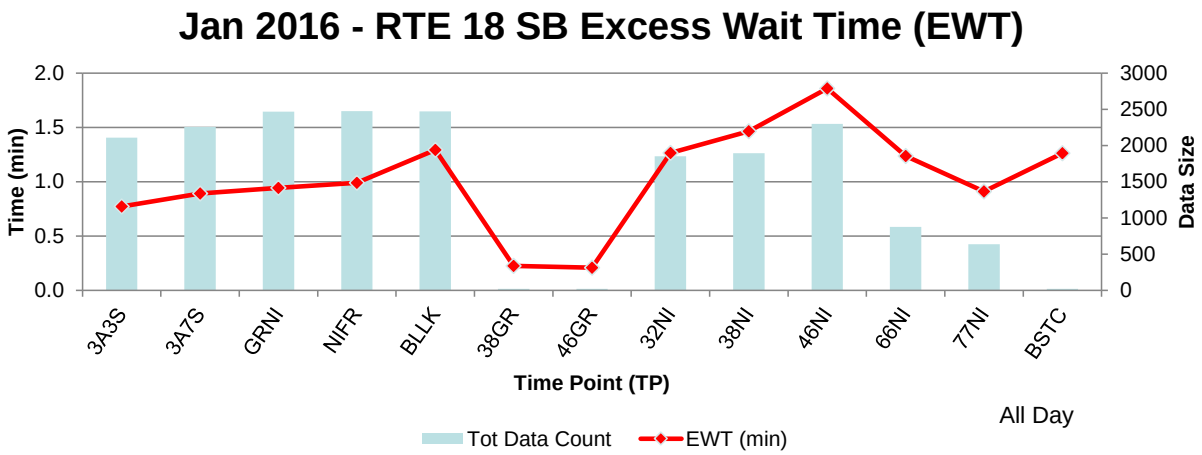

Figure B-14 Bus Route 18 SB EWT by TP

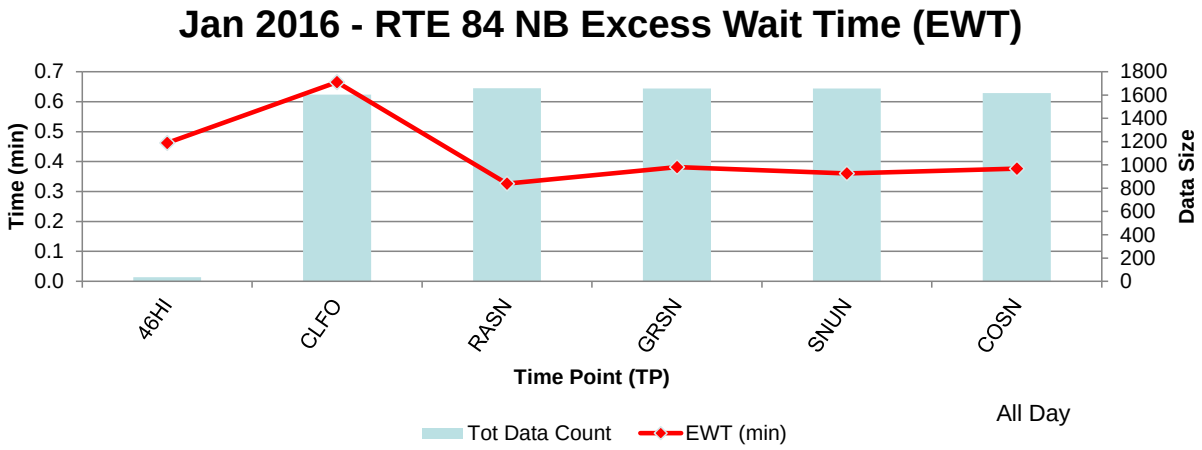

Figure B-15 Bus Route 84 NB EWT by TP

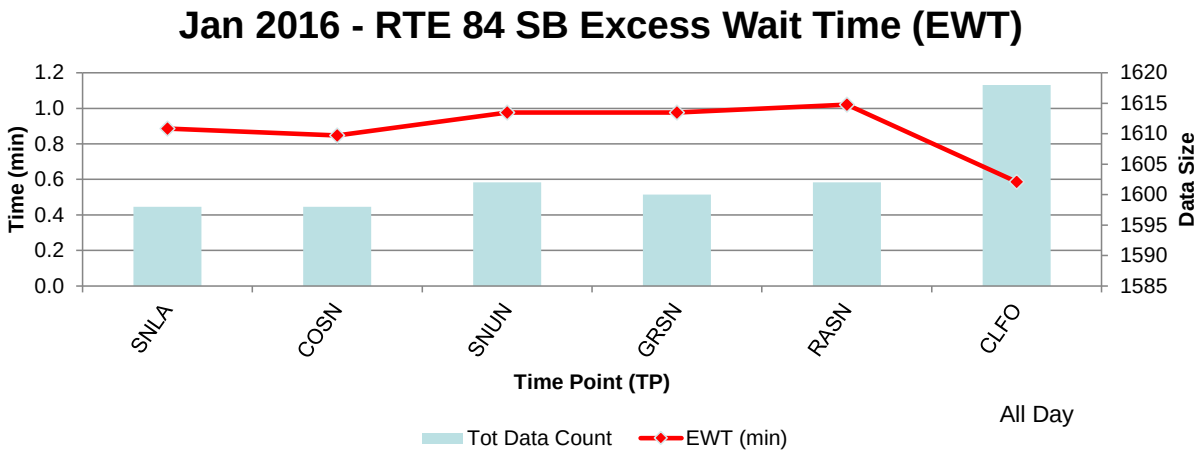

Figure B-16 Bus Route 84 NB EWT by TP

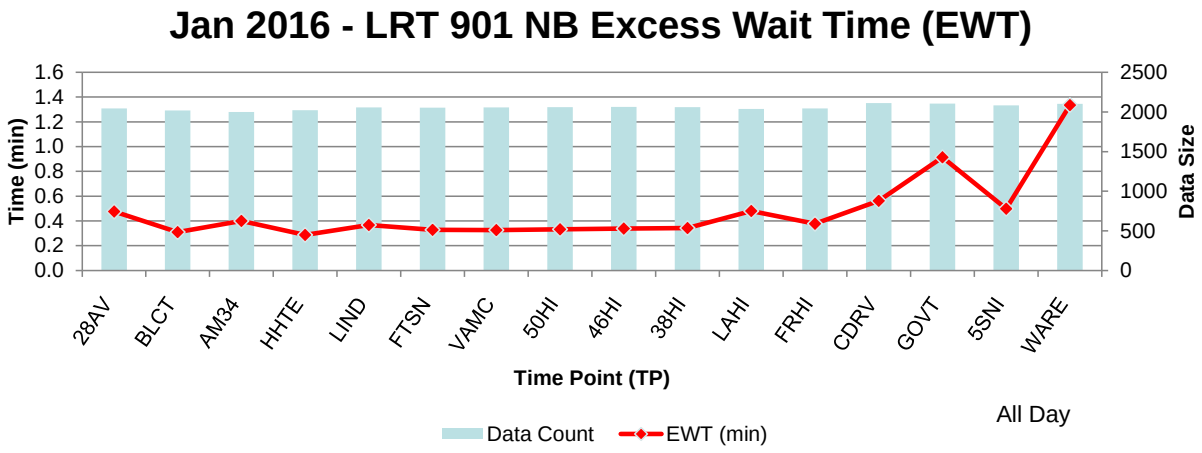

Figure B-17 LRT Blue Line NB EWT by TP

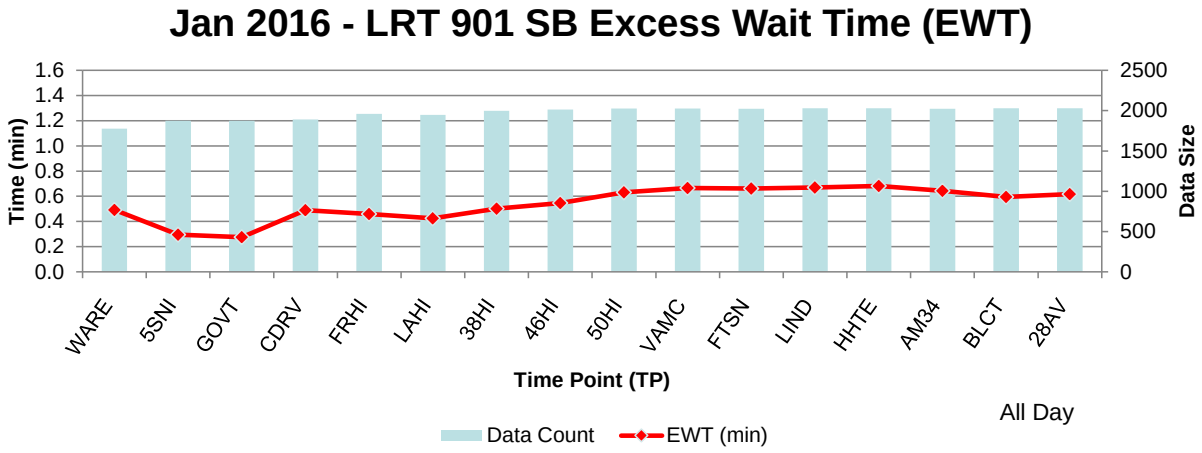

Figure B-18 LRT Blue Line SB EWT by TP

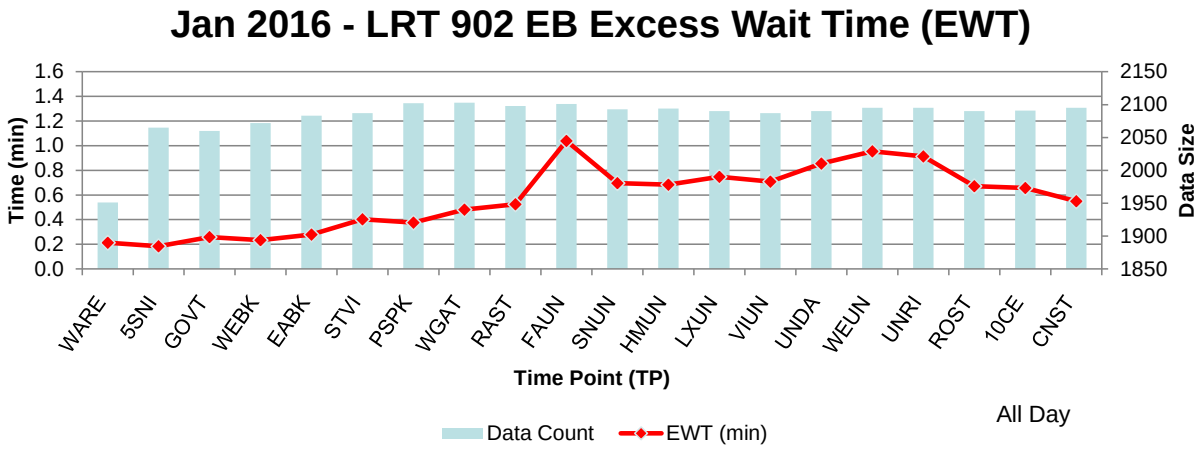

Figure B-19 LRT Green Line EB EWT by TP

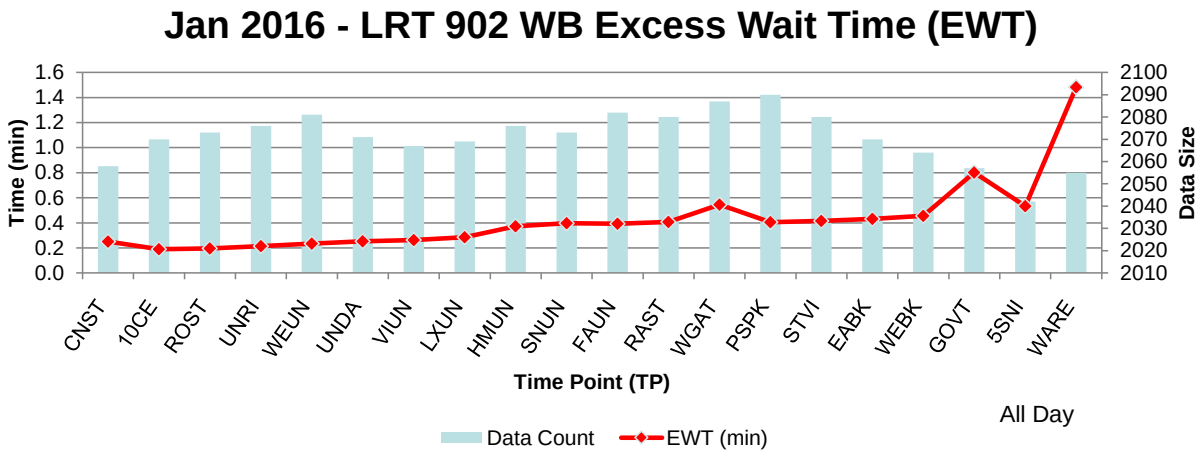

Figure B-20 LRT Green Line WB EWT by TP

B.3 Gap Assessment (GA)

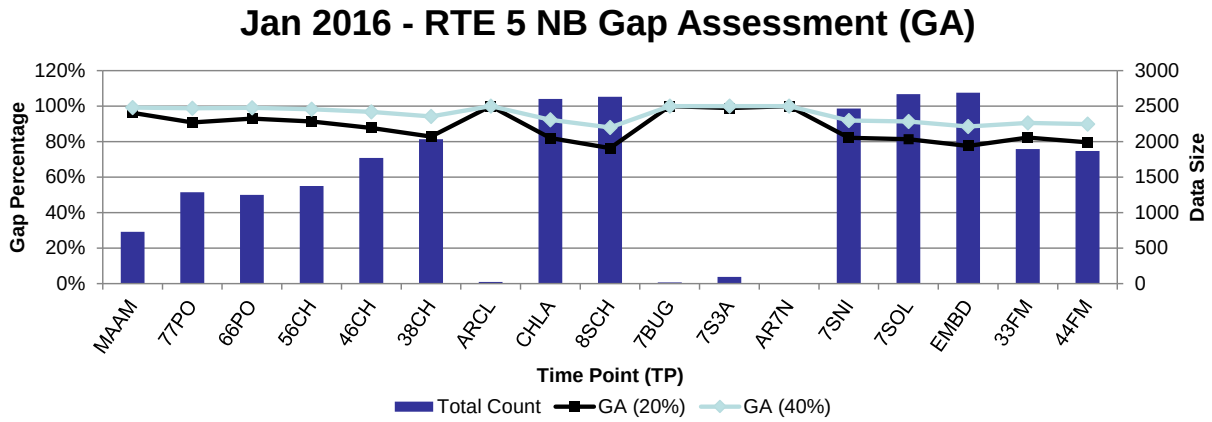

Figure B-21 Bus Route 5 NB Gap Assessment by TP

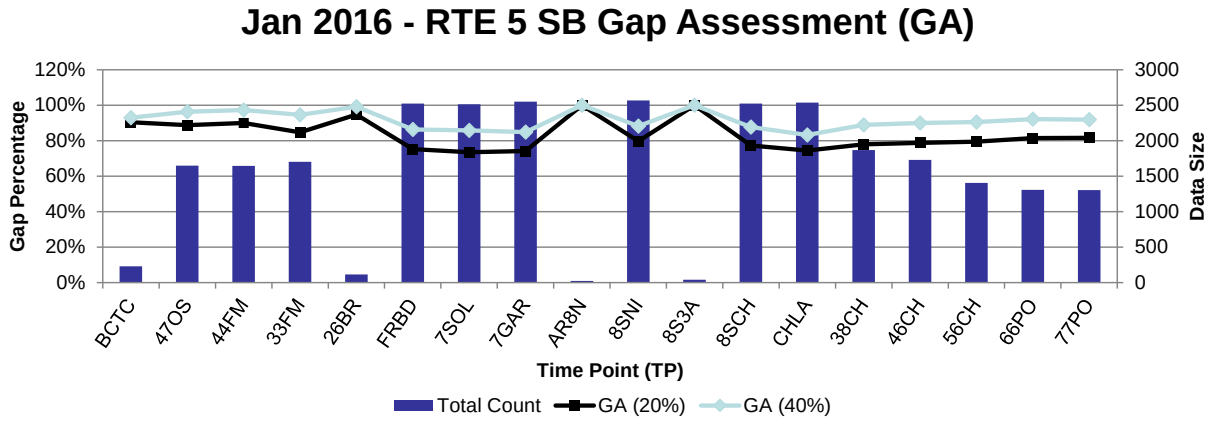

Figure B-22 Bus Route 5 SB Gap Assessment by TP

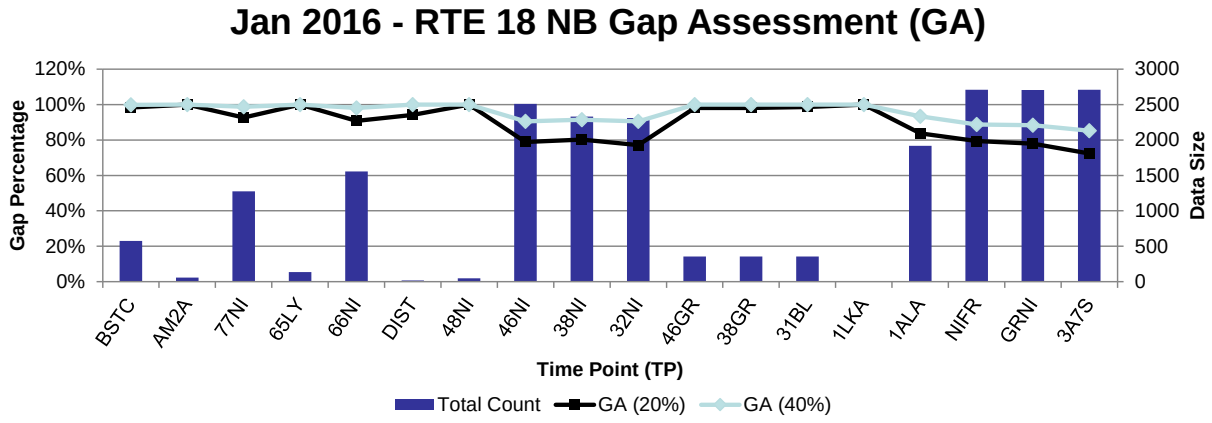

Figure B-23 Bus Route 18 NB Gap Assessment by TP

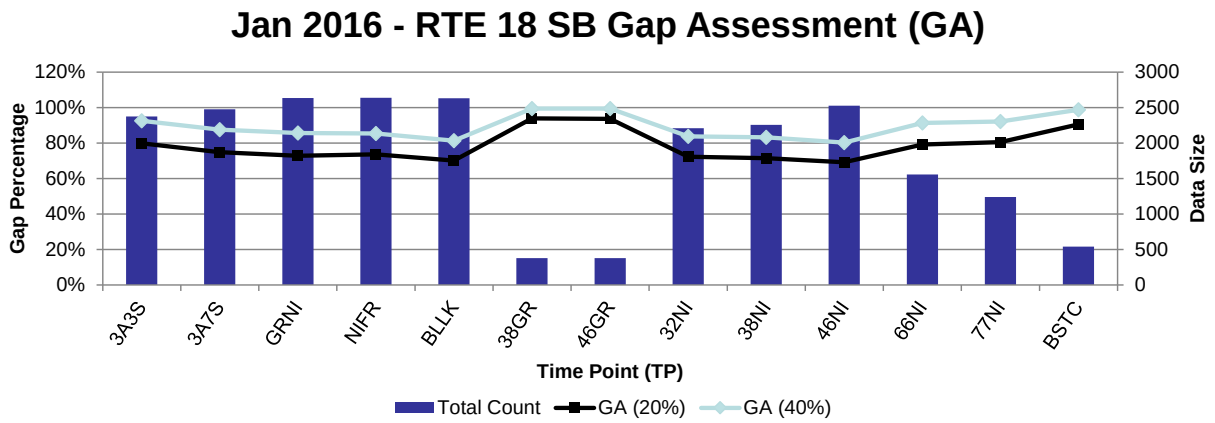

Figure B-24 Bus Route 18 SB Gap Assessment by TP

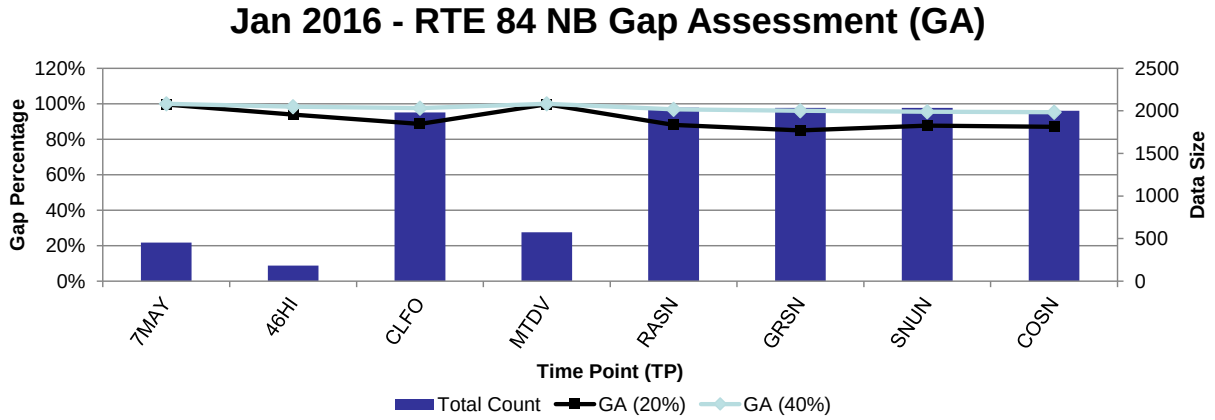

Figure B-25 Bus Route 84 NB Gap Assessment by TP

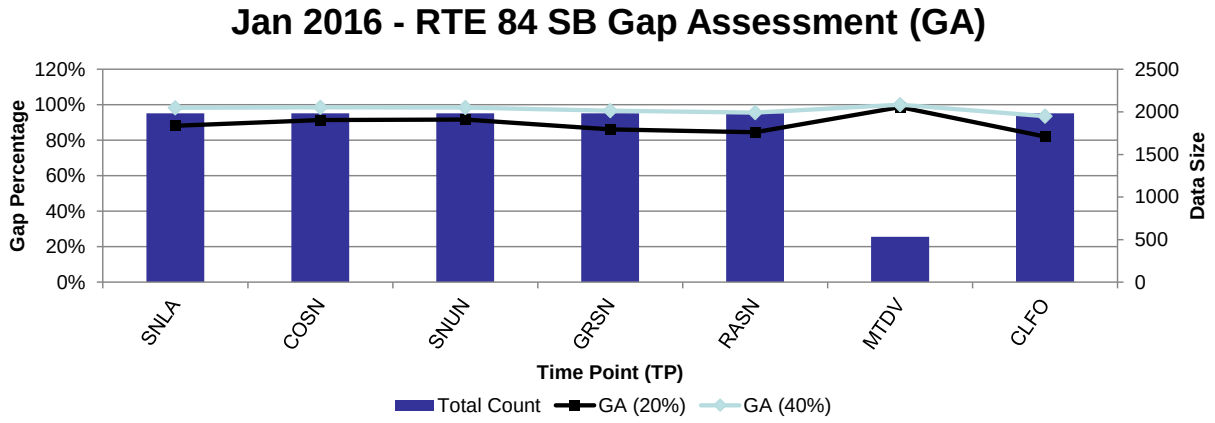

Figure B-26 Bus Route 84 NB Gap Assessment by TP

Appendix C: Monthly Service Reliability Measures

Plots of monthly service reliability measures from January 2014 to April 2016 are included as follows.

C.1 Bus Route 4

Figure C-1 displays the monthly OTP and GA20 of bus route 4 in both directions. The average OTP and GA20 are respectively around 83% and 86% for bus route 4. Figure C-2 displays the monthly EWT and LA90 of bus route 4 in both directions. The average EWT and LA90 are respectively around 1.9 and 6.4 minutes for bus route 4.

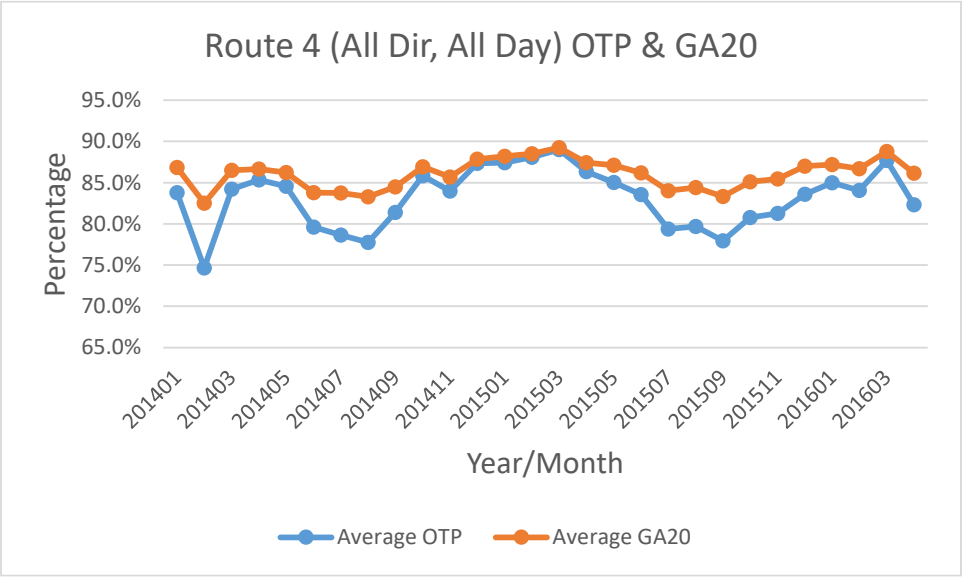

Figure C-1 Monthly OTP and GA20 of Bus Route 4

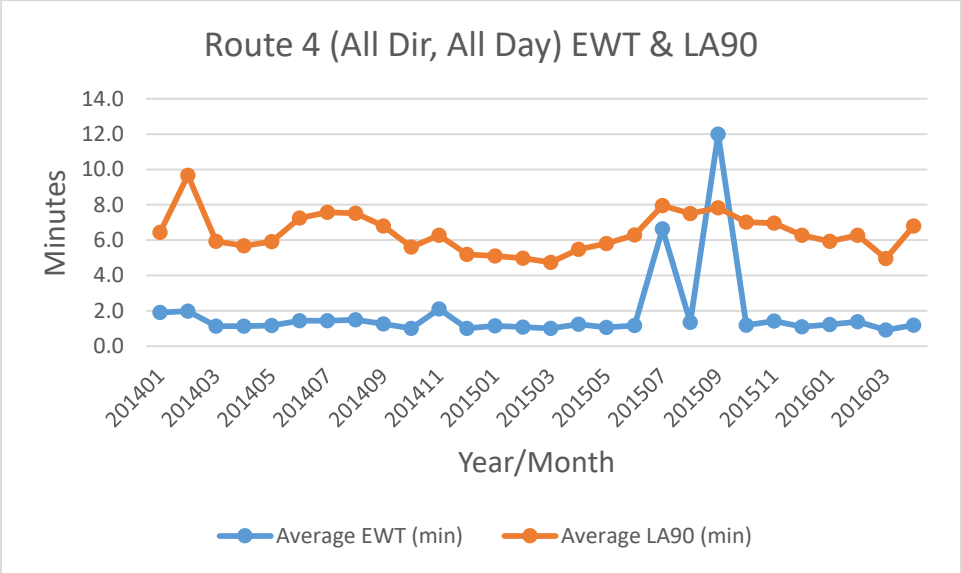

Figure C-2 Monthly EWT and LA90 of Bus Route 4

C.2 Bus Route 5

Figure C-3 displays the monthly OTP and GA20 of bus route 5 in both directions. The average OTP and GA20 are respectively around 81% and 78% for bus route 5. Figure C-4 displays the monthly EWT and LA90 of bus route 5 in both directions. The average EWT and LA90 are respectively around 1.7 and 7.3 minutes for bus route 5.

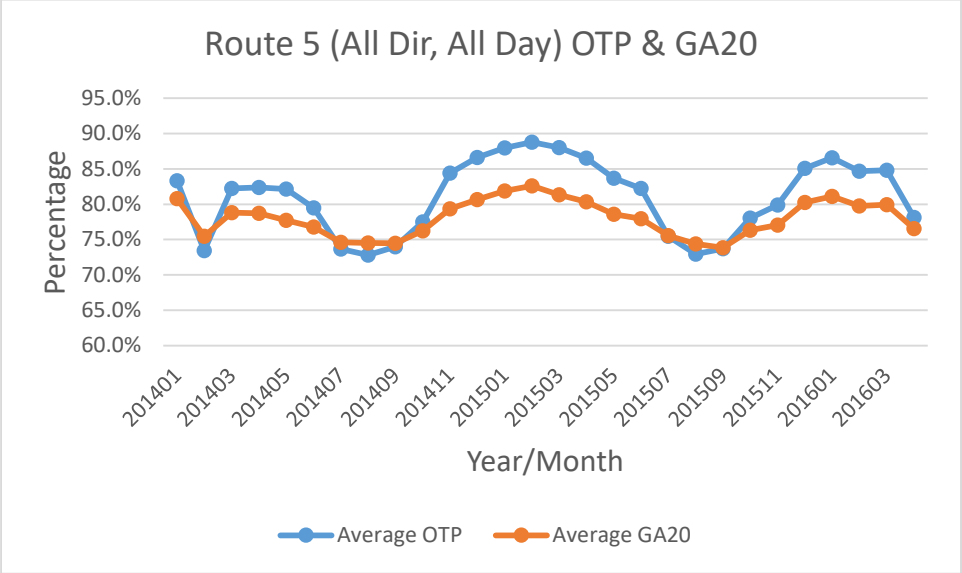

Figure C-3 Monthly OTP and GA20 of Bus Route 5

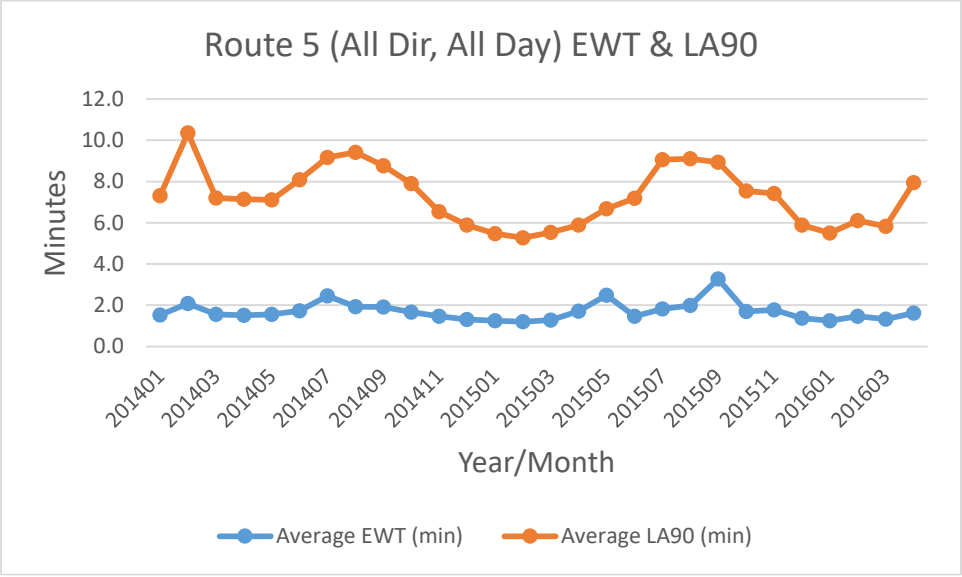

Figure C-4 Monthly EWT and LA90 of Bus Route 5

C.3 Bus Route 6

Figure C-5 displays the monthly OTP and GA20 of bus route 6 in both directions. The average OTP and GA20 are respectively around 82% and 82% for bus route 6. Figure C-6 displays the monthly EWT and LA90 of bus route 6 in both directions. The average EWT and LA90 are respectively around 2.7 and 7.0 minutes for bus route 6.

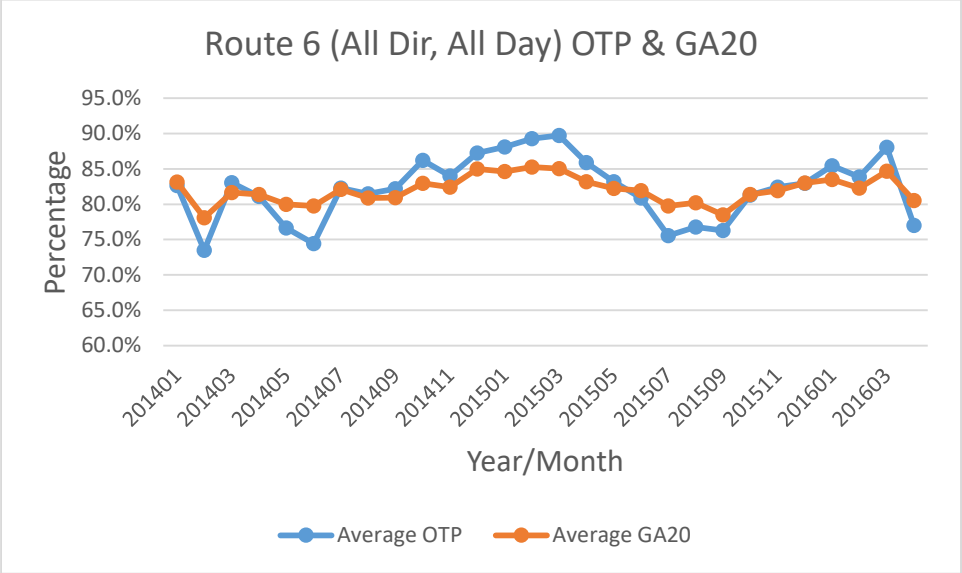

Figure C-5 Monthly OTP and GA20 of Bus Route 6

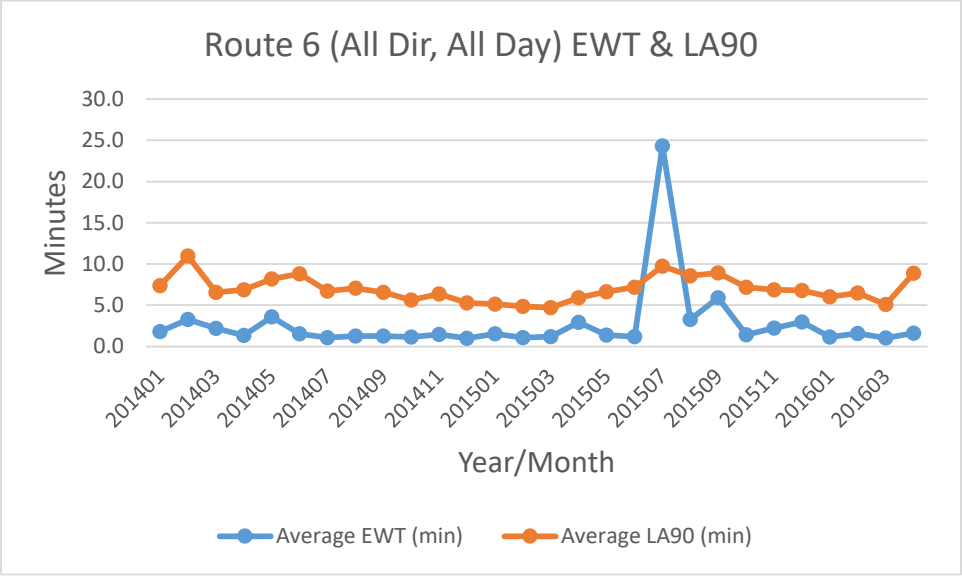

Figure C-6 Monthly EWT and LA90 of Bus Route 6

C.4 Bus Route 10

Figure C-7 displays the monthly OTP and GA20 of bus route 10 in both directions. The average OTP and GA20 are respectively around 78% and 81% for bus route 10. Figure C-8 displays the monthly EWT and LA90 of bus route 10 in both directions. The average EWT and LA90 are respectively around 1.3 and 7.5 minutes for bus route 10.

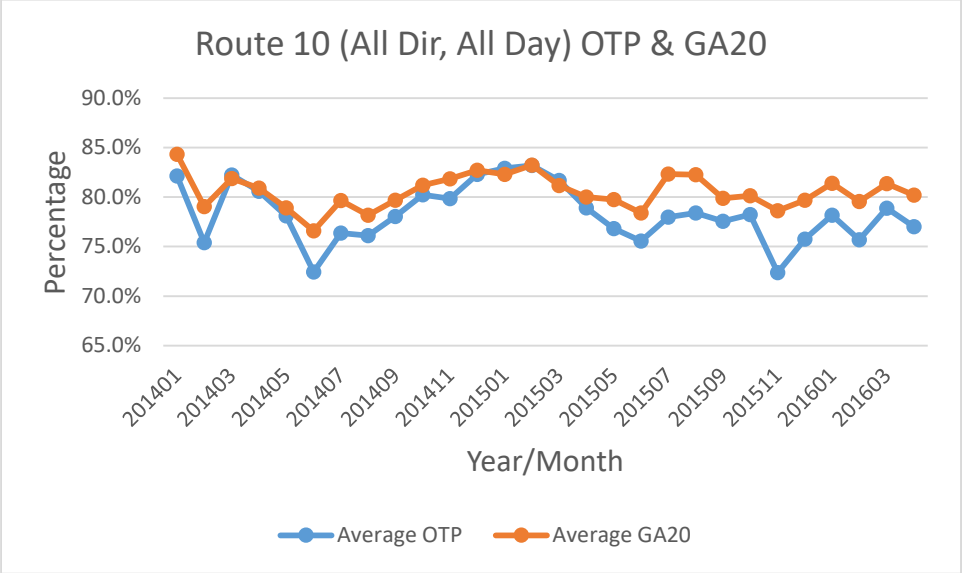

Figure C-7 Monthly OTP and GA20 of Bus Route 10

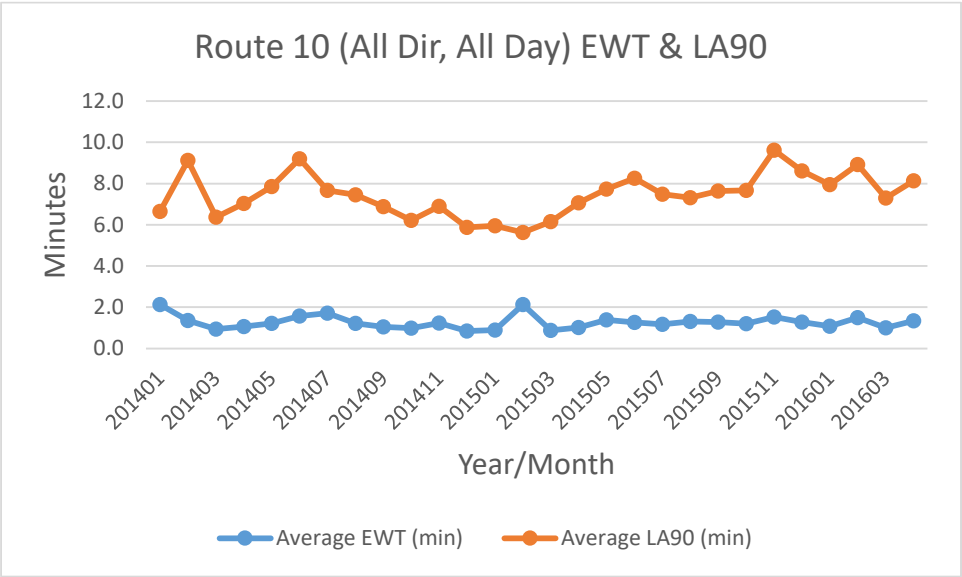

Figure C-8 Monthly EWT and LA90 of Bus Route 10

C.5 Bus Route 17

Figure C-9 displays the monthly OTP and GA20 of bus route 17 in both directions. The average OTP and GA20 are respectively around 81% and 85% for bus route 17. Figure C-10 displays the monthly EWT and LA90 of bus route 17 in both directions. The average EWT and LA90 are respectively around 1.3 and 6.8 minutes for bus route 17.

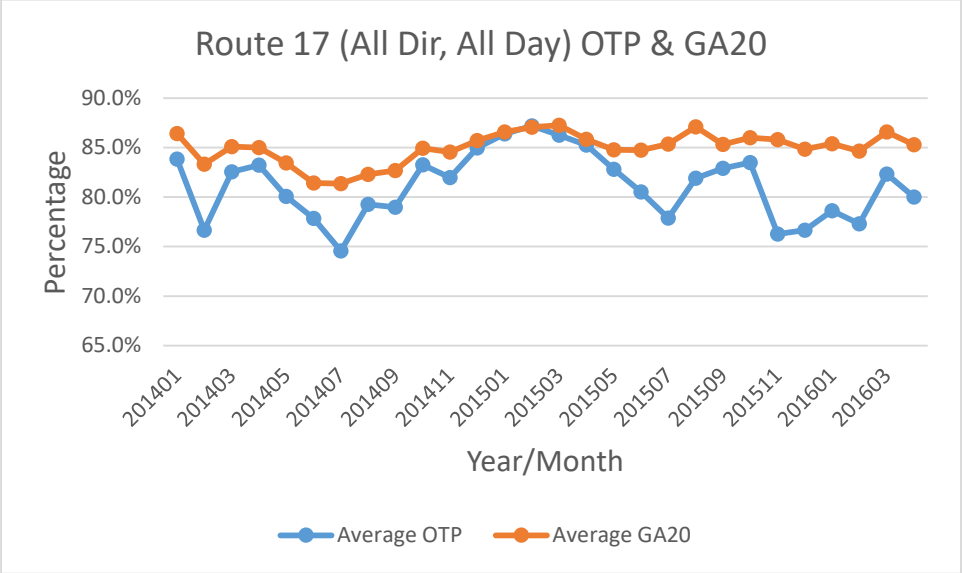

Figure C-9 Monthly OTP and GA20 of Bus Route 17

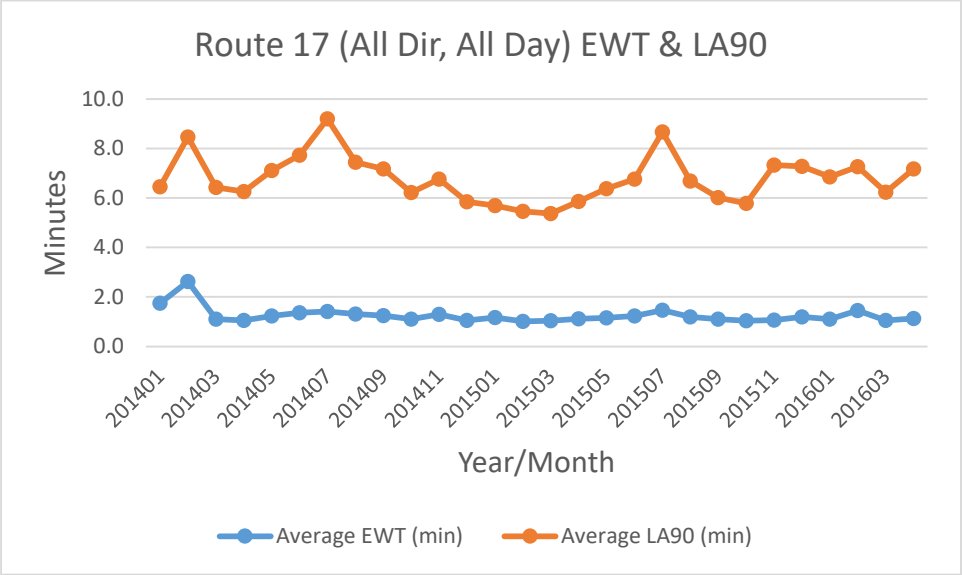

Figure C-10 Monthly EWT and LA90 of Bus Route 17

C.6 Bus Route 18

Figure C-11 displays the monthly OTP and GA20 of bus route 18 in both directions. The average OTP and GA20 are respectively around 81% and 77% for bus route 18. Figure C-12 displays the monthly EWT and LA90 of bus route 18 in both directions. The average EWT and LA90 are respectively around 1.7 and 6.8 minutes for bus route 18. The 9.6 minutes of EWT of route 18 in September 2015 is significant higher than the average EWT over the 28 month period. It may be related to data quality issue of route 18 in that month. The average EWT drops to 1.4 minutes after removing the outlier.

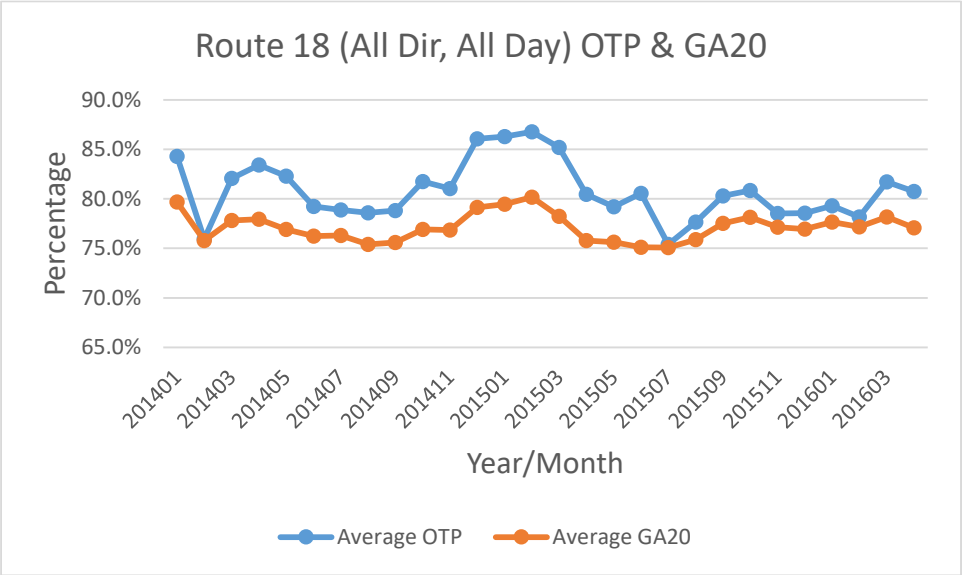

Figure C-11 Monthly OTP and GA20 of Bus Route 18

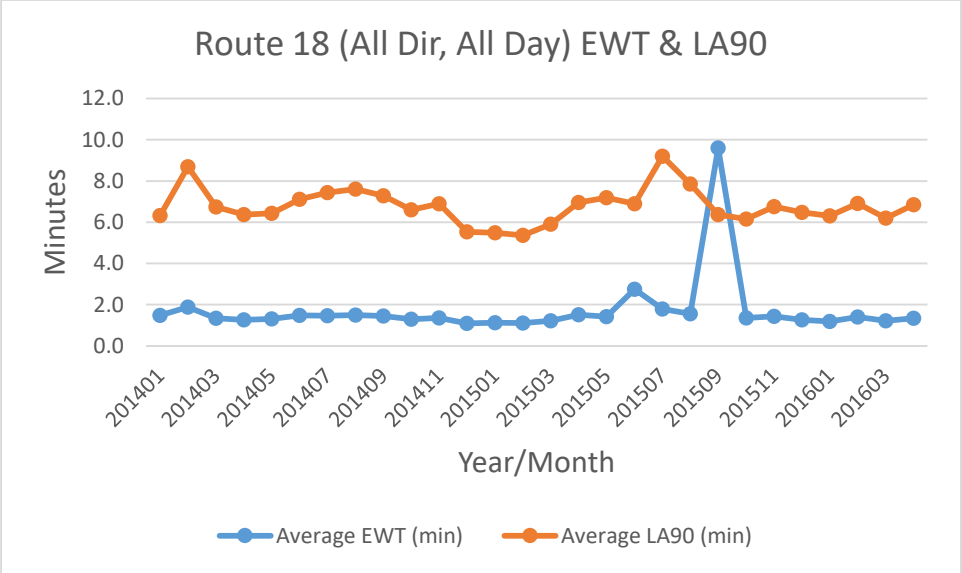

Figure C-12 Monthly EWT and LA90 of Bus Route 18

C.7 Bus Route 19

Figure C-13 displays the monthly OTP and GA20 of bus route 19 in both directions. The average OTP and GA20 are respectively around 80% and 78% for bus route 19. Figure C-14 displays the monthly EWT and LA90 of bus route 19 in both directions. The average EWT and LA90 are respectively around 1.5 and 7.0 minutes for bus route 19.

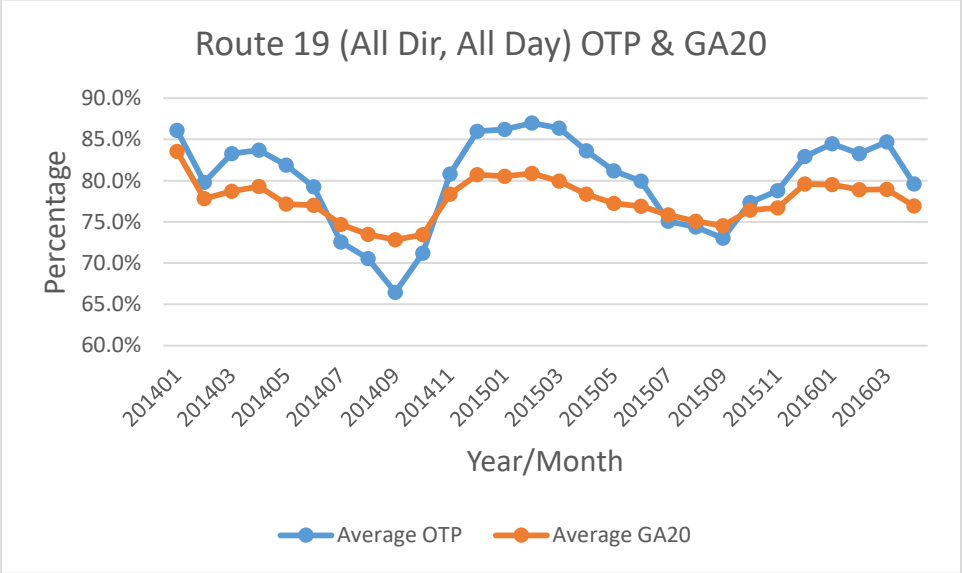

Figure C-13 Monthly OTP and GA20 of Bus Route 19

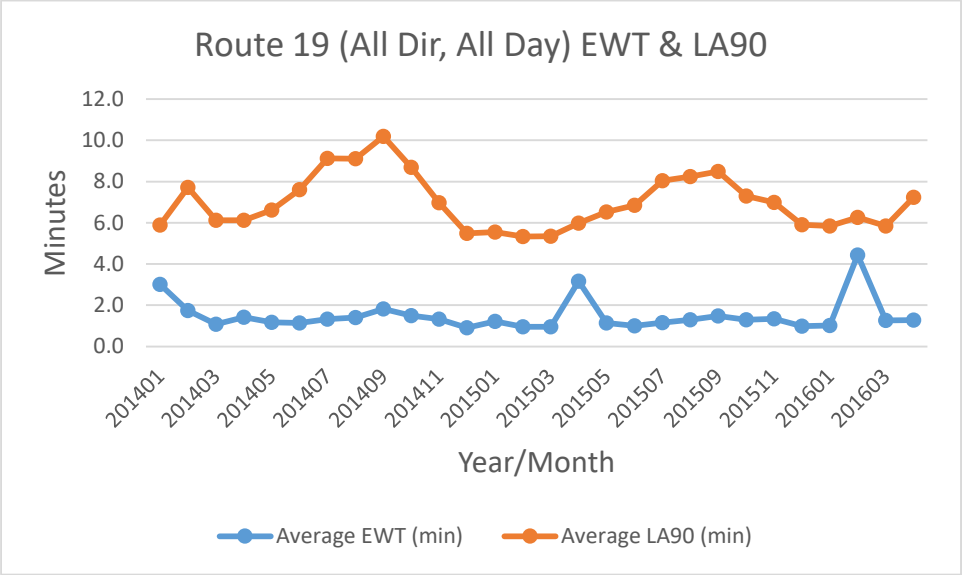

Figure C-14 Monthly EWT and LA90 of Bus Route 19

C.8 Bus Route 54

Figure C-15 displays the monthly OTP and GA20 of bus route 54 in both directions. The average OTP and GA20 are respectively around 86% and 87% for bus route 54. Figure C-16 displays the monthly EWT and LA90 of bus route 54 in both directions. The average EWT and LA90 are respectively around 1.4 and 5.8 minutes for bus route 54. The 24 minutes of EWT of route 54 in March 2014 is significant higher than the average EWT over the 28 month period. It may be related to data quality issue of route 54 in that month. The average EWT reduces to 0.6 minutes after removing the outlier.

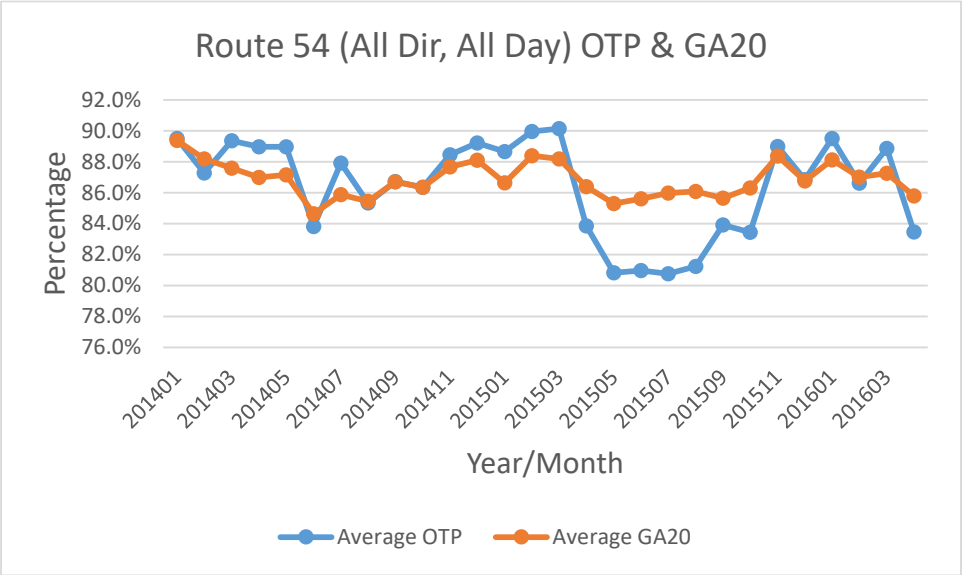

Figure C-15 Monthly OTP and GA20 of Bus Route 54

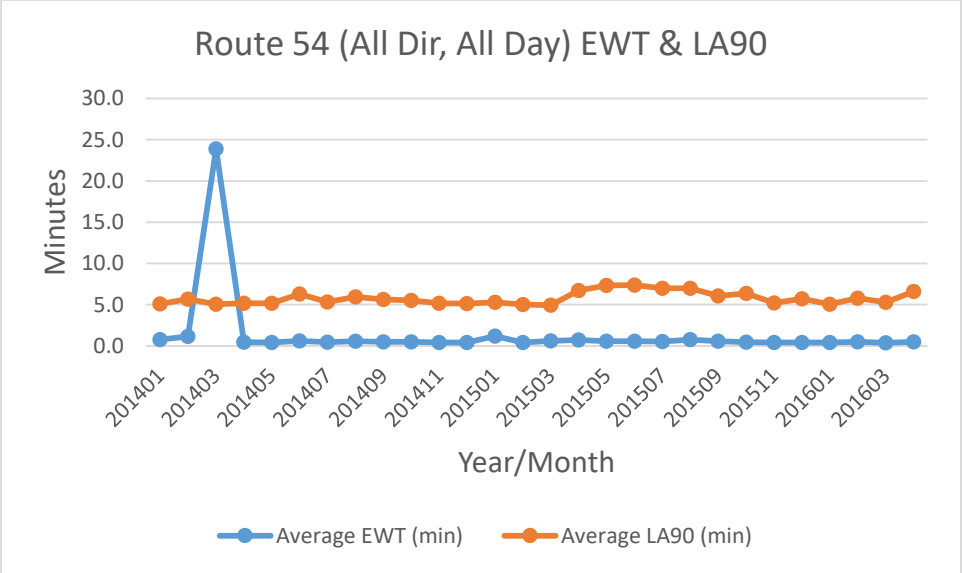

Figure C-16 Monthly EWT and LA90 of Bus Route 54

C.9 Bus Route 84

Figure C-17 displays the monthly OTP and GA20 of bus route 84 in both directions. The average OTP and GA20 are respectively around 89% and 85% for bus route 84. Figure C-18 displays the monthly EWT and LA90 of bus route 84 in both directions. The average EWT and LA90 are respectively around 2.8 and 5.2 minutes for bus route 84. The 43 minutes of EWT of route 84 in September 2015 is significant higher than the average EWT over the 28 month period. It may be related to data quality issue of route 84 in that month. The average EWT drops to 1.3 minutes after removing the outlier.

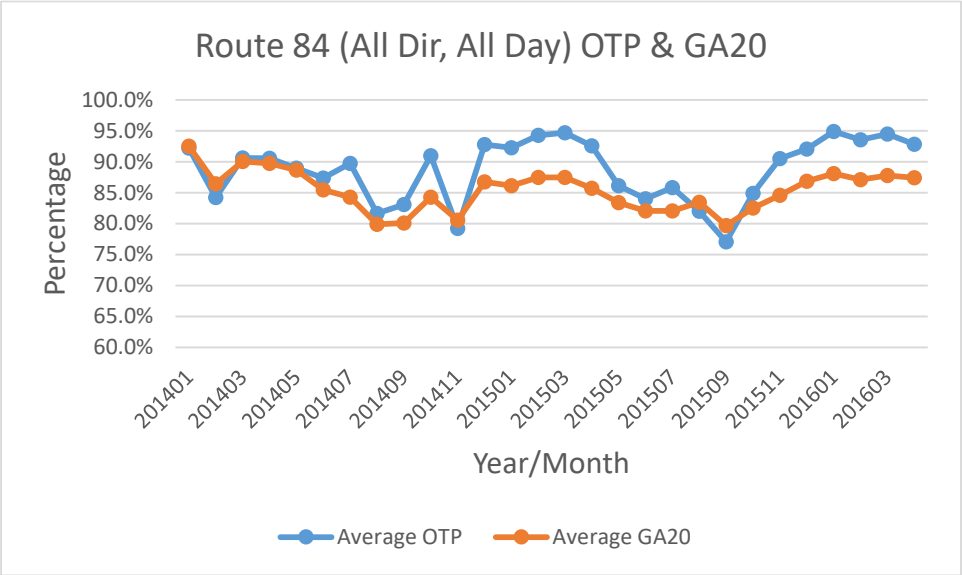

Figure C-17 Monthly OTP and GA20 of Bus Route 84

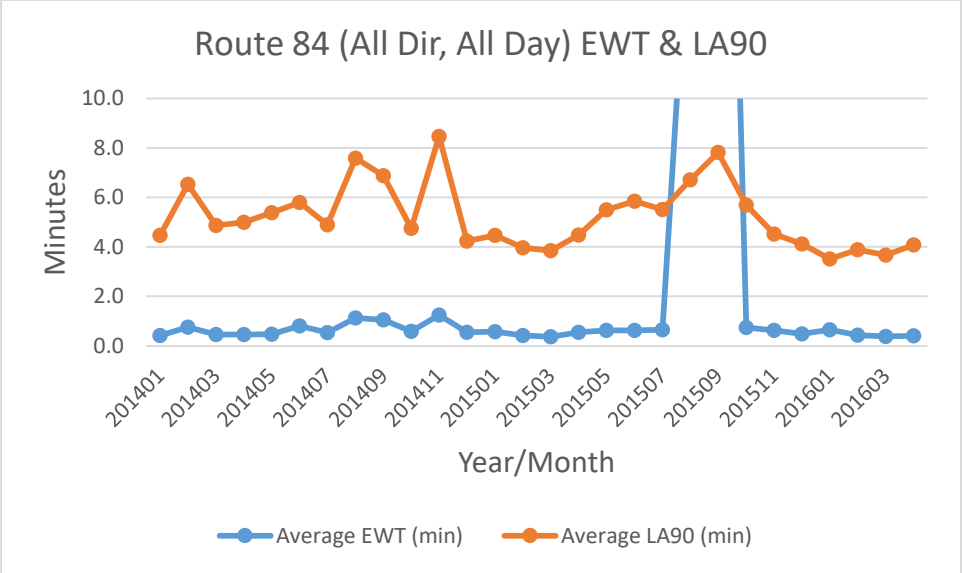

Figure C-18 Monthly EWT and LA90 of Bus Route 84

C.10 Bus Route 515

Figure C-19 displays the monthly OTP and GA20 of bus route 515 in both directions. The average OTP and GA20 are respectively around 93% and 94% for bus route 515. Figure C-20 displays the monthly EWT and LA90 of bus route 515 in both directions. The average EWT and LA90 are respectively around 3.2 and 3.7 minutes for bus route 515. The 82 minutes of EWT of route 515 in February 2014 is significant higher than the average EWT over the 28 month period. It may be related to data quality issue of route 515 in that month. The average EWT reduces to 0.3 minutes after removing the outlier.

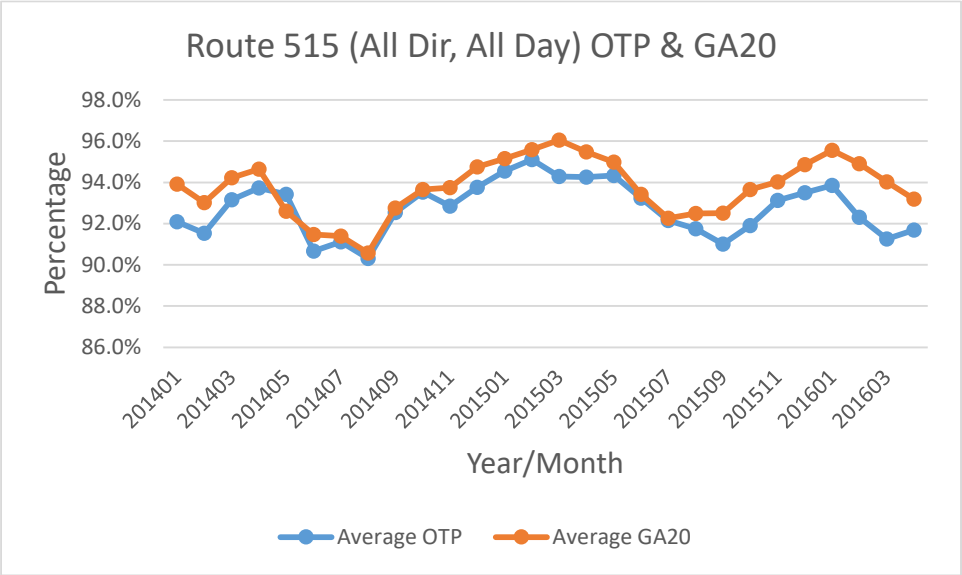

Figure C-19 Monthly OTP and GA20 of Bus Route 515

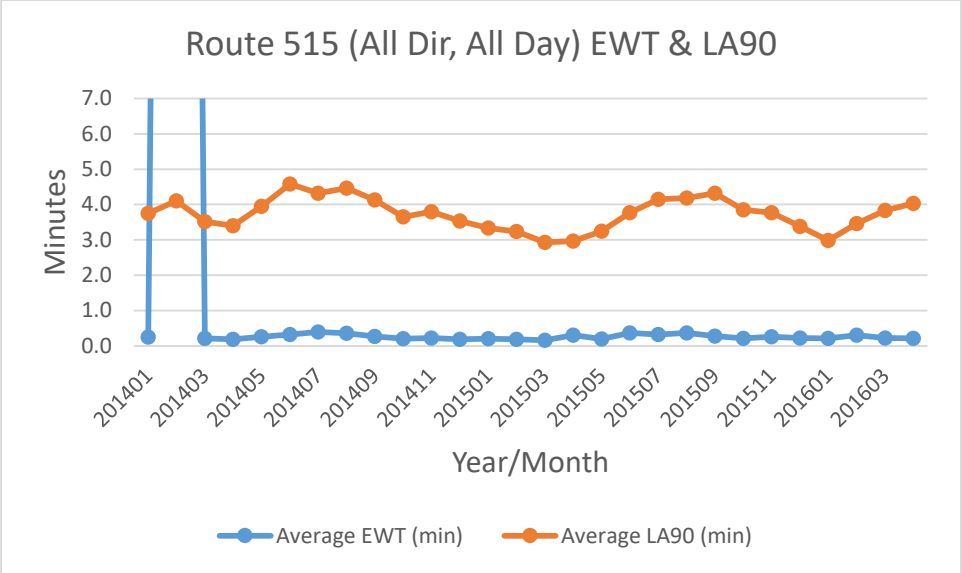

Figure C-20 Monthly EWT and LA90 of Bus Route 515