EVALUATION OF TRANSIT SIGNAL PRIORITY EFFECTIVENESS USING AUTOMATIC VEHICLE LOCATION DATA

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EVALUATION OF TRANSIT SIGNAL PRIORITY EFFECTIVENESS USING AUTOMATIC VEHICLE LOCATION DATA

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

Transit Signal Priority (TSP) is an operational strategy that can speed the movement of in-service transit vehicles (typically bus, light rail, or streetcar) through traffic signals. By reducing control delay at signalized intersections, TSP can improve schedule adherence and travel time efficiency while minimizing impacts to normal traffic operations. These benefits improve the quality of service thereby making it more attractive to choice riders. A TSP system can also allow for fewer buses on the same due to travel time reductions and increased reliability, thus reducing transit operating costs.

Much of the previous research on TSP has focused on signal control strategies and bus stop placement with little of it analyzing the effectiveness of the system using actual data. This study aims to evaluate the effectiveness of the system using a bus route corridor in Portland, Oregon through real-time Automatic Vehicle Locator data. Key measures that TSP is promoted to improve are evaluated, including travel time, schedule adherence and variability. The TSP system on data was collected for two weeks and is compared to an adjacent two weeks of bus data with the TSP system turned off such that there is no skewing of data due to changes in traffic volumes or transit ridership.

This research has shown, that on certain corridors there may be little to no benefit towards TSP implementation and may possibly provide some disbenefit. The direct comparison for TSP on and off scenarios completed for this research yielded no significant differences in reduction in travel time or schedule adherence performance. An additional interesting result was that the standard deviation of the results did not have any specific tendencies with the TSP on or off. Based on these findings, recommendations are made to increase the effectiveness of the system.

CHAPTER 1

INTRODUCTION

Transit Signal Priority (TSP) is an operational strategy that can speed the movement of in-service transit vehicles (typically bus, light rail, or streetcar) through traffic signals. It is a tool being used extensively in other parts of the world to make transit service more reliable, faster, and more cost effective. [1] By reducing control delay at signalized intersections, TSP can improve schedule adherence and travel time efficiency. Another benefit is that TSP enhances transit performance while minimizing impacts to normal traffic operations, including cross-traffic and pedestrians, due to the priority interaction with signal timing plans [2].

Secondary benefits from TSP include that the improved reliability and reduced travel time from TSP implementation increases the quality of service thereby making it competitive with the automobile and more attractive to choice riders. Another benefit is that fewer buses are necessary on the same routes after TSP implementation due to travel time reductions and increased reliability, thus reducing transit operating costs. [3].

TSP is made up of four components. A detection system (1) delivers vehicle data including location, arrival time, and approach. This system is commonly Global Positioning System (GPS) based but can also be roadside detectors. The detection system then requests priority from the traffic control system through communicating with a priority request generator (2). Priority control strategies (3) are then used to process requests and decide how to grant priority. Finally, there is TSP system management software (4) that manages the system, collects data, and generates reports. [1]

1.1 Study Overview

There has been a great deal of research in several areas of TSP. Much of this research has been focused on signal control strategies and bus stop placement with little of it analyzing the effectiveness of the system using actual data. This study aims to evaluate the effectiveness of the system using a portion of the route 72 TriMet bus running down 82nd Avenue in Portland, Oregon. Previous studies on TSP in Portland, Oregon have been performed when the threshold for activating signal priority was 90 seconds late, that has since been reduced to 30 seconds. The data is collected using a GPS based Automatic Vehicle Locator (AVL) system that is equipped on each bus transmitting real time data to a central control center. This AVL system allows Tri-met staff to actively manage the buses and provide passenger information at key stops throughout the Portland-metropolitan area while also archiving data. [4]

This study evaluates the key measures that TSP is promoted to improve. These measures include travel time, schedule adherence, and variability. The TSP system on data was collected for two weeks and is compared to an adjacent two weeks of bus data with the TSP system turned off such that there is no skewing of data due to changes in traffic volumes or transit ridership.

1.2 Literature Review

The literature review in Chapter 2 of this report is divided into two sections. The first section discusses previous evaluations and studies of Portland's TSP system. The second section presents studies focusing primarily on bus stop placement and travel speed and schedule adherence evaluations as well as other studies that pertain to this research such as traffic volumes and TSP interaction.

1.3 Field Data Collection and Processing

Chapter 3 focuses on the processes and methodology used for collecting data for this project. It is divided into sections providing detail on the study corridor, field data collection methods, and field data processing and quality control. The Field Data Collection section is divided into information on the Automatic Vehicle Locator system and the Conditional Priority System.

1.4 Analysis and Findings

Chapter 4 of the report focuses on the analysis and conclusions drawn from the collected field data on 82nd Avenue. The data from the TSP on and off scenarios are analyzed to determine whether there is any difference in overall corridor average travel speeds for with TSP on. Then, this chapter explores the effect of TSP on the schedule adherence.

1.5 Conclusions

Chapter 5 of this thesis presents conclusions from the analysis and findings. It also presents recommendations towards improving TSP performance on this study corridor. Finally, this chapter discusses limitations of the research and provides future research recommendations.

1.6 Appendices

The appendices include additional travel time and schedule adherence figures that are not included in the body of this report. Appendix A includes individual travel time data and Appendix B contains individual schedule adherence charts.

CHAPTER 2

LITERATURE REVIEW

The following chapter contains information gathered from the existing literature concerning bus transit signal priority. This literature review is divided into sections containing Portland, Oregon studies and other studies focusing particularly on bus stop placement and travel speed and schedule adherence evaluations as well as other studies that pertain to this research such as traffic volumes and TSP interaction.

2.1 Portland, Oregon TSP Evaluations

Several studies have evaluated Portland's conditional transit signal priority implementation and are presented in this section. These studies take advantage of the Automatic Vehicle Location (AVL) system on the busses to obtain real-time data. At the time of each of these evaluations, the threshold for activating signal priority was 90 seconds late, which has since been reduced to 30 seconds. Included below are summaries of the major Portland TSP Studies.

2.1.1 Portland Signal Priority: TEA-21 Technical Report (2003)

The City of Portland, TriMet, the Oregon Department of Transportation, and a consultant team led by Kittelson & Associates, Inc performed a summary and evaluation of Portland's TSP system in 2002. [5] This summary outlines the data collection and evaluation of Portland's TSP system for the TEA-21 Signal Priority Project. Bus performance was evaluated for travel time, travel time variability, and on-time performance based on AVL data. Data was collected for eight weeks, four weeks before the TSP and then four weeks with TSP turned on.

Table 2.1 summarizes the travel time analysis and provides a coefficient of variability as a percentage of travel time. The outbound, PM period shows a significant improvement in travel time.

Table 2.1 Bus Travel Time Summary (All Trips) [5]

		TSP On		***TSP Off***		***Differences***	
Direction	**peak**	**average travel time (min)**	**variability (%)**	**average travel time (min)**	**variability (%)**	**average travel time (min)**	**variability (%)**
Outbound	AM	19.7	10.6	20.1	25.5	0.4	14.9
Outbound	PM	24.2	10.2	27.4	26.3	3.1	16.1
Inbound	AM	22.7	8.6	23.1	10.8	0.5	2.2
Inbound	PM	22.1	9.3	23.2	16.6	1.1	7.3

The data was then evaluated using only buses that entered the corridor over 90 seconds late, which is late enough to be granted priority throughout their trip, and accounted for approximately 40% of the trips studied. This data is presented in Table 2.2.

Table 2.2 Bus Travel Time Summary (Late Trips Only) [5]

		TSP On		***TSP Off***		***Differences***	
Direction	**peak**	**average travel time (min)**	**variability (%)**	**average travel time (min)**	**variability (%)**	**average travel time (min)**	**variability (%)**
Outbound	AM	20.2	10.2	20.8	29.3	0.6	19.2
Outbound	PM	25.6	9.6	28.8	26.4	**3.2**	16.7
Inbound	AM	22.8	7.3	23.3	10.1	0.4	2.8
Inbound	PM	22.2	9.2	24.3	18.6	**2.1**	9.4

This analysis shows a travel time reduction of 2.1 to 3.2 minutes with TSP turned on, amounting to 8 – 11% of the total travel time in the PM peak hour. The reduced variability with TSP on, as shown in Table 22, results in improved on-time performance and reliability. The travel time distribution is presented in Figure 2.1.

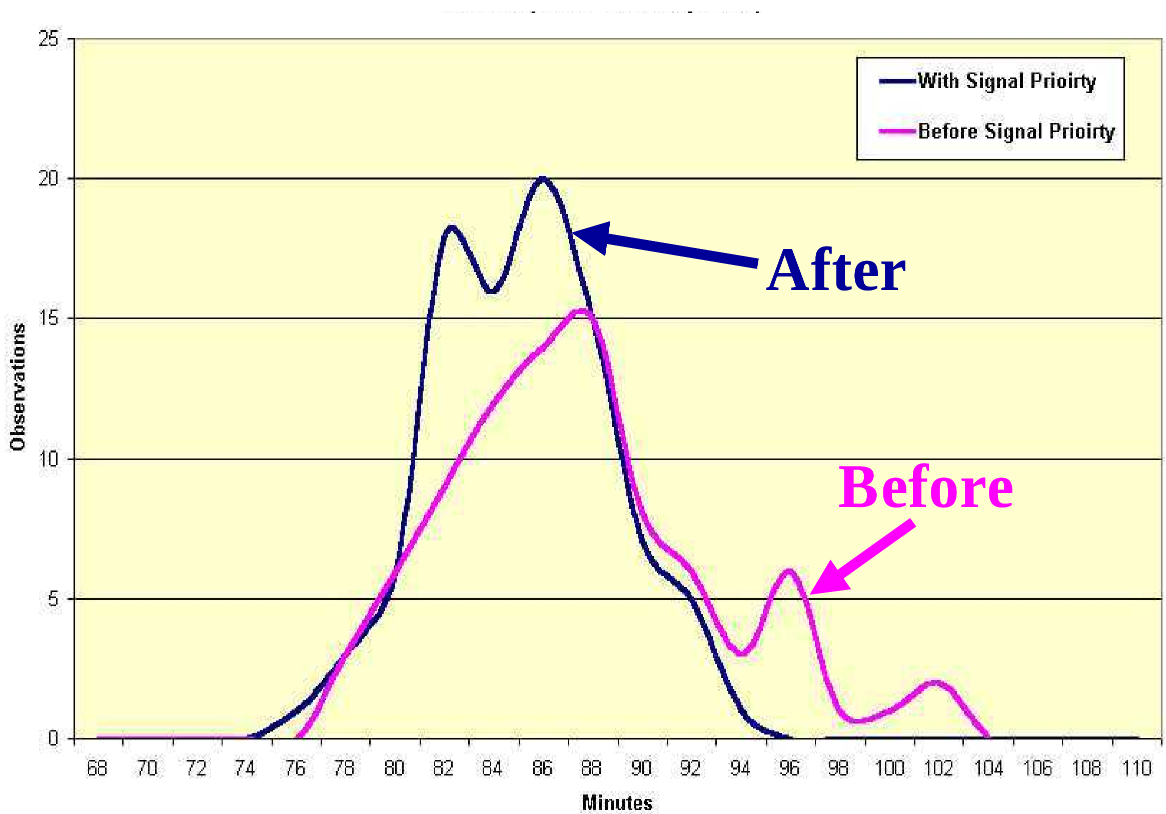


Figure 2.1 Run Time Distribution – PM Peak Trips [5]

The results of this study show that the AVL system in Portland can reduce travel time and improve schedule reliability by working in conjunction with signal priority.

2.1.2 Byrne et al. (2005)

This study [4] focused on one intersection in Portland using hardware-in-the-loop simulation to study the effects of signal priority on transit performance. The study focused specifically on bus stop placement to address whether a green extension plan should be used if there is passenger activity at a nearside stop. Four scenarios, nearside stops without TSP, nearside stops with TSP, farside stops without TSP, and farside stops with TSP, were studied and also broken down further into green extension or red truncation plans. These scenarios were evaluated using actual field conditions and a combination of simulation software (VISSIM) and a field signal controller at an actual intersection in Portland.

The results of the travel time analysis are provided in Table 2.3. These results demonstrate that TSP provides a travel time benefit to farside stops with TSP, but may reduce performance for nearside stops. Table 2.4 summarizes the researchers' findings on delay. The bus stop placement without TSP yields similar results for average delay and standard deviation. The authors hypothesize that this similar control delay may be related to an adjacent queue preventing vehicle re-entry into the traffic stream. These results also indicate that TSP provides a benefit to farside stops but has the potential to negatively affect bus delay at nearside stops. Furthermore, a comparison of the standard deviation is useful in evaluating travel time variability. As seen in Table 2.4, that authors note that implementation of TSP at farside bus stops considerably reduces standard deviation and thus reduces that potential for buses to fall behind schedule. Overall, this research has demonstrated a 33% reduction in signal delay when TSP is used at farside stops and an increase in delay at nearside stops.

Table 2.3 Travel Times per Bus Simulation Results [4]

	NearSide without TSP	FarSide without TSP	NearSide with TSP	FarSide with TSP
Average Bus Travel Time (Sec.)	79.1	76.8	84.1	68.3

Table 2.4 Simulation Results for Delay per Bus [4]

Bus	NearSide w/o TSP Delay (s)	NearSide w/ TSP Delay (s)	Overall Delay Savings (s)	FarSide w/o TSP Delay (s)	FarSide w/ TSP Delay (s)	Overall Delay Savings (s)
Average (NB/SB)	27.6	32.5	+4.9	25.2	16.7	-8.5
Standard Deviation	5.34	5.56		5.18	2.05	

2.1.3 Kimpel et al. (2005)

A study [6] conducted by researchers at Portland State University evaluated the impacts of TSP on running time variability using AVL data. The data was collected on six TriMet bus routes in 2001-2002 with no TSP and 2002-2003 after TSP implementation. During these data collection periods, the threshold for activating signal priority was 90 seconds late and has since been reduced to 30 seconds. The overall results showed a negligible decrease from 33.2 to 33.1 minutes of mean actual running time following TSP implementation. Though two, outbound, PM routes showed substantial reductions in running time. For running time variation, 11 of the 24 analysis segments showed a statistically significant difference; four showing a decrease and seven experiencing an increase following TSP implementation. These mixed results in bus performance did not find any “across-the-board” benefits following TSP implementation. However, this study did not isolate the effect of traffic and ridership growth from year to year. Changes in peak periods, net increases in ridership, and changes in running time variability on other routes were not addressed.

2.2 Other TSP Research

This section focuses on non-Portland TSP research. The focus of many of these studies is on bus stop placement and travel speed and schedule adherence evaluations. Other studies that pertain to this research such as traffic volumes and TSP interaction are also highlighted.

2.2.1 Liao and Davis (2007)

This paper [7] studied adaptive signal priority for a bus route in Minneapolis through micro-simulation. As presented in Figure 2.2, their results indicate that a 12-15% reduction in bus travel time during the AM peak period and a 4-11% reduction in travel time during the PM peak periods are achievable through signal priority. The authors believe that lower reduction in travel time during the PM peak period is due to the bus stop locations. Their study corridor consisted mainly of nearside bus stops that were blocked by longer queues in the PM peak period. The intersection queues also caused the bus to wait longer to find an acceptable gap in order to rejoin the traffic. The priority request was beneficial however, in that it helped clear the queue to provide service and reduce the bus clearance time.

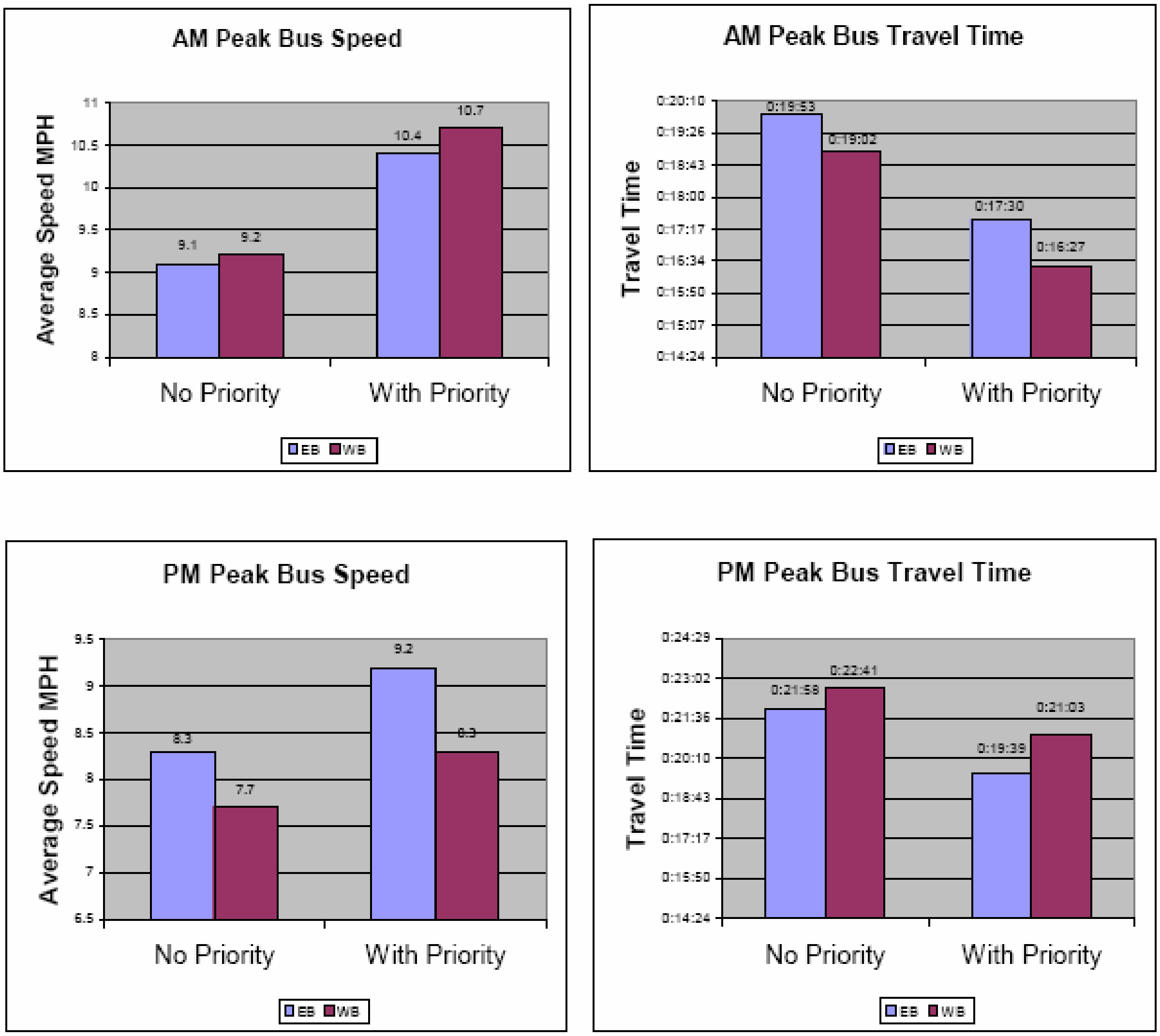


Figure 2.2 AM and PM Peak Bus Speed and Travel Time [7]

2.2.2 Ngan, Sayed, and Abdelfatah (2004)

This research [8] studied signal priority on the 98 B-line bus route in Vancouver, BC using VISSIM micro-simulation software. The researchers found that TSP is most effective under moderate-to-heavy traffic conditions. Bus performance with TSP, as measured by travel time, decreases as traffic volumes, thus encountering lower traffic delay. This is demonstrated in Figure 2.3.

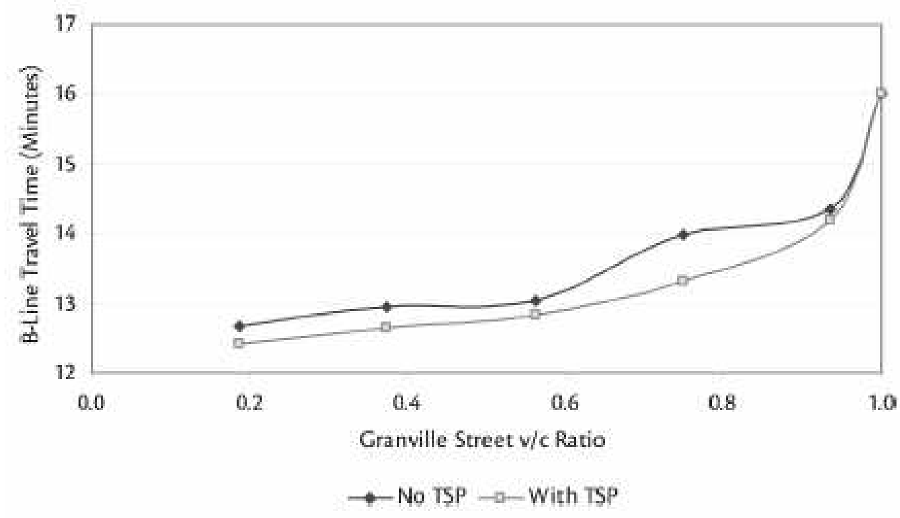


Figure 2.3 Impact on Bus Travel Time [8]

The study also found an impact from bus stop location on bus performance. As illustrated in Figure 2.4, a nearside bus stop causes higher delay to the study corridor buses than far side bus stops. This is due to a significant portion of the green extension is wasted during passenger loading and unloading. The authors note that it is possible to address some of the nearside ineffectiveness through using delay times if dwell time at a bus stop is consistent or placing the call immediately downstream of the stop.

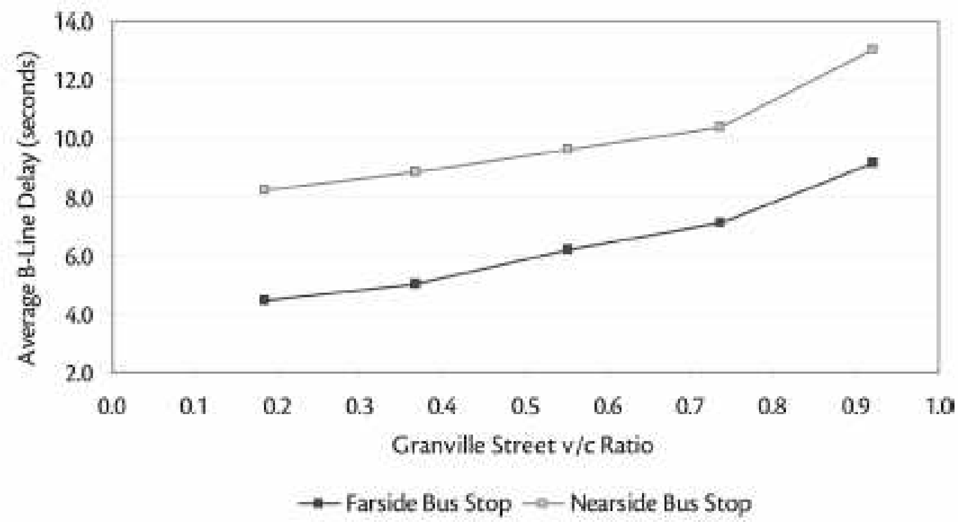


Figure 2.4 Bus Stop Location Impact on Average Bus Delay (with TSP) [8]

FIGURE 2.5 shows the percentage increase in bus delay on the study corridor when moving bus stops from the farside to the nearside of an intersection.

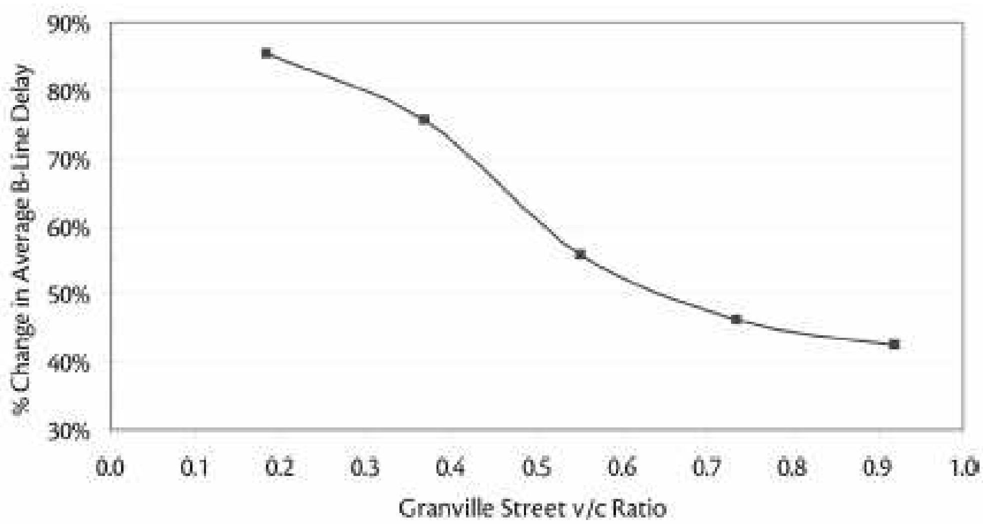


Figure 2.5 Nearside Bus Stop Impact on TSP Effectiveness [8]

Finally, the authors also noted that removing signal coordination from a corridor increases the entire corridor delay, attributed to an increase in the main street delay. Only minimal improvements were found on the cross streets when removing coordination since green time for the cross streets is maintained when there is no TSP call.

2.2.3 Muthuswamy, McShane, and Daniel (2006)

This study [3] used simulation to study TSP on a study corridor in Newark, NJ. IT found that the benefits of TSP are not uniform along a corridor and that at cross streets with heavy traffic volumes, TSP should be restricted or suppressed to avoid excessive delays at these cross streets.

2.2.4 Sacramento: Watt Avenue Transit Priority Evaluation (2006)

This study [9] evaluated Watt Avenue in Sacramento, CA using AVL data. Data was collected for one week in April 2004 for the three peak periods of traffic flow: AM, midday, and PM. For comparison data some buses were outfitted TSP transponders while others did not. As shown in Table 2.5, this study found that the buses with TSP experienced between 14 and 71 seconds of travel time savings compared to the non-TSP buses traveling over the same segment, a travel time decrease of 4%. These savings are relatively small however, as the route travel time is approximately 40 minutes. Travel time reliability was increased in two out of the six time periods when compared to non-TSP buses.

Table 2.5 Travel Times for TSP and Non-TSP Buses, All Segments [9]

Route	TSP	Travel Times (sec) Avg	Stnd Dev	Count
NB, Weekday, Peak *	TSP	2248	229	26
	No TSP	2265	203	24
NB, Weekday, Off Peak	TSP	1787	189	84
	No TSP	1858	175	41
NB, Weekend *	TSP	1630	175	39
	No TSP	1678	166	26
SB, Weekday, Peak *	TSP	1854	186	26
	No TSP	1917	158	25
SB, Weekday, Off Peak *	TSP	1696	189	92
	No TSP	1710	187	45
SB, Weekend	TSP	1576	143	42
	No TSP	1637	156	28

*Results are not statistically significant at the 5 percent confidence level.

2.2.5 Virginia Tech Transit Signal Priority Evaluation (2006)

This report [10] studied a corridor in the Northern Virginia area to evaluate the benefits of basic green-extension TSP using field-collected GPS data. Results showed overall travel time improvements of 3% to 6% and presented in table 2.6. The study also found that the TSP strategies reduced transit-vehicle intersection delay by as much as 23%. In addition, the field study found that TSP benefits were maximized under moderate to low levels of congestion. Bus stop location was also studied in simulation and found that near-side bus stops resulted in increased system-wide delays of 2.85% over non-TSP operations, while mid-block and far-side bus stops resulted in network-wide savings of 1.62%.

Table 2.6 Detailed Travel Time Results [10]

			TSP On	TSP Off	Benefit
NB Trips	AM Peak (6:30 AM - 9:30 AM)	Average Travel Time	0:30:54	0:30:08	-2.54%
		Number of Trip	18	18	
	Mid Peak (11 AM - 2 PM)	Average Travel Time	0:30:47	0:31:48	3.20%
		Number of Trip	16	20	
	Non Peak	Average Travel Time	0:25:36	0:27:15	6.07%
		Number of Trip	34	41	
SB Trips	AM Peak (6:30 AM - 9:30 AM)	Average Travel Time	0:26:45	0:28:23	5.75%
		Number of Trip	23	28	
	Mid Peak (11 AM - 2 PM)	Average Travel Time	0:29:47	0:29:08	-2.27%
		Number of Trip	7	10	
	Non Peak	Average Travel Time	0:25:22	0:26:28	4.17%
		Number of Trip	19	22	

2.2.6 98 B-Line Bus Rapid Transit Evaluation Study (2003)

This evaluation [11] studied the 98 B-Line, an approximately 8 mile bus corridor from the Airport to Downtown Vancouver, BC. Data was collected from buses with AVL systems and an active TSP system and compared to recent, manually collected data prior to TSP implementation. The results found only small differences in bus travel time in the before and after data as presented in Table 2.7. However, the results suggest that the TSP system has made travel times less variable, as measured by the standard deviation, by 40 – 50%.

Table 2.7 Travel Time Statistics, Airport Station – West Hastings Street [11]

	Northbound			Southbound		
	AM Peak (6:30-9:00)	**Mid-day** (9:00-15:00)	**PM Peak** (15:00-18:00)	**AM Peak** (6:30-9:00)	**Mid-day** (9:00-15:00)	**PM Peak** (15:00-18:00)
Before						
Average (minutes)	26.3	28.6	27.9	29.1	30.9	36.8
Standard Deviation	3.6	3.8	2.3	3.3	5.1	3.8
Sample Size	5	9	10	7	10	6
After						
Average (minutes)	27.3	28.5	28.4	30.5	32.5	34.2
Standard Deviation	1.9	2.3	2.4	2.0	2.6	2.6
Sample Size	8	61	27	104	219	151
F-test value	0.13	0.02	0.97	0.04	0.00	0.15

Schedule adherence data with and without TSP was compared to determine the impact of TSP on service reliability. In the Downtown Vancouver section, the variability of schedule adherence has decreased with TSP throughout the day in the southbound direction and during the mid-day in the northbound direction, demonstrating the improved performance from TSP on this corridor. The schedule adherence results are presented in Table 2.8.

Table 2.8 Schedule Adherence Statistics Downtown Vancouver Section [11]

	Northbound			Southbound		
	AM Peak (6:00-9:00)	**Mid-day** (9:00-15:00)	**PM Peak** (15:00-18:00)	**AM Peak** (6:00-9:00)	**Mid-day** (9:00-15:00)	**PM Peak** (15:00-18:00)
Before						
Average (minutes)	-1.2	-0.9	-1.3	3.4	3.9	4.6
Standard Deviation	2.7	4.5	2.6	3.6	3.1	4.4
Sample Size	31	118	59	59	127	81
After						
Average (minutes)	0.0	1.7	1.6	-0.1	1.1	0.8
Standard Deviation	2.5	2.6	2.5	2.1	2.7	2.6
Sample Size	322	623	409	330	720	441
F-test value	0.47	0.00	0.60	0.00	0.06	0.00

2.2.7 Garrow and Machemehl (1997)

This study [12] investigated TSP using CORSIM micro-simulation to study the effect of TSP on the surrounding traffic environment. They found that signal priority is often justified during non-peak periods but that there are severe negative impacts on the cross-street traffic during peak periods--specifically, if the cross-street saturation level is above 1.0 with a 10-second green extension or above 0.9 with a 20-second green extension. Therefore, the authors suggest that TSP is only justified during peak periods when the level of transit usage is high. The results are shown in Table 2.9. This is relevant to the 82nd Avenue study corridor as it has several intersections with high-volume east-west arterials connecting to Downtown Portland.

Table 2.9 Negative Impacts Accruing on Cross-Streets Due to Signal Priority (Assumed Bus Headway = 10 minutes) [12]

Cross Street Saturation	Green Extension = 10 sec.	Green Extension = 20 sec.
Saturation Level = 0.8	Minimal	Moderate
Saturation Level = 0.9	Moderate	Significant
Saturation Level = 1.0	Significant	Significant

2.3 Literature Review Summary

This chapter identified several studies relating to the effectiveness of transit signal priority. This review of the relevant research focused on travel speed and schedule adherence as measures of effectiveness of these systems. The results of this review found mixed results on the benefits of TSP investment. The Vancouver studies and Minneapolis study are among cities that have found a great benefit in travel time and, more importantly, schedule reliability. Portland studies have found mixed results with signal priority, however no evaluation of the system has been performed since the signal priority threshold has been reduced to 30 seconds. Other cities, such as Sacramento, have not found as a great a benefit after TSP implementation. One reason for this reduced performance can be linked to bus stop placement; the literature overwhelmingly supports farside bus stop placement over nearside placement. This is due to several reasons, most importantly that uneven dwell times at stops as well as queues not allowing buses back into the traffic stream. Finally, the Garrow and Muthuswamy studies both found great disbenefits of TSP at intersections with high volume roadways.

CHAPTER 3

FIELD DATA COLLECTION AND PROCESSING

The data collection portion of this evaluation took place on a two mile corridor of the Number 72 bus route traveling along NE/SE 82nd Avenue in Portland, Oregon. The data collection occurred over two, two-week periods in July and August, 2007 during which there were no significant events or holidays.

This chapter will focus on the processes and methodology used for collecting data for this project. It is divided into sections covering the Study Corridor, Field Data Collection, Field Data Processing and Quality Control. The Field Data Collection section is divided into information on the Automatic Vehicle Locator system and the Conditional Priority System.

3.1 Study Corridor

The study corridor of NE/SE 82nd Avenue, also designated as State Highway 213, was chosen due to the high bus ridership and its function as a major north/south arterial. Bus route 72 has the highest bus ridership in TriMet's system [13] and 82nd Avenue has an AADT of approximately 29,000 in 2007. [14] Therefore, this corridor provides a characteristic representation of TriMet's bus routes within the City of Portland. As demonstrated in Figure 3.1, the 2 mile corridor length includes 16 northbound and 16 southbound bus stops and 9 signalized intersections. The corridor is bound to the north by NE Hassolo Street, just south of a transfer station with TriMet's Blue and Red MAX light rail lines, and to the south by SE Woodward Street.

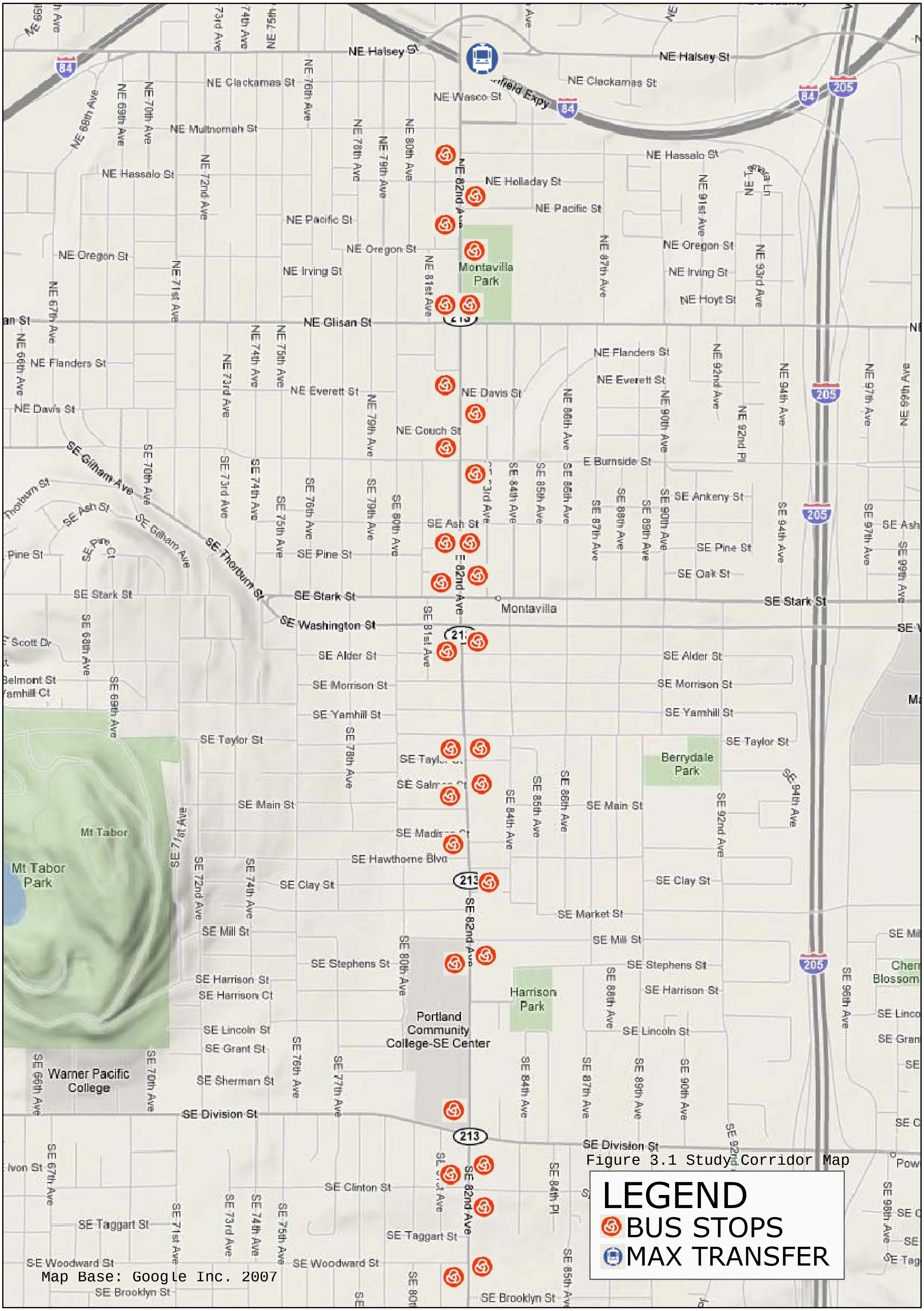


Figure 3.1 Study Corridor Map

3.1.1 Corridor Conditions

This corridor is a major arterial serving several developing neighborhoods and business districts. The roadway section is 60 feet wide curb to curb consisting of two travel lanes in each direction and a continuous center turn lane. Narrow sidewalks exist on both sides that are typically six feet wide and impeded with signs and utility poles. The speed limit is posted at 35 miles-per-hour. Generally, the development patterns along this corridor are auto-centric with large set-backs and non-shared driveways.

Figure 3.2 NE 82nd Avenue in Portland, Oregon [photo: Jonathan Maus, BikePortland.org]

This route has a large pedestrian population due to many senior housing facilities and a large lower income population, contributing to a very high public transit use. The corridor is also a location for many destinations as well as transfer points to all east-west bus lines running downtown. [13]

3.2 Field Data Collection

The field data was recorded during two, two-week time periods, one with the TSP on and the other with the TSP turned off. These periods were July 22 – August 4, 2007 and August 12 – August 25, 2007, for the TSP on and off, respectively. The data collection periods each began on a Saturday and ended on a Sunday and had no scheduled significant events or holidays. Real time data of the buses as they moved through the corridor was collected through Global Positioning System (GPS) enabled busses that monitored the vehicle location and transmitted this information wirelessly to the transit control center.

3.2.1 Automatic Vehicle Location System

TriMet implements TSP through the transit system's automatic vehicle location (AVL) system. This AVL system, installed on all buses in the fleet, monitors and controls bus operations through on-board GPS receivers and is connected to a Bus Dispatch System (BDS). The BDS is connected to an on-board computer containing the bus's route and schedule information allowing to bus to determine schedule status on a real-time basis. With this system, the buses send time-stamped vehicle location coordinates in real time to the transit control center. This data is archived and also enhances the transit quality of service by providing riders accurate information about bus arrival times at stops. Travel time and average travel speed between stops as well as the vehicle's schedule status (whether it is late, on time, or early) according to that vehicle's schedule can also be calculated from the time-stamped location information from the buses. Data on dwell time, which doors opened, and the number of passengers entering and exiting the buses are also collected and transmitted with the location information. [4]

3.2.2 Conditional Priority System

The AVL system permits “smart” buses that are able to selectively request signal priority. TriMet has implemented TSP using conditional priority that is dependent on the status of the bus with respect to its schedule and if certain other criteria are met. These criteria include the following and are summarized in Figure 3.3:

- The bus is within the City of Portland. Signals outside of the City boundary are not connected to the system.
- The bus is in route and in service.
- The bus is ready to proceed along the route. This is determined by whether the doors are open or closed.
- The bus is 30 seconds or more behind schedule.

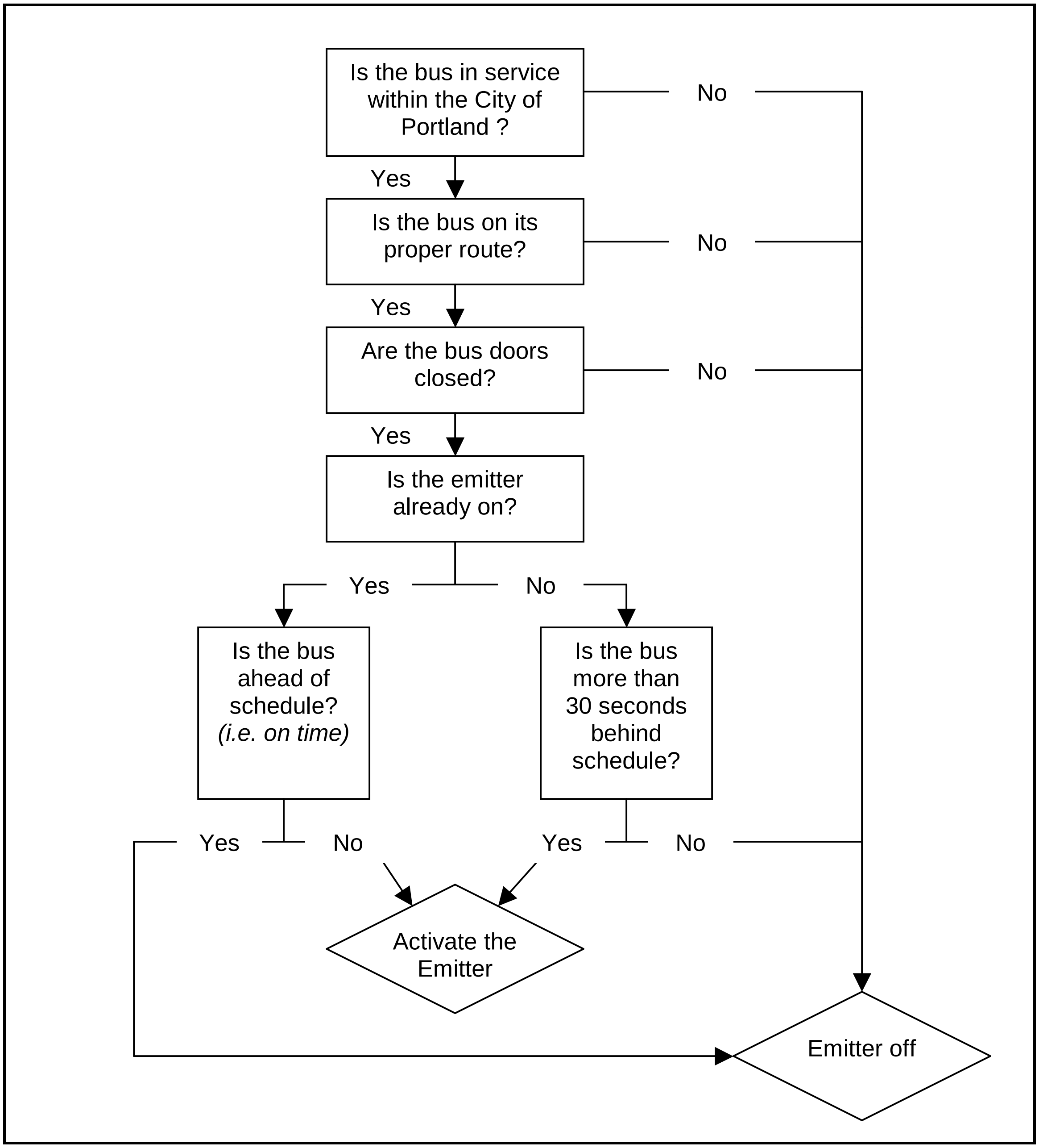


Figure 3.3 Decision Framework for Emitter Activation [4]

If these conditions are all satisfied, the bus will activate the Opticon infrared emitter to request priority. The City of Portland uses Wapiti Microsystems Software as their traffic signal software which provides a range of priority options. Priority can include red truncation, green extension, or a combination of the two. Figure 3.4 shows the priority strategy decision framework as implemented by the controller software.

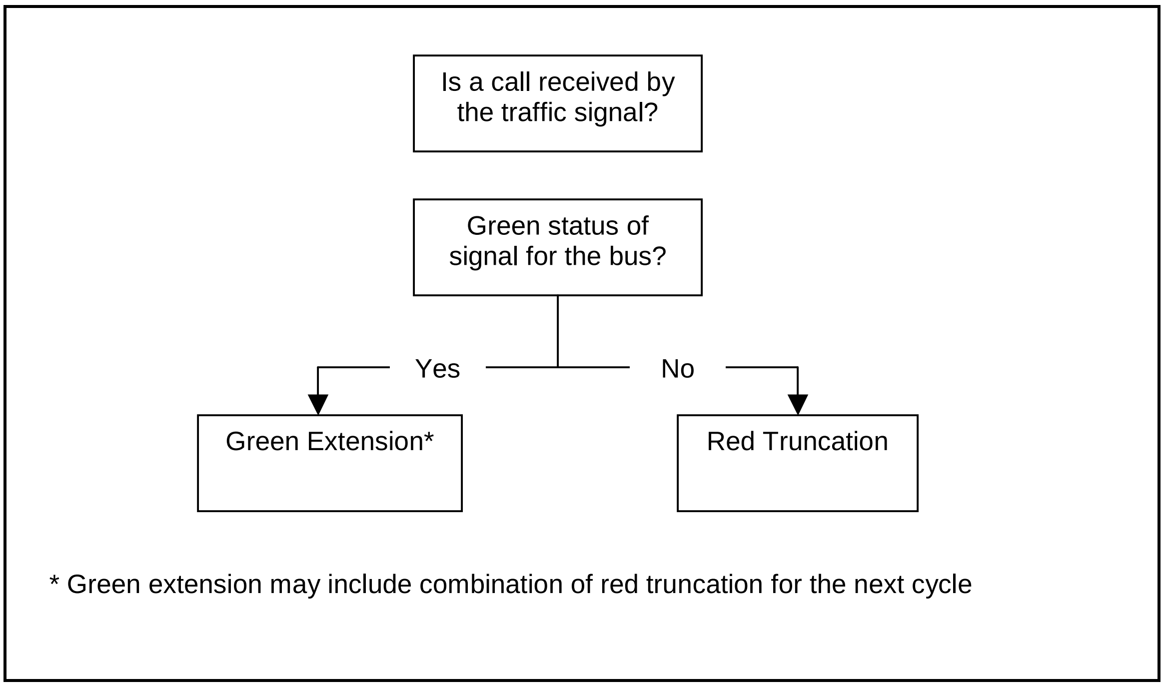


Figure 3.4 Decision Framework for TSP Strategy to Employ [4]

The particular priority strategy is determined by when in the signal cycle the priority request is received. Priority is implemented while keeping the corridor in coordination by adjusting forceoffs and modifying coordination timing plans. [4] Figure 3.5 presents a graphical representation of the general signal priority concept.

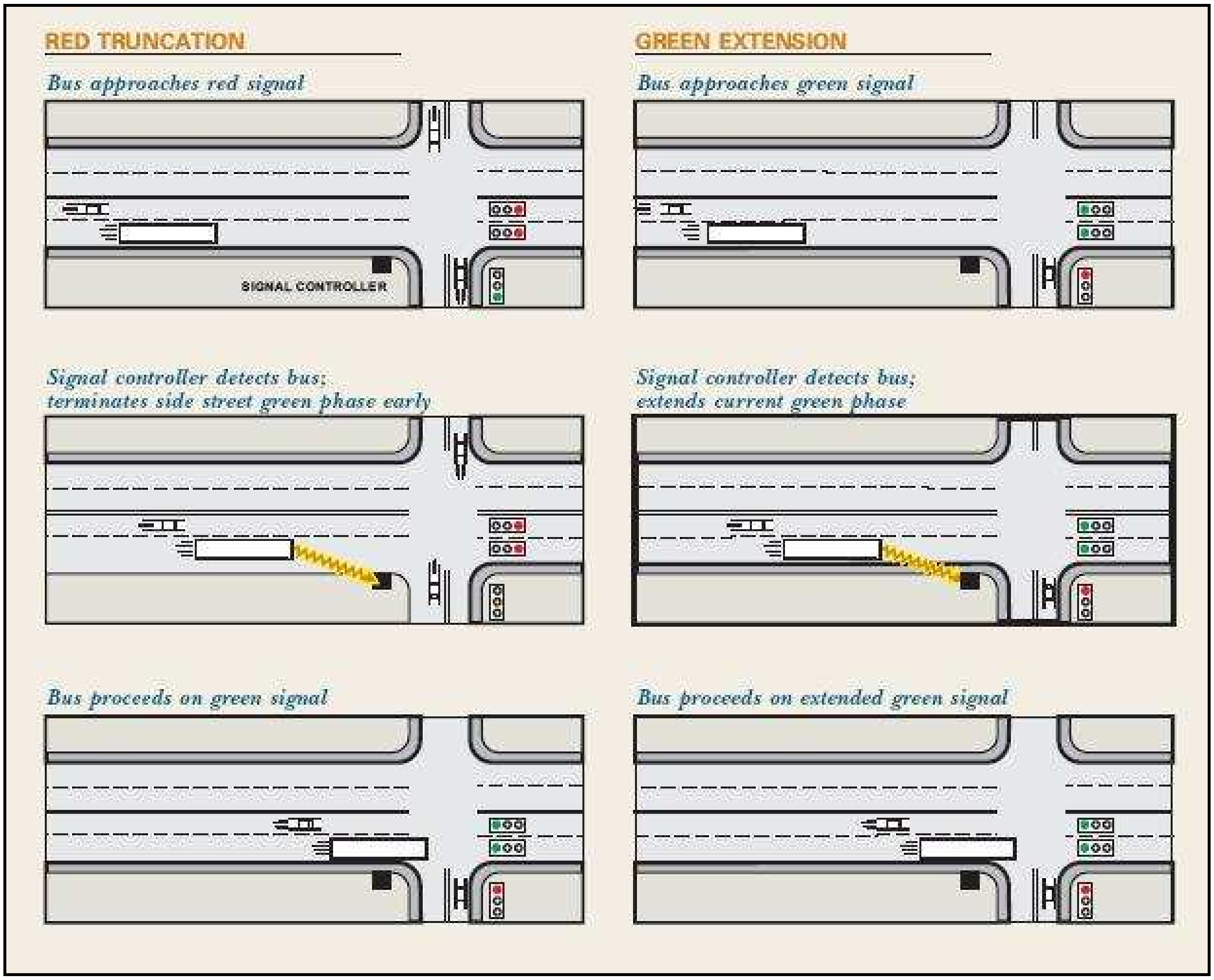


Figure 3.5 General Signal Priorty Concept [15]

3.3 Field Data Processing and Quality Control

3.3.1 Data Processing

The raw data was received as two separate data sets, one for TSP on period and one for the TSP off period. Each data set has over 43,000 separate entries associated with a specific segment and time. These entries contain 45 attributes including time, date, direction, location, schedule, passenger load, dwell time, door openings, peak periods, trip number, and speed information. This information was brought into Microsoft Access and Excel 2003 for analysis.

Queries in Access grouped information for specific time periods by both the northbound and southbound directions. These time periods include the AM peak, PM peak, non-peak, and full day for weekdays, weekends, and the entire study period. Using this query feature in Access, the grouped data was further analyzed for corridor travel time and schedule adherence. The query results were then exported into Excel for statistical analysis.

3.3.2 Quality Control

Quality Control of the data performed on the data sets for the total time periods by direction and TSP status. Travel time data was sorted in Excel by average vehicle speed and each value was associated with a percentile and Z-value of the data set. The speeds were then examined and any average travel speed greater than 40 mph was removed. Where the TSP was turned off, these values all had a Z-value greater than 3.0 and accordingly, all the data points greater than 3.0 for the slow travel speeds were also removed. The data for the TSP on scenarios had no Z-values greater than 3.0, but the high travel speeds accounted for approximately 0.5% of the data set. Therefore, approximately 0.5% was taken out of the slow travel speeds as well. These outliers are attributed to GPS malfunction and as Table 3.1 shows, the amount of outliers removed accounted for no more than 1.1% of any data set. The columns labeled border values are the nearest outlier values to the kept data points and the max value is the highest or lowest outlier value. Table 3.2 shows the change in standard deviation with little change in the mean.

Table 3.1 Travel Time Outlier Determination

Direction	TSP	Border Value Speed (mph)	Border Value Z-Value	Border Value Percentile	Max Value Speed (mph)
NB	OFF	60.6	3.51	0.4%	1786.4
		7.5	3.88	99.7%	3.7
		Total Percentile		*0.7%*	
SB	OFF	57.3	3.24	0.1%	174.7
		7.7	3.07	99.0%	3.5
		Total Percentile		*1.1%*	
NB	ON	40.6	1.65	0.5%	210.2
		7.8	1.78	99.6%	1.2
		Total Percentile		*0.9%*	
SB	ON	41.2	1.82	0.6%	203.8
		7.4	2.11	99.6%	1.1
		Total Percentile		*1.0%*	

Table 3.2 Statistical Comparison of Travel Time Data Set With and Without Outliers

Direction	TSP		Mean	Std. Dev.
NB	OFF	With Outliers	514.8	113.2
		Outliers Removed	514.9	98.2
SB	OFF	With Outliers	554.4	130.4
		Outliers Removed	549.8	112.1
NB	ON	With Outliers	529.4	214.8
		Outliers Removed	523.2	99.0
SB	ON	With Outliers	556.3	208.2
		Outliers Removed	553.3	113.1

These outliers found in the travel time scenarios were associated and removed from the schedule adherence data sets as well. As outlined in Table 3.3, the removal of the outliers had little effect on mean.

Table 3.3 Statistical comparison of schedule adherence data set with and without outliers

Direction	TSP		Mean	Std. Dev.
NB	OFF	With Outliers	-7.8	78.5
		Outliers Removed	-8.3	77.7
SB	OFF	With Outliers	-40.5	100.5
		Outliers Removed	-43.1	96.3
NB	ON	With Outliers	-1.7	80.8
		Outliers Removed	-2.2	79.1
SB	ON	With Outliers	-41.9	97.8
		Outliers Removed	-41.6	97.5

CHAPTER 4

ANALYSIS AND FINDINGS

This chapter discusses the analysis of the collected field data on 82nd Avenue. As detailed in Chapter 3, the dataset contains over 43,000 data points for route segments for each the TSP on and TSP off scenarios. First, the data were analyzed to determine whether there is any difference in overall corridor average travel speeds for the with TSP on. Then, this chapter explores the effect of TSP on the schedule adherence.

4.1 Travel Time

It is expected that signal priority will yield lower average travel times for buses along a route than conventional signal systems. Average bus travel time through the study corridor in both the northbound and southbound directions is calculated for the total study period as well as by service day and time of day from the AVL data. Two descriptive statistics, the mean and standard deviation, are examined to determine bus performance. The mean of a lower travel time indicates a higher average travel speed. Lower standard deviation is an indication of service reliability as the buses travel, and thus arrive, at a more consistent rate.

4.1.1 Northbound Travel Times

The means and standard deviations for selected time periods are shown and compared between the two TSP scenarios in Table 4.1. Significance in the difference of means was determined through a two-tailed t-test with a 95% confidence interval.

Table 4.1Travel Time Comparison: Northbound

		TSP OFF	TSP ON	SIGNIFICANT?
Total Study Period	Mean (s)	**514.9**	523.2	NO
	Std Dev	**98.2**	99.0	
Weekday AM Peak	Mean (s)	**480.0**	490.4	NO
	Std Dev	**63.1**	79.2	
Weekday PM Peak	Mean (s)	**622.8**	651.8	NO
	Std Dev	**87.6**	94.2	
Weekday Non-Peak	Mean (s)	**507.3**	513.2	NO
	Std Dev	93.7	**89.7**	
Weekend	Mean (s)	**502.9**	507.0	NO
	Std Dev	96.5	**91.3**	

As presented in Table ##, while the results show a lower travel time with the TSP turned off for each time period, none of these differences were significant. This is an unexpected result, as signal priority is designed to speed the movement of transit vehicles through the corridor. In addition, the TSP appears to have an adverse effect on reliability as the standard deviations are lower with the TSP turned off during the total and peak travel periods.

The following Figures 4.2-4.5 highlight the travel time differences with the TSP turned on and off with the full range of observations during the principal time periods. These observations have been organized by travel time to ease in direct comparison.

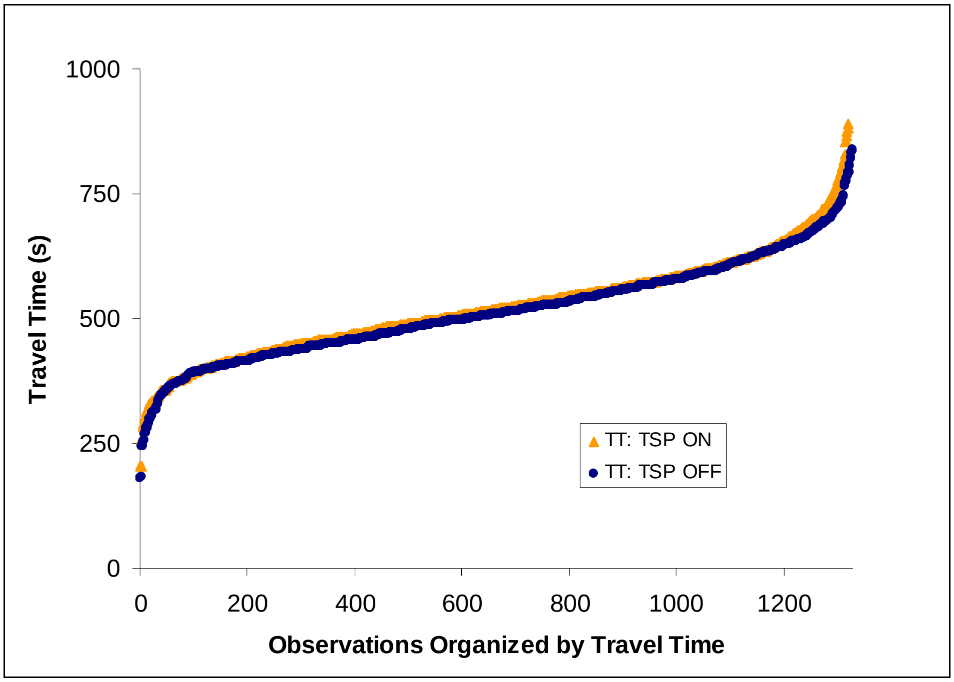


Figure 4.1 Comparison of Average Vehicle Travel Times Northbound: Total Study Period

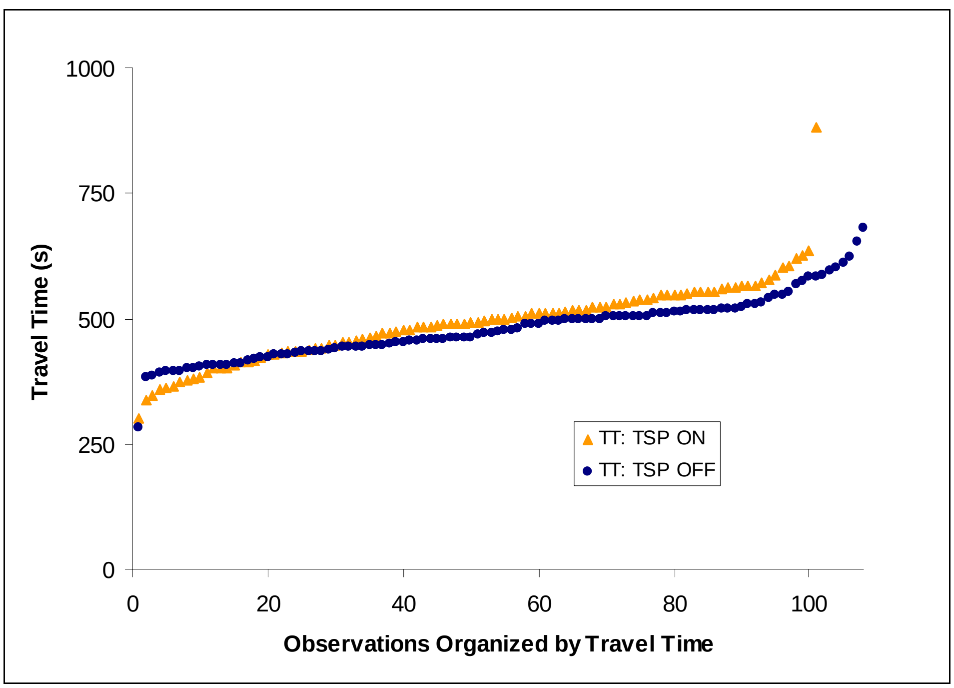


Figure 4.2 Comparison of Average Vehicle Travel Times Northbound: Weekday, AM Peak Period

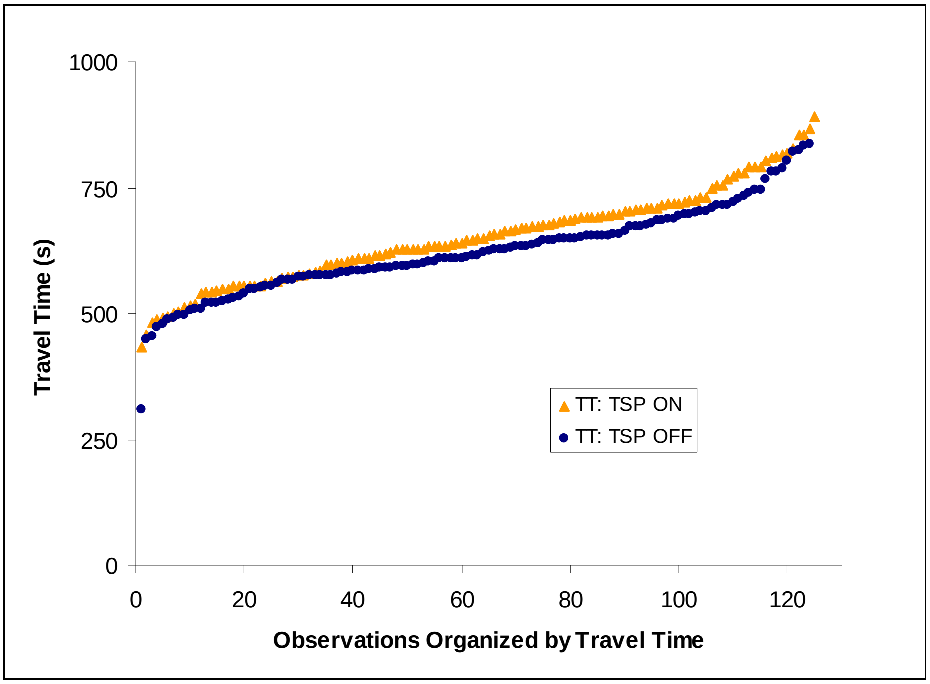


Figure 4.3 Comparison of Average Vehicle Travel Times Northbound: Weekday, PM Peak Period

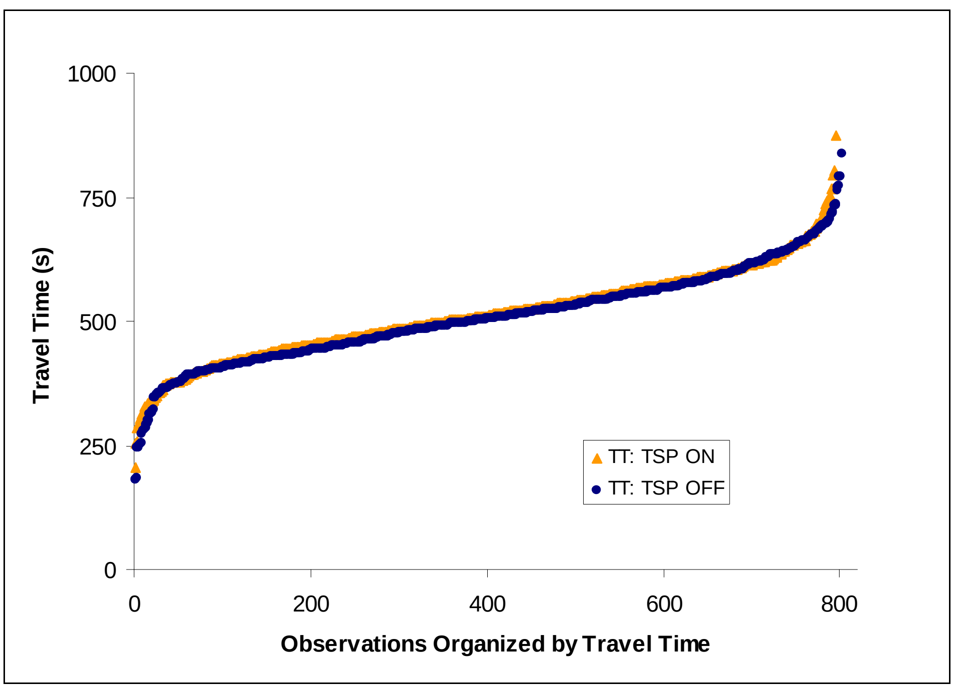


Figure 4.4 Comparison of Average Vehicle Travel Times Northbound: Weekday, Non-Peak Period

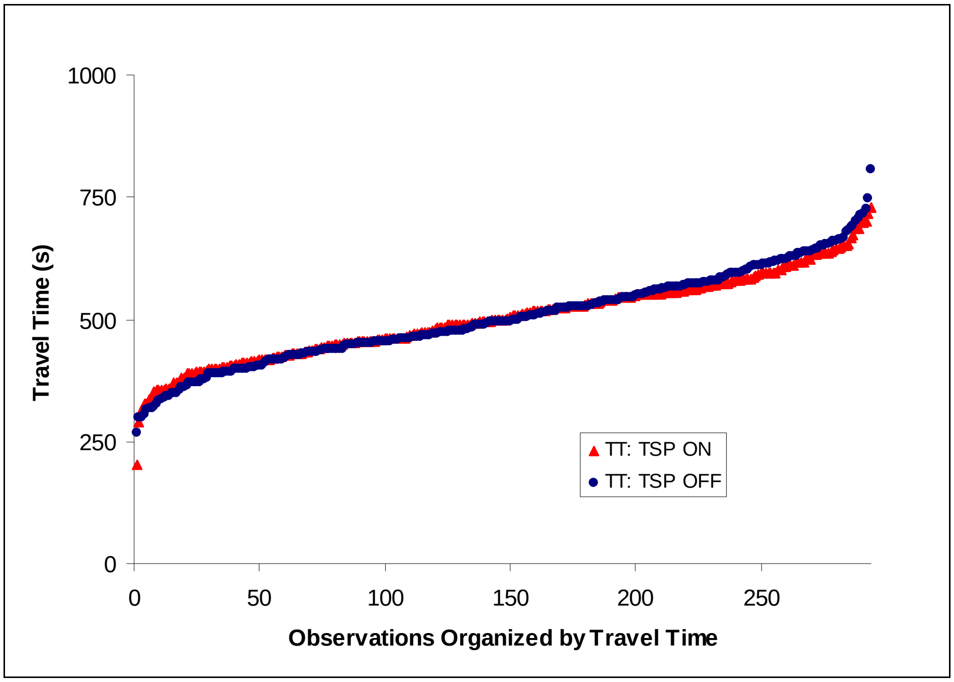


Figure 4.5 Comparison of Average Vehicle Travel Times Northbound: Weekend

Consistent with findings of a lack of significant difference between the means, these figures show a similar relationship and distribution. There are only slight differences between the two data sets which include a slightly greater range of travel times with the TSP turned on and the TSP on data points typically fall slightly above the TSP data points.

Figures of additional time periods and individual scenarios are presented in Appendix A.

4.1.2 Southbound Travel Times

The means and standard deviations for selected time periods are shown and compared between the two TSP scenarios in Table 4.2. Significance in the difference of means was determined through a two-tailed t-test with a 95% confidence interval.

Table 4.2 Travel Time Comparison: Southbound

		TSP		
		OFF	**ON**	**SIGNIFICANT?**
Total Study Period	Mean (s)	**549.8**	553.3	NO
	Std Dev	**112.1**	113.1	
Weekday AM Peak	Mean (s)	489.4	**477.1**	NO
	Std Dev	**69.9**	85.2	
Weekday PM Peak	Mean (s)	**597.1**	630.2	NO
	Std Dev	104.7	**95.8**	
Weekday Non-Peak	Mean (s)	**556.8**	560.8	NO
	Std Dev	112.0	**111.2**	
Weekend	Mean (s)	526.7	**524.5**	NO
	Std Dev	112.0	**111.9**	

As presented in Table ##, while the results show a lower travel time in most periods with the TSP turned off, none of these differences were significant. Again, this result is unexpected. Unlike in the northbound direction however, the standard deviation is lower in the TSP on scenario is most cases. Although during the critical AM peak period and the total study period, the standard deviation was lower in the TSP off scenarios. Therefore, while the results are not as consistent, the TSP still appears to have an adverse effect on reliability in several periods.

The following Figures 4.6-4.10 highlight the travel time differences with the TSP turned on and off with the full range of observations during the principal time periods. These observations have been organized by travel time to ease in direct comparison.

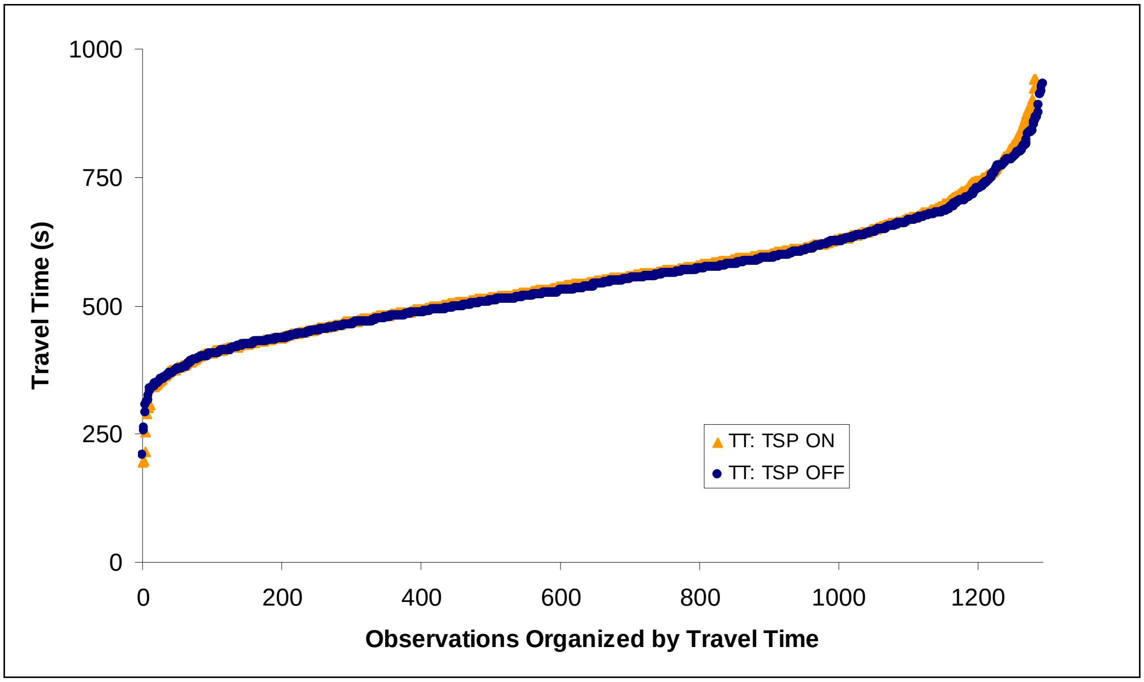


Figure 4.6 Comparison of Average Vehicle Travel Times
Southbound: Total Study Period

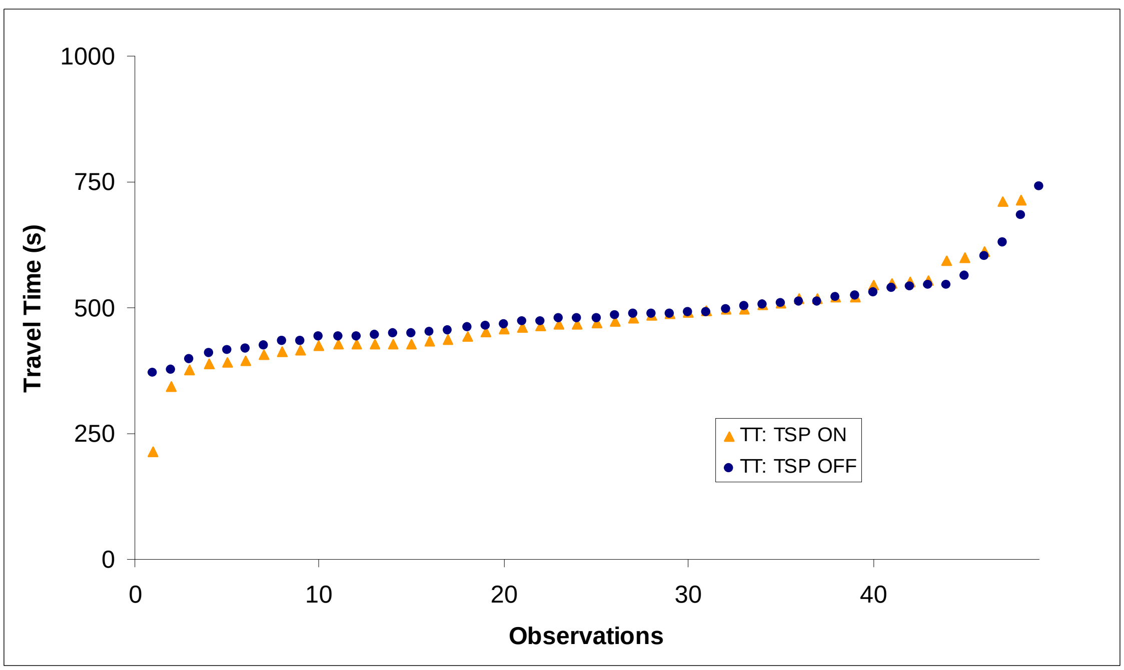


Figure 4.7 Comparison of Average Vehicle Travel Times
Southbound: Weekday, AM Peak Period

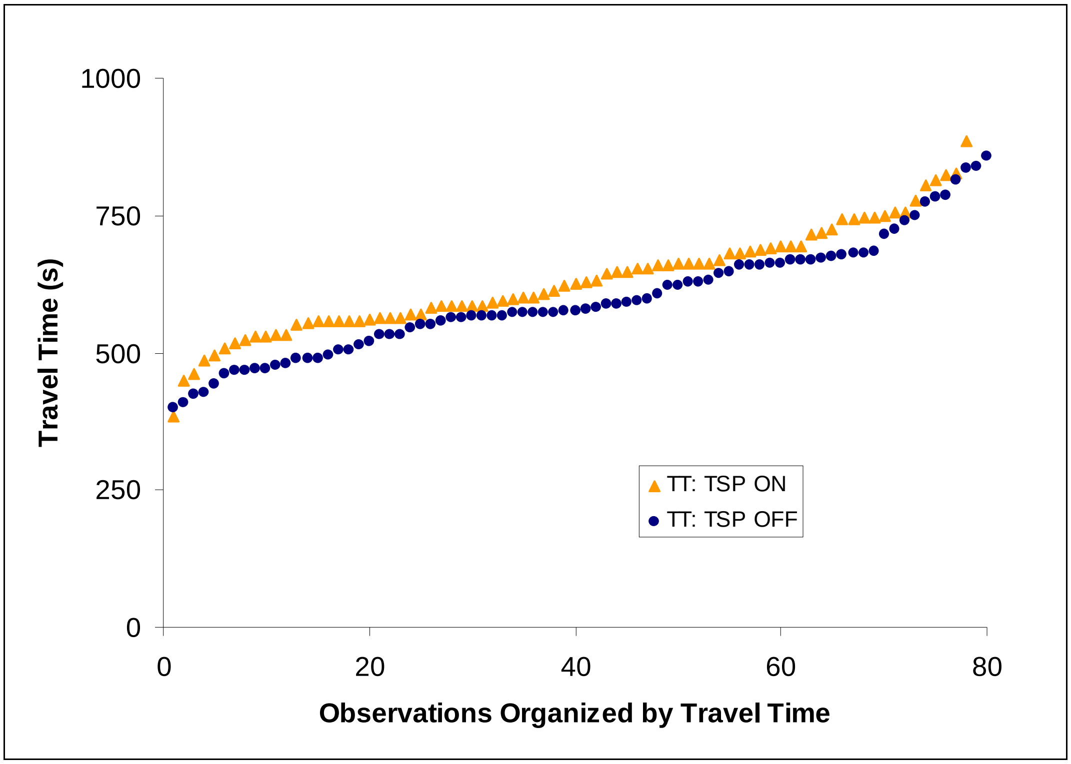


Figure 4.8 Comparison of Average Vehicle Travel Times Southbound: Weekday, PM Peak Period

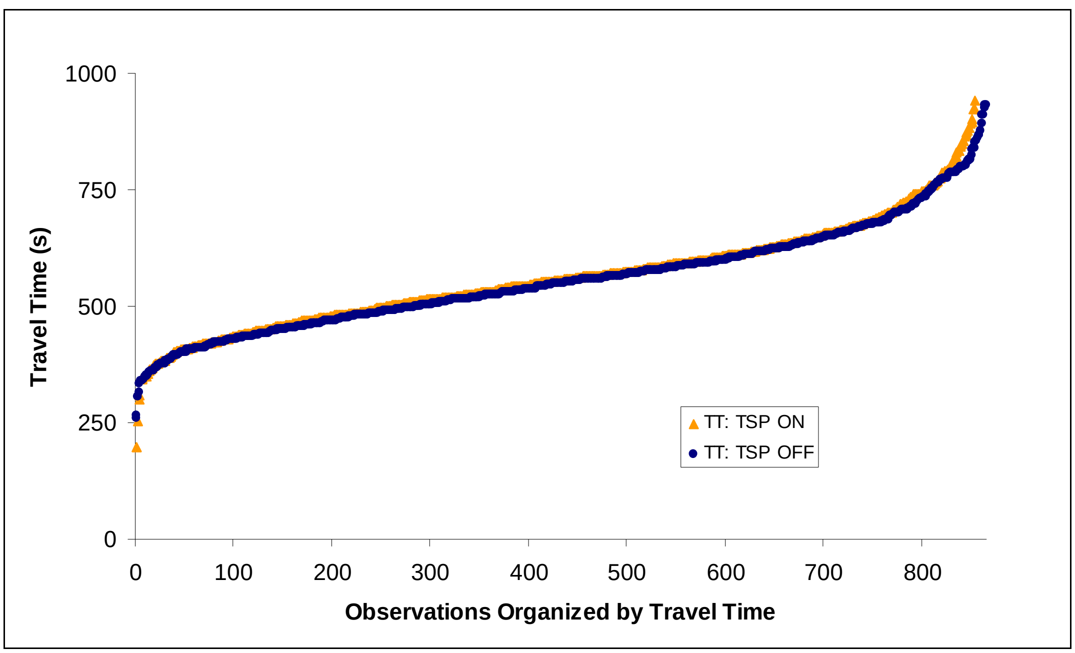


Figure 4.9 Comparison of Average Vehicle Travel Times Southbound: Weekday, Non-Peak Period

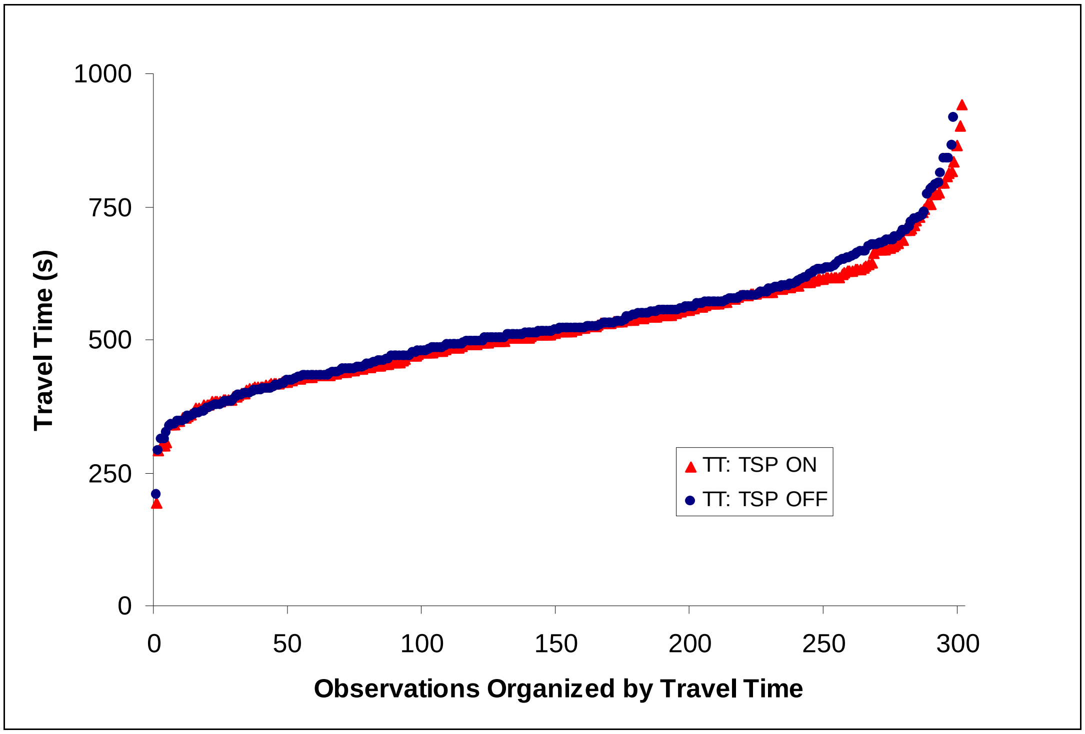


Figure 4.10 Comparison of Average Vehicle Travel Times Southbound: Weekend

Consistent with findings of a lack of significant difference between the means, these figures show a similar relationship and distribution. There are only slight differences between the two data sets which include a slightly greater range of travel times with the TSP turned on and the TSP on data points typically fall slightly above the TSP data points.

Figures of additional time periods and individual scenarios are presented in Appendix A.

4.2 Schedule Adherence

One of the benefits of signal priority is that it has been found to increase schedule adherence and thus make transit more appealing to choice riders. In this study schedule adherence was evaluated on the 82nd Avenue study corridor through an analysis of the AVL data. This was performed through subtracting the seconds that the bus is behind schedule when entering the corridor by the seconds that the bus is behind schedule when leaving the corridor. This value is the amount of time that the bus is gaining in the corridor to minimize schedule delays. Buses ahead of schedule is far worse than buses behind schedule but, as the AVL data does not provide information about when the emitter is on or off, all data sets were evaluated. To offset this unknown information, the results also examine the frequency of a bus entering the corridor behind schedule becoming ahead of schedule. Buses were considered behind schedule when they entered the corridor more than 30 seconds behind schedule as this is the time that the emitter is turned on. When exiting the corridor, ahead of schedule is considered any time before the scheduled stop. The same time periods as the travel time analysis are highlighted in this section.

4.2.1 Northbound Schedule Adherence

The means and standard deviations for selected time periods are shown and compared between the two TSP scenarios in Table 4.3; a negative number signifies the bus making up time in the corridor, with respect to the schedule. Significance in the difference of means was determined through a two-tailed t-test with a 95% confidence interval.

Table 4.3 Increase in Late Arrival Comparison: Northbound

		TSP		
		OFF	**ON**	**SIGNIFICANT?**
Total Study Period	Mean (s)	**-8.3**	-2.2	NO
	Std Dev	**77.7**	79.1	
Weekday AM Peak	Mean (s)	**-2.2**	11.1	NO
	Std Dev	**60.2**	63.0	
Weekday PM Peak	Mean (s)	**-7.8**	18.1	NO
	Std Dev	**79.1**	90.3	
Weekday Non-Peak	Mean (s)	-13.3	**-10.8**	NO
	Std Dev	78.6	**77.3**	
Weekend	Mean (s)	**2.5**	6.7	NO
	Std Dev	**79.7**	80.6	

As presented in Table 4.3, the results show an improvement in schedule difference with the TSP turned off for each time period, however none of these differences were significant. As with travel time, this result is unexpected, as conditional signal priority is designed to improve schedule adherence.

The goal of improving the late arrival rates is beneficial only until the scheduled arrival time, after which it becomes unfavorable and reduced the quality of service. With the conditional TSP system, the emitter turns off once the bus reaches its schedule arrival. Table 4.4 attempts to isolate the buses which had the emitter on through the corridor, taking into account that the conditional priority system only provides priority once buses are at least 30 seconds behind schedule. The TSP off scenario similarly isolates these values for comparison. The bolded values indicate greater performance.

Table 4.4 Schedule Status Comparison: Northbound

		TSP: OFF		TSP: ON	
	Population	**Percent of buses entering corridor behind schedule**	**Percent of buses entering corridor behind schedule and exiting ahead of schedule**	**Percent of buses entering corridor behind schedule**	**Percent of buses entering corridor behind schedule and exiting ahead of schedule**
Total Study Period	All buses	**66%**	6%	68%	5%
	Only buses entering behind schedule		*9%*		***7%***
Weekday AM Peak	All buses	**33%**	4%	42%	0%
	Only buses entering behind schedule		*11%*		***0%***
Weekday PM Peak	All buses	79%	3%	79%	4%
	Only buses entering behind schedule		***4%***		*5%*
Weekday Non-Peak	All buses	**70%**	8%	72%	5%
	Only buses entering behind schedule		*11%*		***8%***
Weekend	All buses	**60%**	4%	65%	6%
	Only buses entering behind schedule		***6%***		*9%*

Note: Behind schedule: ≥ 30 seconds
Ahead of schedule: < 0 seconds

As highlighted in Table 4.4, in all but the PM peak period, the TSP on scenario had a greater percentage of buses entering the study corridor behind schedule. However, the TSP on scenario recovered better in the total, AM peak, and non-peak periods as a lower percentage of buses that entered the corridor late got ahead of schedule by the time they exited the corridor.

The following Figures 4.11-4.15 highlight the schedule adherence changes through the corridor with the TSP turned on and off with the full range of observations during the principal time periods. These observations have been organized by travel time to ease in direct comparison.

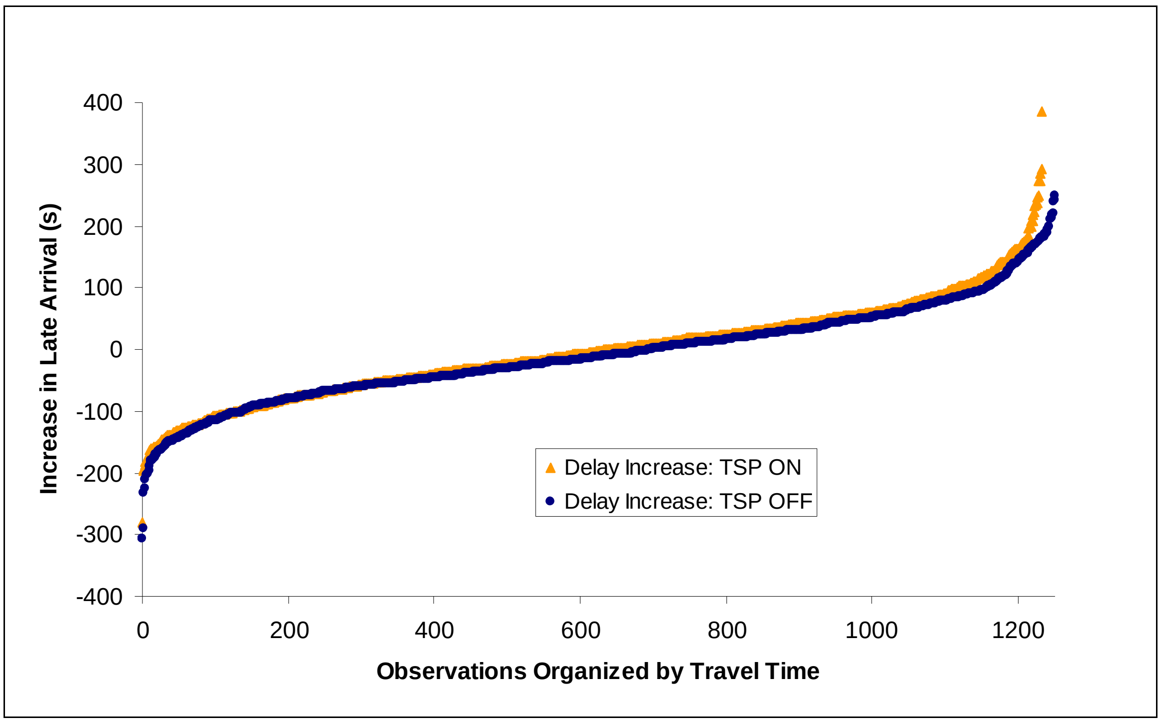


Figure 4.11 Comparison of Increase in Late Arrival to Schedule Through Corridor Northbound: Total Study Period

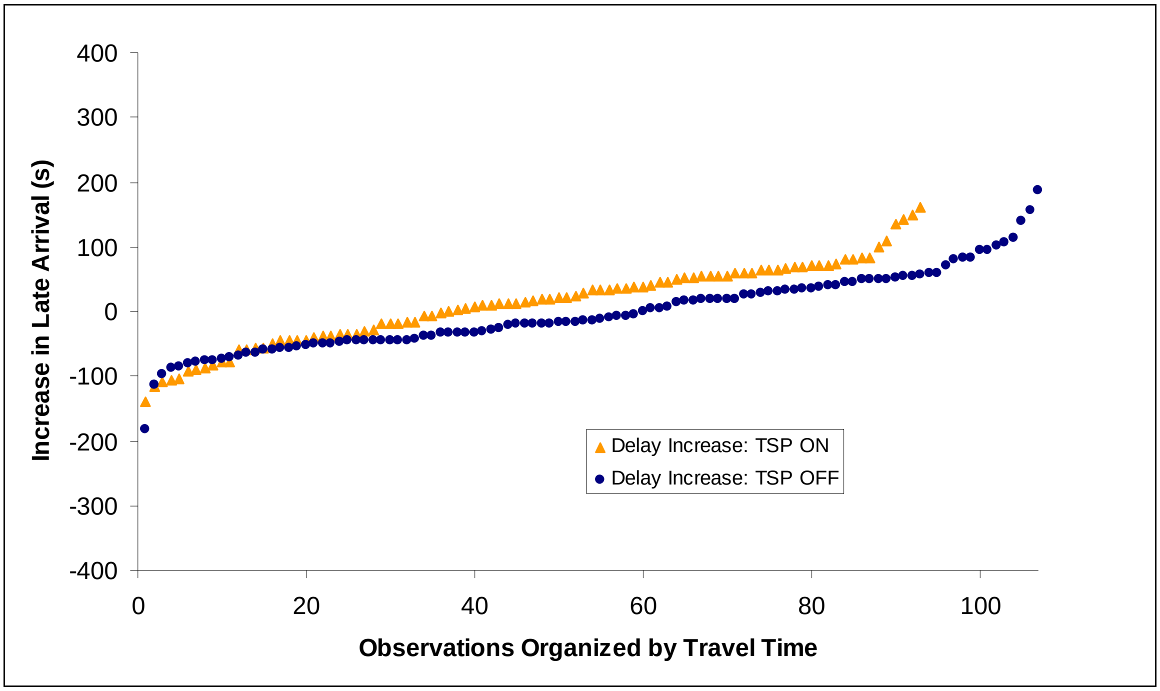


Figure 4.12Comparison of Increase in Late Arrival to Schedule Through Corridor Northbound: Weekday, AM Peak Period

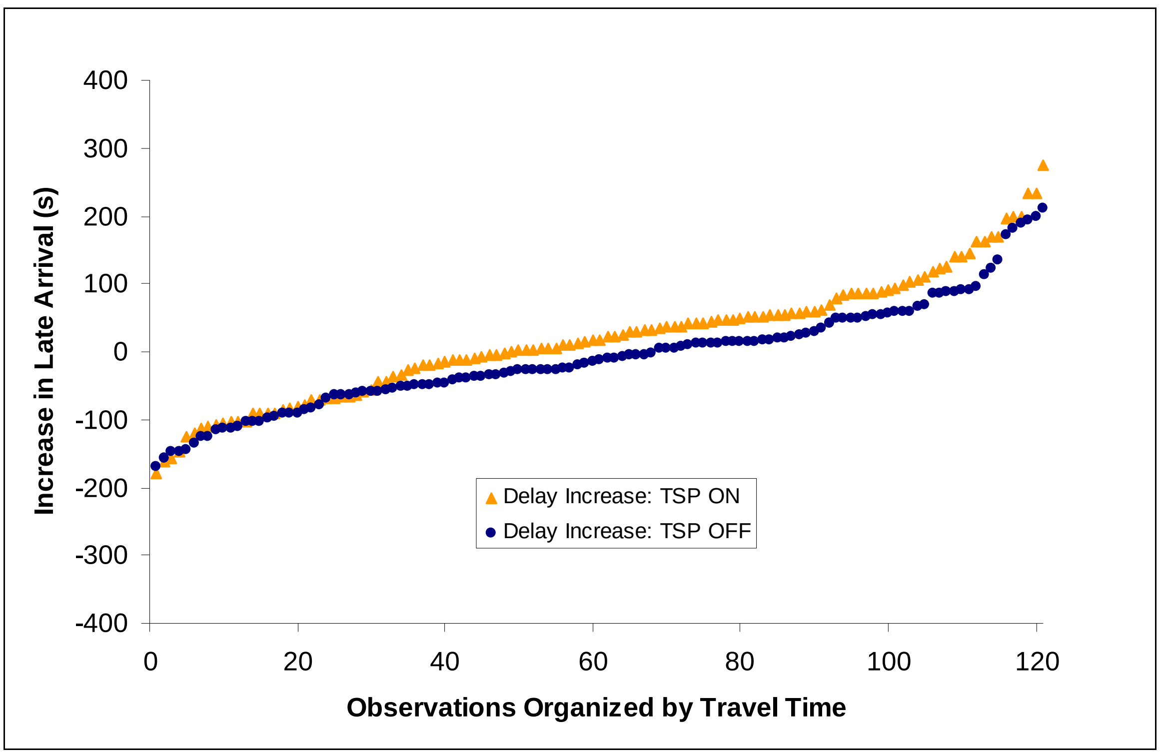


Figure 4.13 Comparison of Increase in Late Arrival to Schedule Through Corridor Northbound: Weekday, PM Peak Period

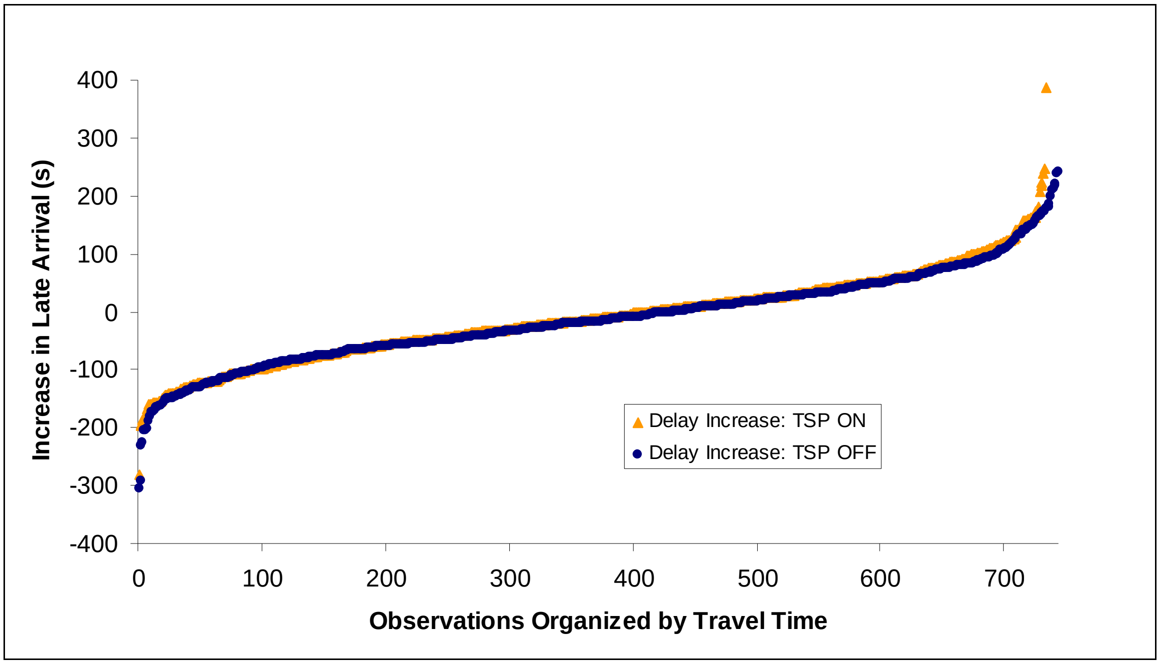


Figure 4.14 Comparison of Increase in Late Arrival to Schedule Through Corridor Northbound: Weekday, Non-Peak Period

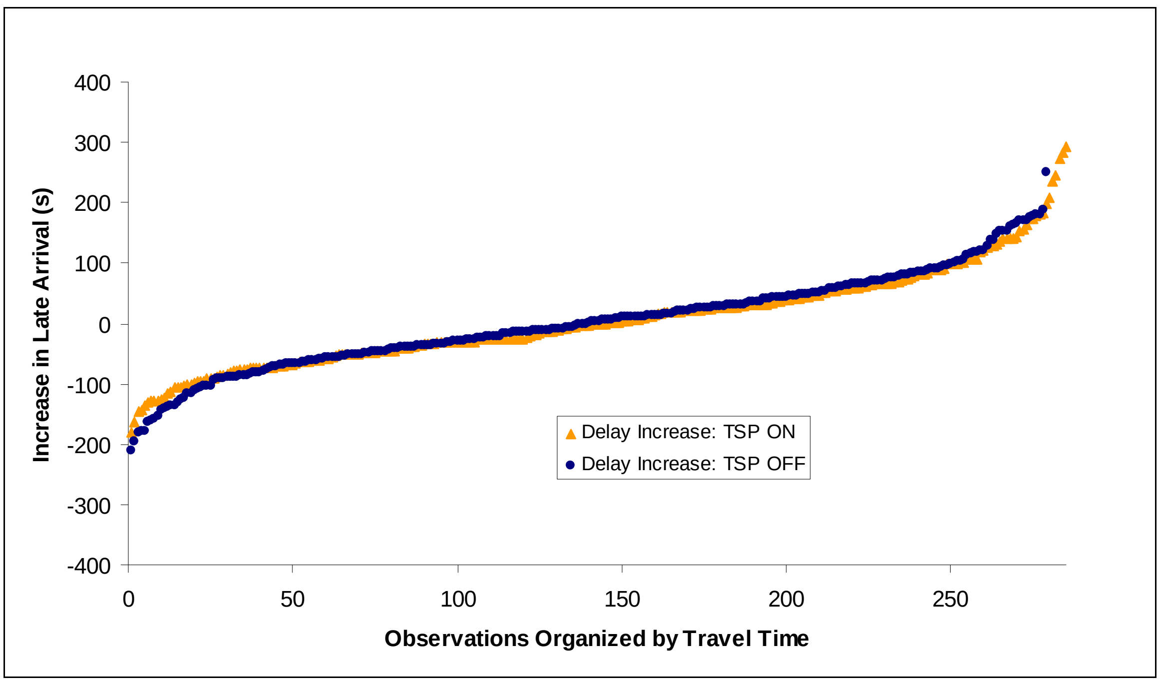


Figure 4.15 Comparison of Increase in Late Arrival to Schedule Through Corridor Northbound: Weekend

Consistent with the findings of a lack of significant difference between the means, these figures show a similar relationship and distribution. There are only slight differences between the two data sets including a slightly greater range of schedule difference times with the TSP turned on and the TSP on data points typically fall slightly above the TSP data points, indicating less recovery from delayed vehicles.

Figures of additional time periods and individual scenarios are presented in Appendix B.

4.2.2 Southbound Schedule Adherence

The means and standard deviations for selected time periods are shown and compared between the two TSP scenarios in Table 4.5; a negative number signifies the bus making up time in the corridor, with respect to the schedule. Significance in the difference of means was determined through a two-tailed t-test with a 95% confidence interval.

Table 4.5 Increase in Late Arrival Comparison: Southbound

		TSP		
		OFF	**ON**	**SIGNIFICANT?**
Total Study Period	Mean (s)	-43.1	**-41.6**	NO
	Std Dev	**96.3**	97.5	
Weekday AM Peak	Mean (s)	15.7	**10.1**	NO
	Std Dev	**58.4**	74.4	
Weekday PM Peak	Mean (s)	**-49.9**	-20.2	NO
	Std Dev	98.0	**88.0**	
Weekday Non-Peak	Mean (s)	**-40.6**	-38.8	NO
	Std Dev	**92.2**	93.5	
Weekend	Mean (s)	**-58.3**	-63.4	NO
	Std Dev	**107.9**	108.5	

As presented in Table 4.5, the results show mixed results in schedule difference with the TSP turned off and on for each time period, though none of the differences are found to be significant. As with travel time, this result is unexpected, as conditional signal priority is designed to improve schedule adherence.

The goal of improving the late arrival rates is beneficial only until the scheduled arrival time, after which it becomes unfavorable and reduced the quality of service. With the conditional TSP system, the emitter turns off once the bus reaches its schedule arrival. Table 4.6 attempts to isolate the buses which had the emitter on through the corridor, taking into account that the conditional priority system only provides priority once buses are at least 30 seconds behind schedule. The TSP off scenario similarly isolates these values for comparison. The bolded values indicate greater performance.

Table 4.6 Schedule Status Comparison: Southbound

	Population	TSP: OFF		TSP: ON	
		Percent of buses entering corridor behind schedule	**Percent of buses entering corridor behind schedule and exiting ahead of schedule**	**Percent of buses entering corridor behind schedule**	**Percent of buses entering corridor behind schedule and exiting ahead of schedule**
Total Study Period	All buses	**44%**	8%	46%	10%
	Only buses entering behind schedule		***18%***		*22%*
Weekday AM Peak	All buses	**24%**	0%	45%	2%
	Only buses entering behind schedule		***0%***		*5%*
Weekday PM Peak	All buses	**43%**	9%	44%	4%
	Only buses entering behind schedule		*21%*		***9%***
Weekday Non-Peak	All buses	46%	8%	46%	10%
	Only buses entering behind schedule		***19%***		*22%*
Weekend	All buses	**43%**	8%	45%	13%
	Only buses entering behind schedule		***18%***		*29%*

Note: Behind schedule: ≥ 30 seconds
Ahead of schedule: < 0 seconds

As highlighted in Table 4.6, in all but the weekday non-peak period, the TSP on scenario had a greater percentage of buses entering the study corridor behind schedule. The TSP on scenario also recovered worse in all but the PM peak period as a higher percentage of buses that entered the corridor late got ahead of schedule by the time they exited the corridor.

The following Figures 4.16-4.20 highlight the schedule adherence changes through the corridor with the TSP turned on and off with the full range of observations during the principal time periods. These observations have been organized by travel time to ease in direct comparison.

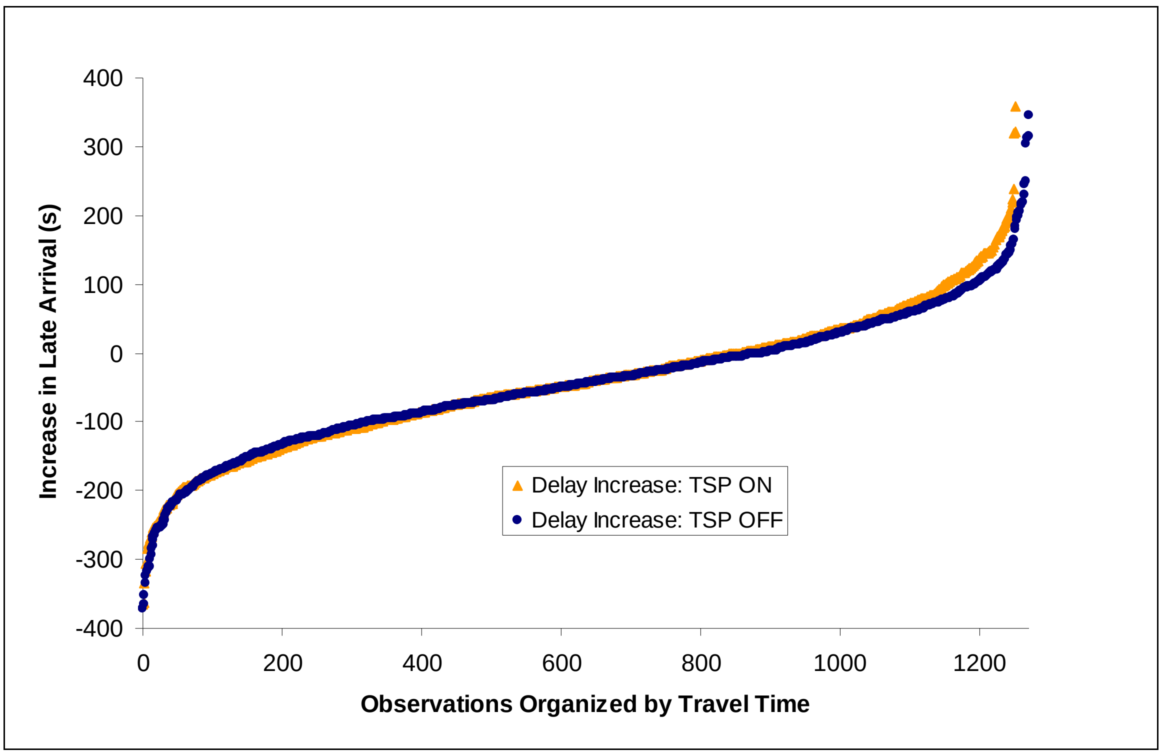


Figure 4.16 Comparison of Increase in Late Arrival to Schedule Through Corridor Southbound: Total Study Period

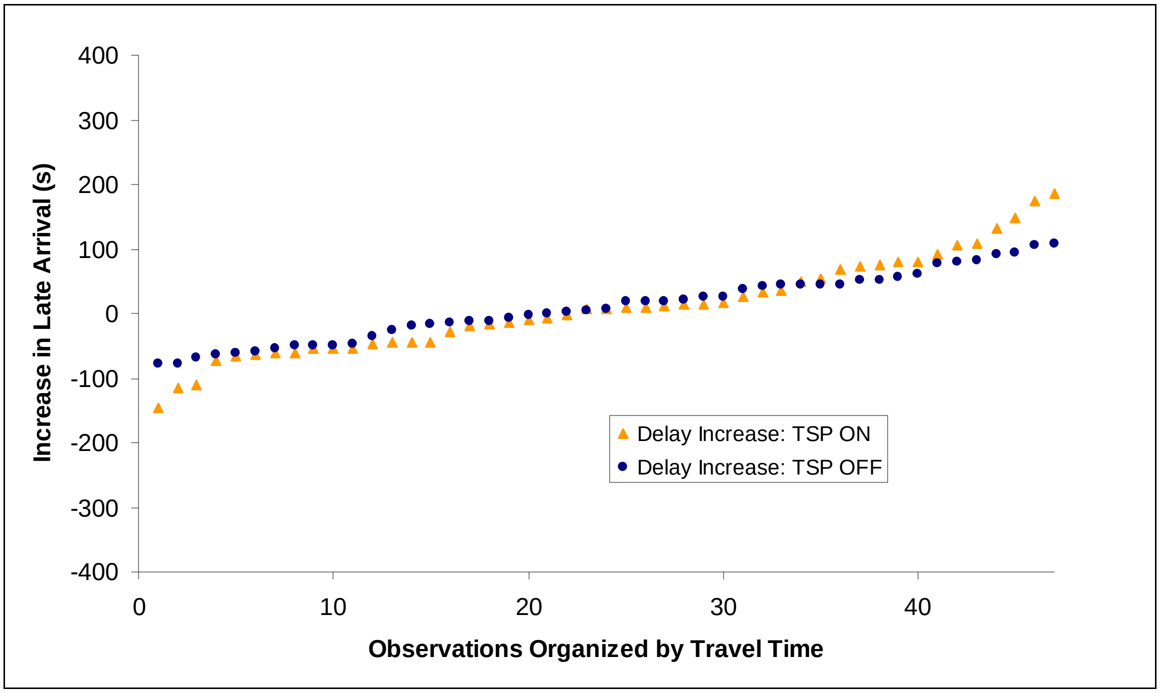


Figure 4.17 Comparison of Increase in Late Arrival to Schedule Through Corridor Southbound: Weekday, AM Peak Period

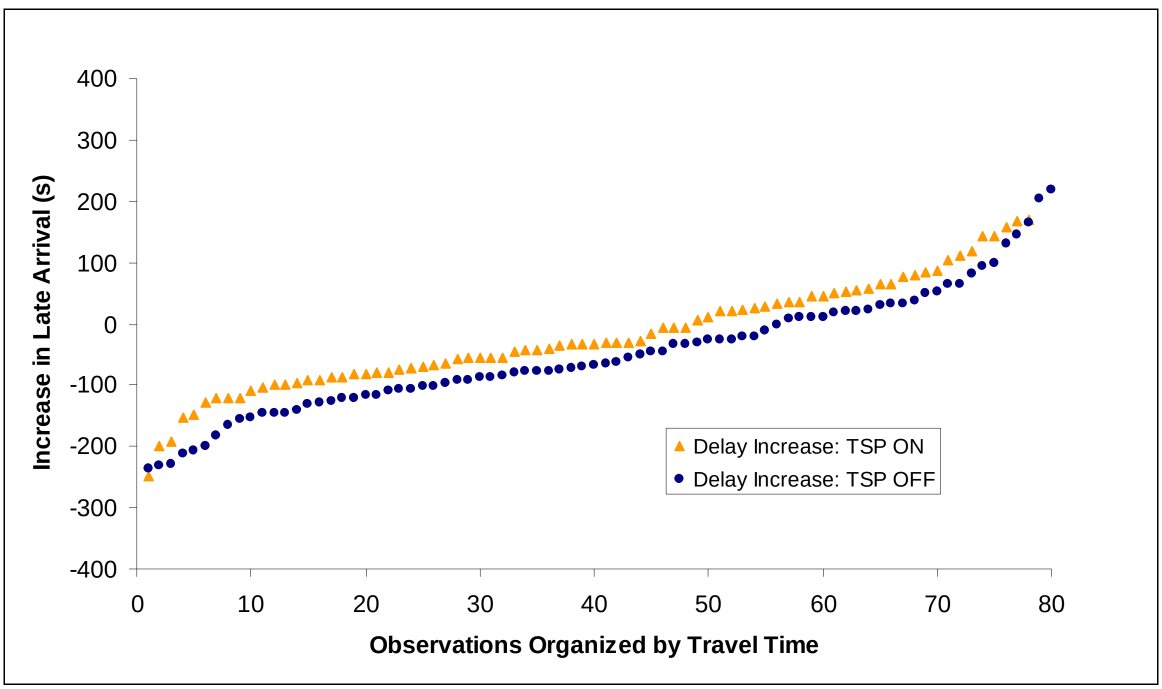


Figure 4.18 Comparison of Increase in Late Arrival to Schedule Through Corridor Southbound: Weekday, PM Peak Period

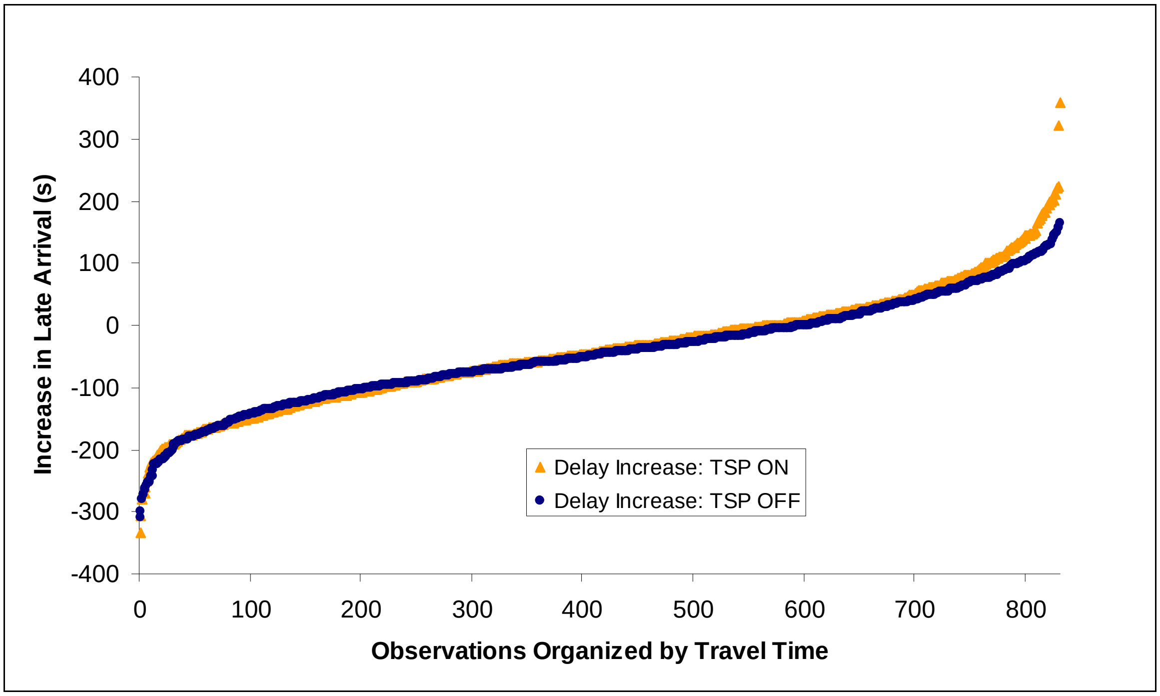


Figure 4.19 Comparison of Increase in Late Arrival to Schedule Through Corridor Southbound: Weekday, Non-Peak Period

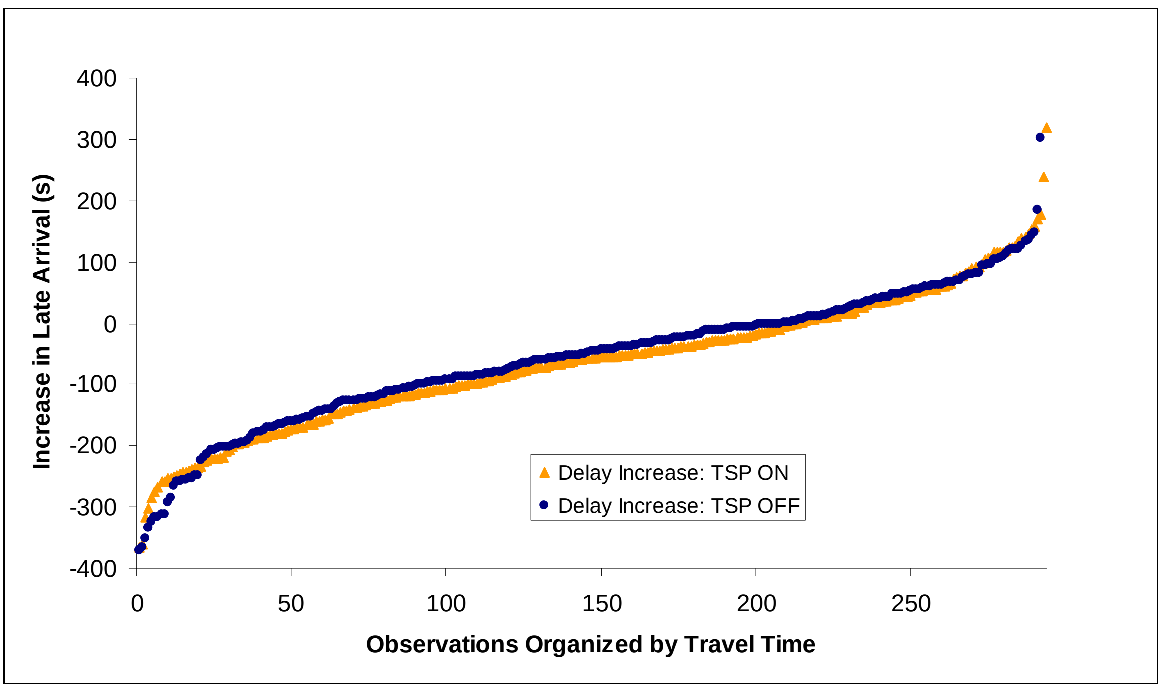


Figure 4.20 Comparison of Increase in Late Arrival to Schedule Through Corridor Southbound: Weekend

Consistent with the findings of a lack of significant difference between the means, these figures show a similar relationship and distribution.

Figures of additional time periods and individual scenarios are presented in Appendix B.

4.3 Summary of Analysis and Findings

Chapter 4 of this report focused on the analysis and findings of the data collection of this report. It was found that TSP provides no significant difference in travel times on this corridor. It does however decrease reliability due to a higher standard deviation in travel times in both directions. It was also found that there is no significant difference in schedule adherence with TSP on this corridor. Additionally, there were mixed results for schedule recovery with no clear benefit of TSP.

CHAPTER 5

CONCLUSIONS

Transit signal priority is often regarded as an effective way to increase the quality and transit service through gains in travel speed and, more importantly, schedule reliability. This reliability leads to an increase in choice riders and also has the advantage of more consistent recovery times at the end of routes, reducing the number of buses needed to service a route. This research has shown however, that on certain corridors there may be little to no benefit towards TSP implementation and may possibly provide some disbenefit. These benefits of transit signal priority were studied as the average bus operating speed and schedule adherence on the. The direct comparison for TSP on and off scenarios completed for this research yielded no significant differences in reduction in travel time or schedule adherence performance. An additional interesting result was that the standard deviation of the results did not have any specific tendencies with the TSP on or off. It was expected that the standard deviation would be consistently lower with the TSP on, indicating improved schedule reliability. Chapter 5 of this report will focus on conclusions drawn from the research of this Portland bus corridor and improvements that could be made.

5.1 Bus Stop Placement

The literature review for this study highlights the impact of bus stop placement at intersections on TSP. An examination of the study corridor reveals that out of all the bus stops 44% occur at the nearside of a signalized intersection and 13% at the farside in the northbound direction. In the southbound direction 31% of all bus stops are placed on the nearside of signalized intersections and 19% on the farside. These placements are detailed in Tables 5.1 and 5.2 and Figure 5.1.

Table 5.1 Bus Stop Positions – Northbound

Direction:	**NB**	*Length:*	*10480 ft*
Stop Location	***Stop ID***	***Block Position***	***Signalized?***
SE 82nd & Woodward	8061	Near-Side	Yes
SE 82nd & Clinton	7947	Near-Side	No
SE 82nd & Division	7957	Near-Side	Yes
2200 Block SE 82nd	7922	Mid-Block	N/A
SE 82nd & Mill	8007	Near-Side	Yes
SE 82nd & Hawthorne	7979	Near-Side	No
SE 82nd & Salmon	8037	Far-Side	No
SE 82nd & Yamhill	8065	Near-Side	Yes
SE 82nd & Washington	7928	Near-Side	Yes
SE 82nd & Stark	8047	Far-Side	Yes
SE 82nd & Ash	7930	Near-Side	No
SE 82nd & E Burnside	7936	Near-Side	Yes
NE 82nd & Davis	7955	Near-Side	Yes
NE 82nd & Glisan	7972	Far-Side	Yes
NE 82nd & Oregon	8014	Mid-Block	N/A
NE 82nd & Holladay	7987	Mid-Block	N/A
% Nearside Stops:		*63%*	
% Nearside Stops & Signalized:		***44%***	
% Farside Stops:		*19%*	
% Farside Stops & Signalized:		***13%***	

Table 5.2 Bus Stop Positions – Southbound

Direction:	**SB**	*Length:*	*10860 ft*
Stop Location	***Stop ID***	***Intersection Position***	***Signalized?***
NE 82nd & Hassalo	7978	Mid-Block	N/A
NE 82nd & Pacific	7932	Mid-Block	N/A
NE 82nd & Glisan	7973	Near-Side	Yes
NE 82nd & Davis	7956	Near-Side	Yes
NE 82nd & E Burnside	7937	Near-Side	Yes
SE 82nd & Ash	7931	Far-Side	No
SE 82nd & Stark	8048	Near-Side	Yes
SE 82nd & Alder	7929	Near-Side	No
SE 82nd & Yamhill	8066	Far-Side	Yes
SE 82nd & Main	8004	Near-Side	No
SE 82nd & Hawthorne	7980	Near-Side	No
SE 82nd & Mill	8008	Far-Side	Yes
2200 Block SE 82nd	7923	Mid-Block	N/A
SE 82nd & Division	7958	Near-Side	Yes
SE 82nd & Clinton	7948	Near-Side	No
SE 82nd & Woodward	8062	Far-Side	Yes
% Nearside Stops:		*56%*	
% Nearside Stops & Signalized:		***31%***	
% Farside Stops:		*25%*	
% Farside Stops & Signalized:		***19%***	

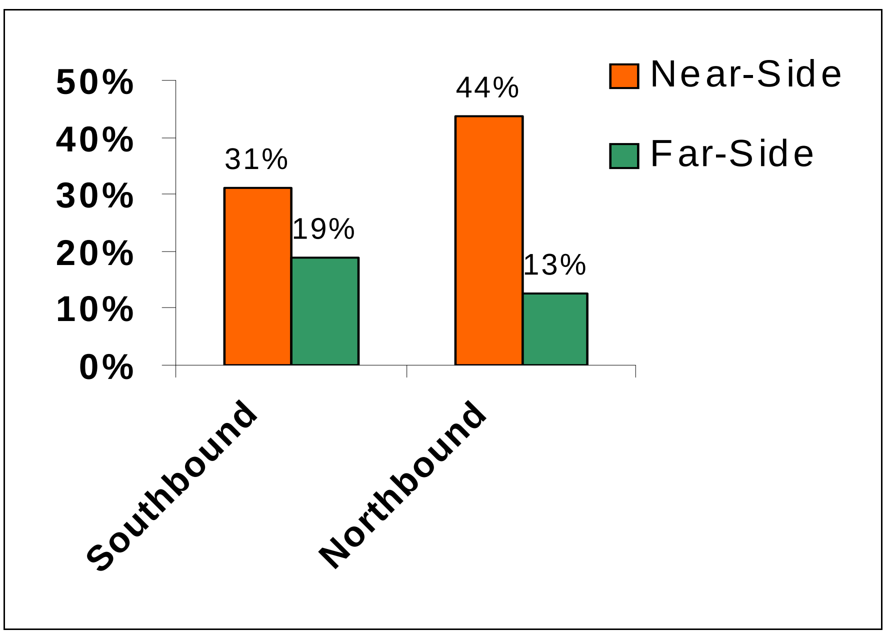


Figure 5.1 Percentage of Bus Stops that are Located Nearside of a Signalized Intersection

To account for potential changes in rider profile, the percentage of stops the buses made was compared between scenarios. It is found that for the total study period the buses stopped at 41% of the total stops with the TSP off and 43% of the stops with the TSP on in both the northbound and southbound directions. These stop percentages, as well as the percentages for other time periods shown in Figures 5.2 and 5.3, represent negligible differences that would not account for much change in bus performance.

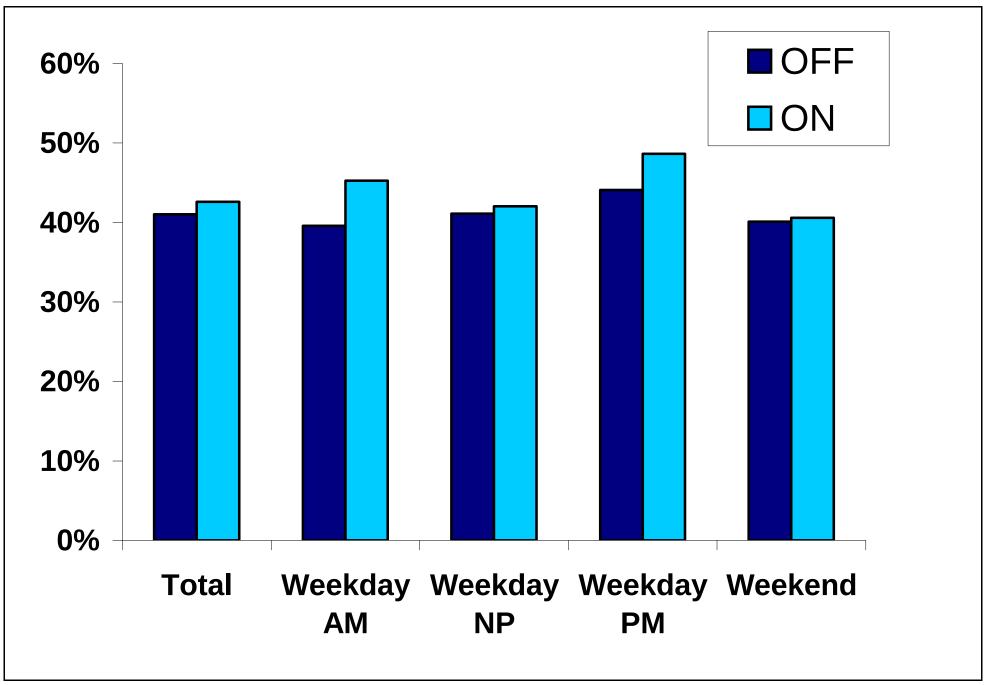


Figure 5.2 Bus Stop Percentage - Northbound

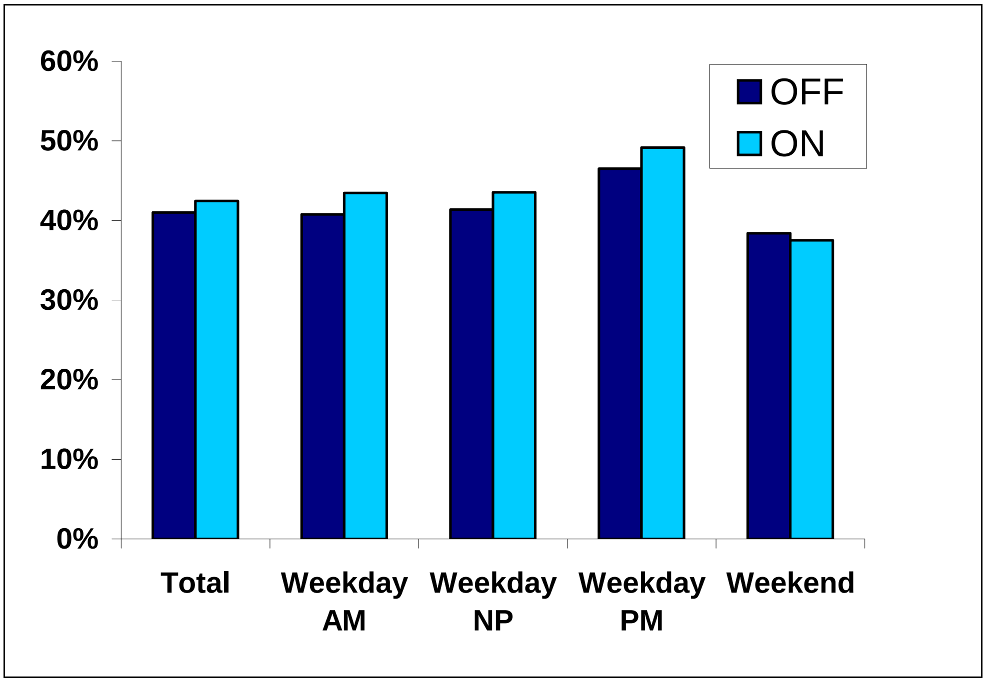


Figure 5.3 Bus Stop Percentage - Southbound

Relocation of the nearside stops would likely increase the effectiveness of the TSP system. However, relocation may not be a feasible option for many of the locations since they serve as transfer stops for east/west bus routes. These transfer stops are placed on the same corner, such that the other route is on the farside, so that passenger amenities can be combined and that riders do not have to cross the street. Therefore, other improvements must be made to the system to improve the effectiveness. These improvements should be made to the TSP algorithm to make decisions to not place a call at particular stops or to know when a call has been received and will no longer be used. Improvements to the TSP system to mitigate such bus stop placement problems include the following:

- Integrating the on-board stop request with the priority request relay to eliminate the portion of ineffective plans occurring from passenger alighting. [5]

- To eliminate the ineffective plans that occur from passenger boarding, passenger detection at stops could be installed. This is an expensive proposal however, that would not be effective in all cases. [5]
- Eliminate extension plans at intersections with nearside stops. [5]
- Eliminate extension plans at nearside stops with high stop frequency through examining AVL data that includes passenger counts.

5.2 Traffic Signal Timing and Cross-Street Traffic Considerations

Another explanation for the lack of TSP effectiveness on this corridor is delay from the cross-streets with high traffic volumes. The two-mile corridor is intersected by three east/west arterials (NE Glisan Street, SE Stark Street/SE Washington Street, and SE Division Street) running between I-285 and Downtown.

As Garrow [12] has shown, during peak periods TSP can cause severe negative impacts on cross-street traffic, particularly with high saturation levels. These impacts are mitigated on intersecting arterials by adjusting the effective green ratio, g/C, to improve traffic flow. The g/C ratio is then lower on the study corridor to accommodate the high traffic volumes on the cross-streets. The minimum green times on the cross-streets are also increased and thus reduce the amount of time that the priority call is able to "steal." The high pedestrian volume on 82nd Avenue, which contributes to the high bus ridership, also creates limitations in signal timing as pedestrian calls occur frequently. Table 5.3, identifies these limitations in signal timing that likely contribute to the unexpected performance.

Table 5.3 Traffic Signal Timing Considerations for Signal Priority [5]

Parameter	Limitation	Comment
Pedestrian Detection	Lack of pedestrian detection (push buttons for actuation) requires the opposing pedestrian phase to time every cycle	Presence of pedestrian detection increases the potential responsiveness of the intersection to serve transit
Pedestrian Timing	Time for Flashing Don't Walk can not be reduced in any case	Pedestrian detection reduces the need to recall pedestrian phases each cycle, thereby improving the responsiveness to transit
Multi-phase intersections	Phase skipping is not allowed in the State of Oregon, thus minimum vehicle times and clearance times must be considered for all phases (Legislative limitation)	Additional phases at intersections increase the amount of required time for service
Cycle lengths	Low cycle lengths reduce the flexibility of the engineer to extend the timing provided to the bus, although may provide better responsiveness overall	The tradeoff between flexibility and efficiency at the intersections has been consistently discussed, lower cycle length typically improves bus operations

5.3 Limitations of This Research

There were certain limitations with the research. Overall, the data set included a tremendous amount of useful data that was well sorted. There are a couple of additional attributes that should be added to the data set for further analysis. First, the data did not include the TSP emitter status. This would be helpful to isolate the effect of TSP performance through comparing it to bus runs when the emitter did not turn on. Bus driver information is another attribute that should be included in the data set. This information would allow for the analysis to account for drivers' tendencies.

Another limitation of the research was the corridor length. A longer study corridor would provide more accurate data for a bus route. This is because the longer travel times would make the results less sensitive to variable dwell times and other delays.

5.4 Future Research Recommendations

There are several topics that future research should study. The first would be the study the effect of the arterial cross-streets. These streets have high vehicular volumes and bus routes that are also running TSP. How they interact and impact each other needs further study. Another area of focus is to study the effect of eliminating extension plans at nearside bus stops with frequent stops. This could be done through microsimulation of the corridor using the bus stop rates in the AVL data. In both of these proposed studies, a longer corridor length should be used that encompasses more major arterials and bus stops.

APPENDIX A

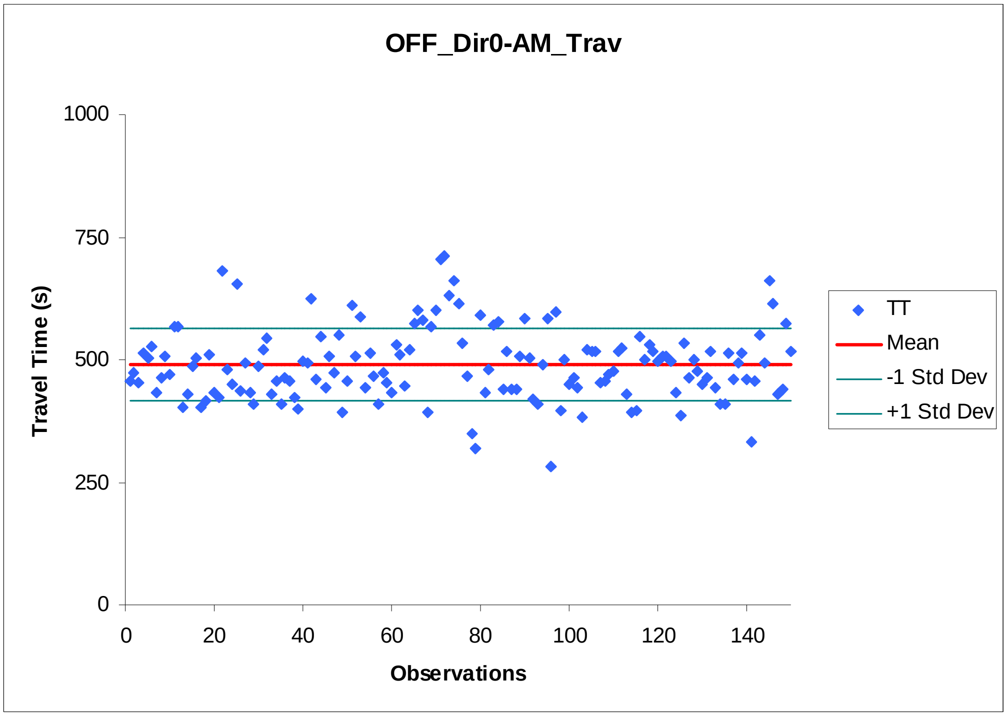


Figure A.1 Northbound Vehicle Travel Times, AM Peak Period, TSP OFF

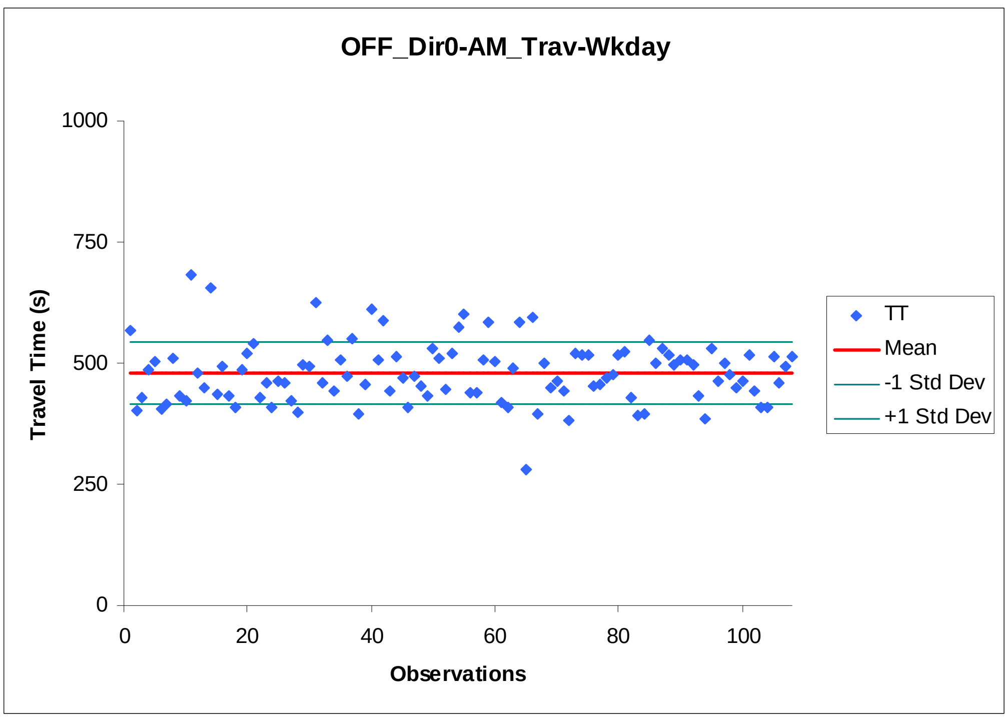


Figure A.2 Northbound Vehicle Travel Times, Weekday AM Peak Period, TSP OFF

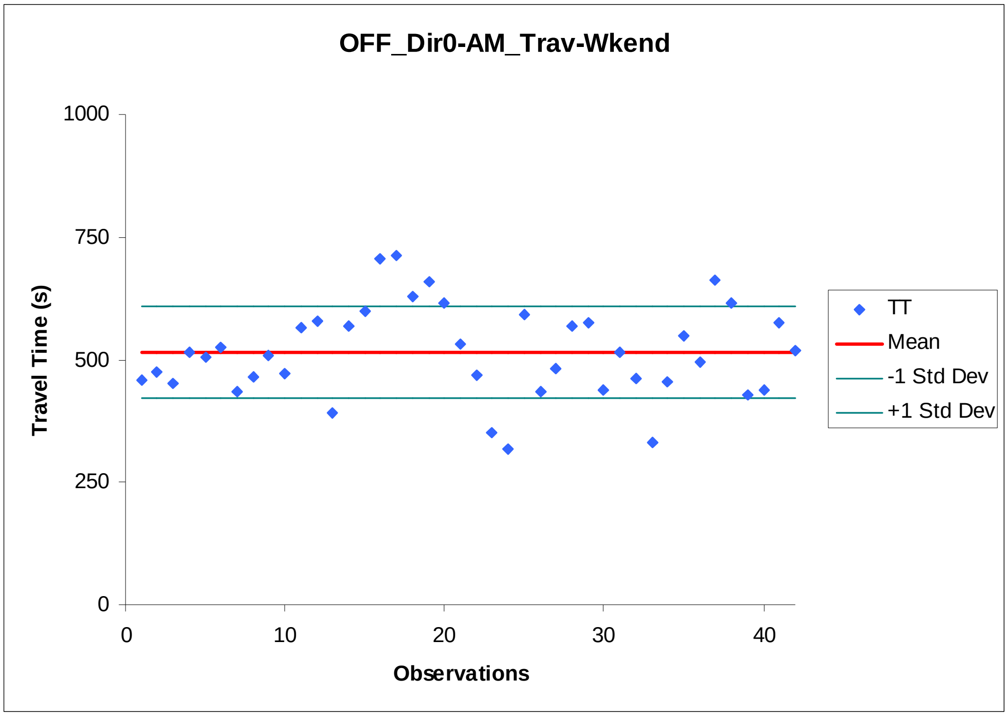


Figure A.3 Northbound Vehicle Travel Times, Weekend AM Peak Period, TSP OFF

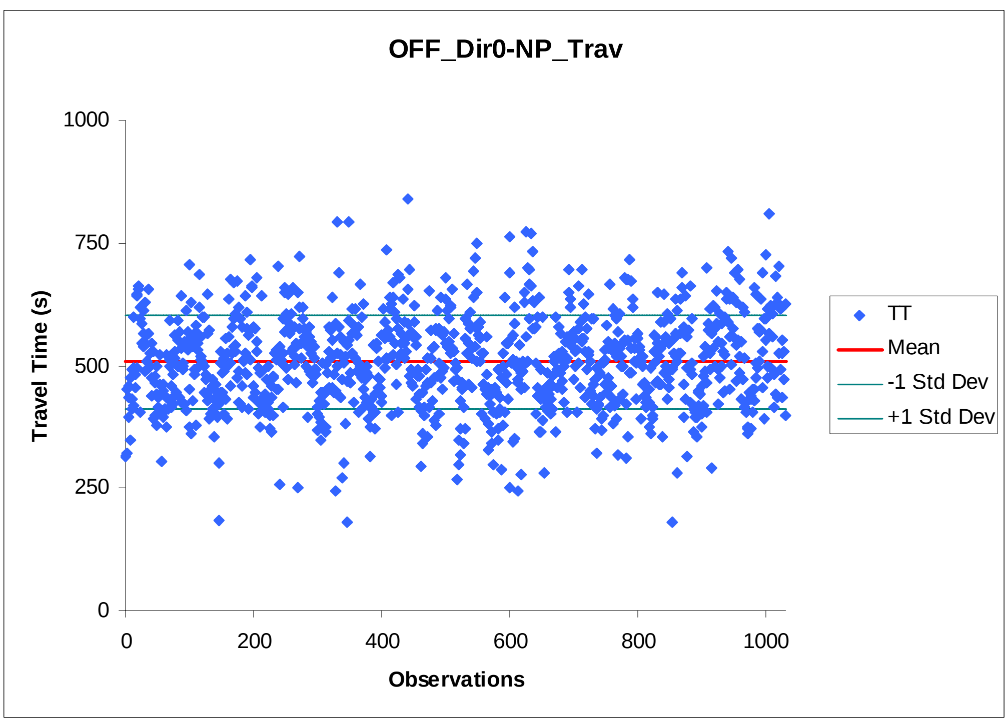


Figure A.4 Northbound Vehicle Travel Times, Non-Peak Period, TSP OFF

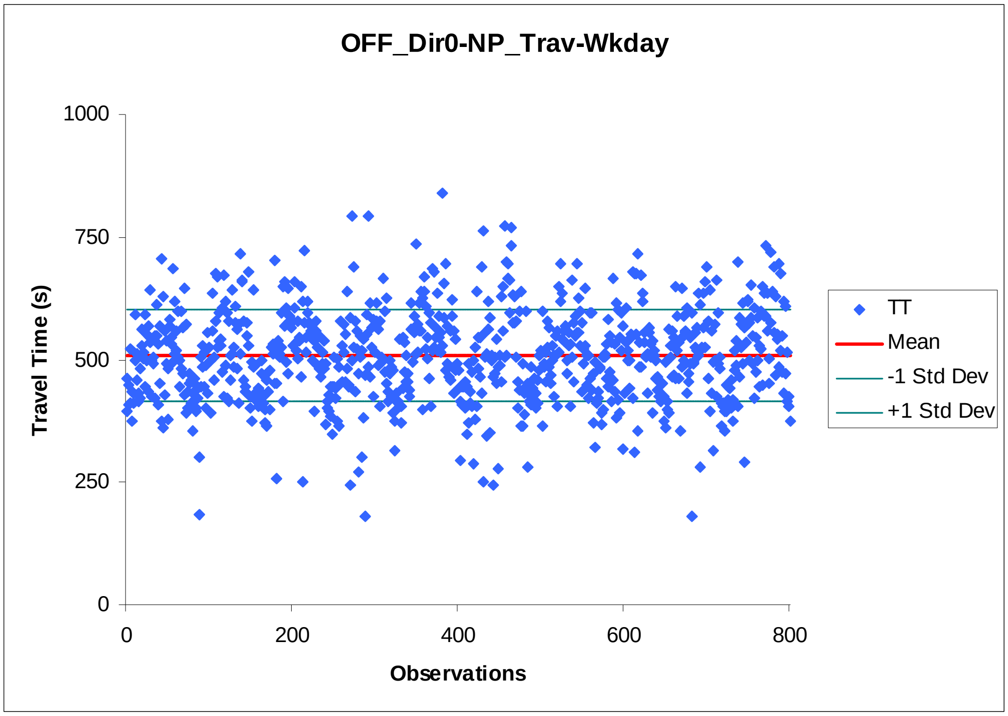


Figure A.5 Northbound Vehicle Travel Times, Weekday Non-Peak Period, TSP OFF

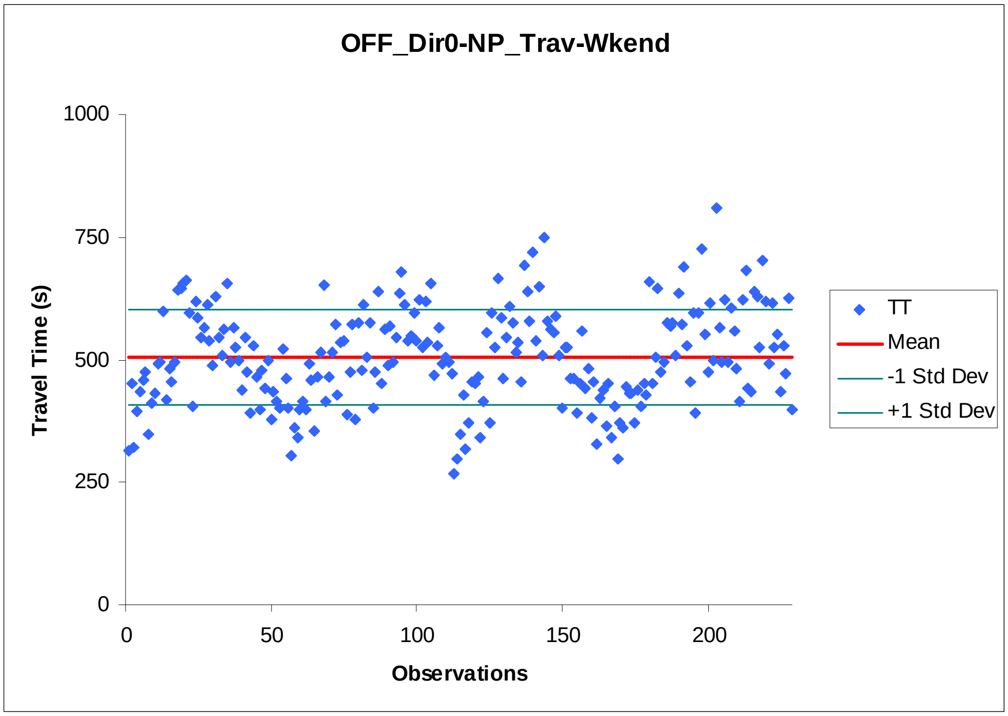


Figure A.6 Northbound Vehicle Travel Times, Weekend Non-Peak Period, TSP OFF

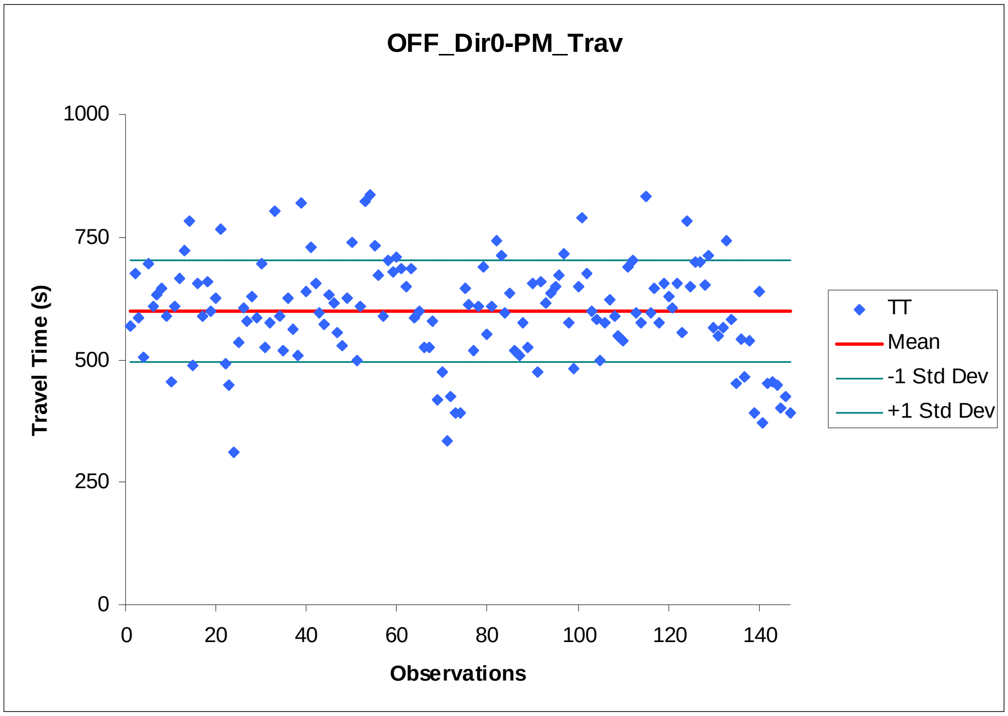


Figure A.7 Northbound Vehicle Travel Times, PM Peak Period, TSP OFF

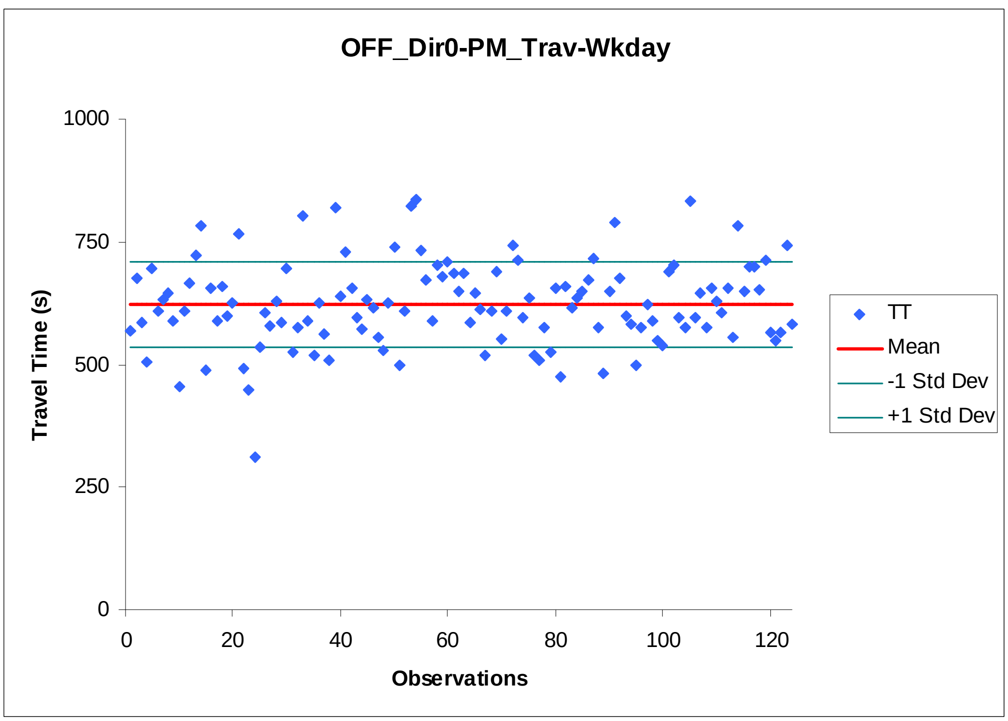


Figure A.8 Northbound Vehicle Travel Times, Weekday PM Peak Period, TSP OFF

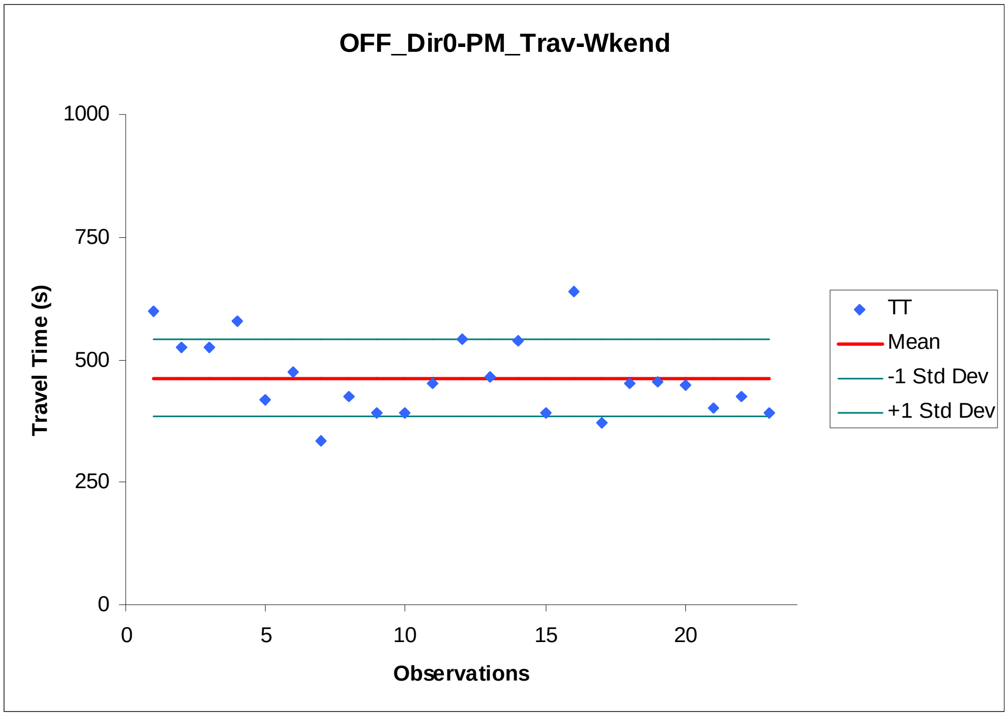


Figure A.9 Northbound Vehicle Travel Times, Weekend PM Peak Period, TSP OFF

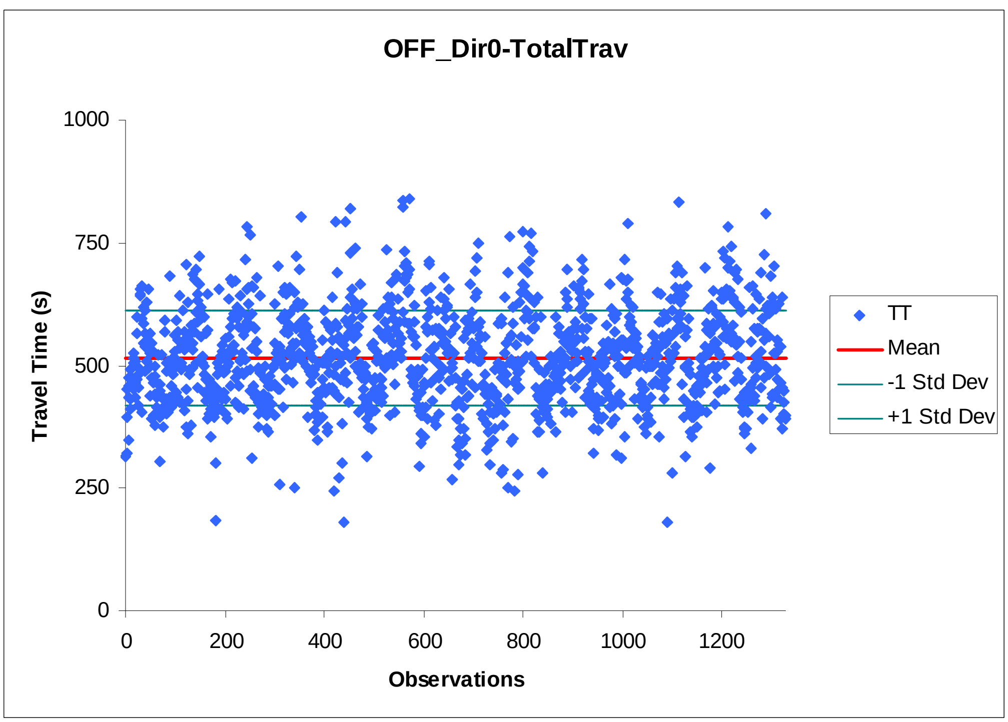


Figure A.10 Northbound Vehicle Travel Times, Total Study Period, TSP OFF

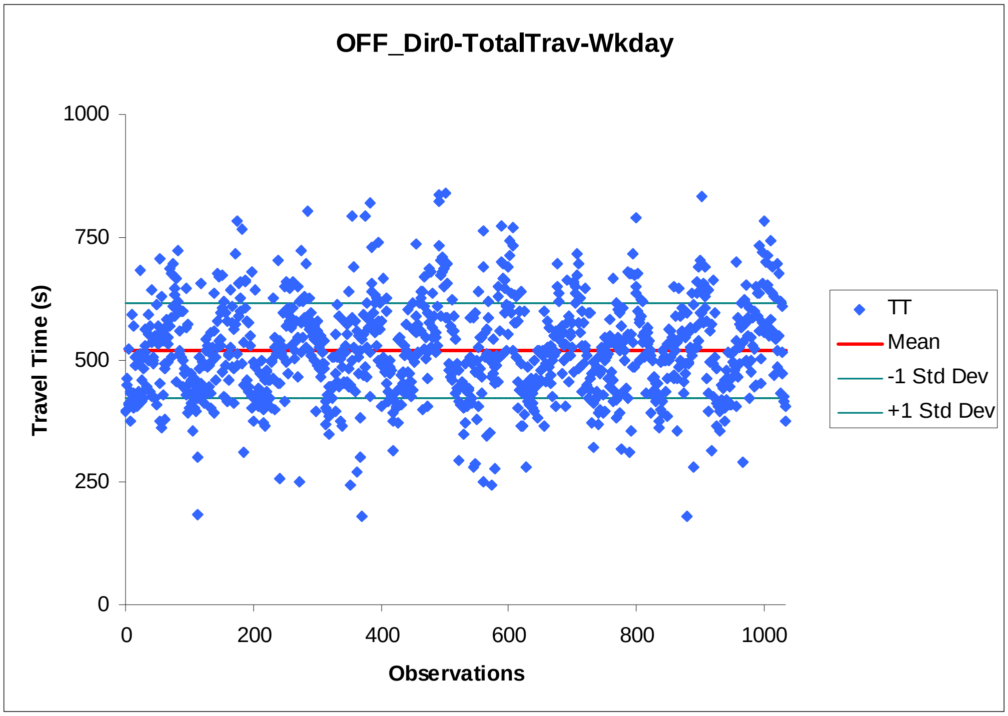


Figure A.11 Northbound Vehicle Travel Times, Weekday Total Study Period, TSP OFF

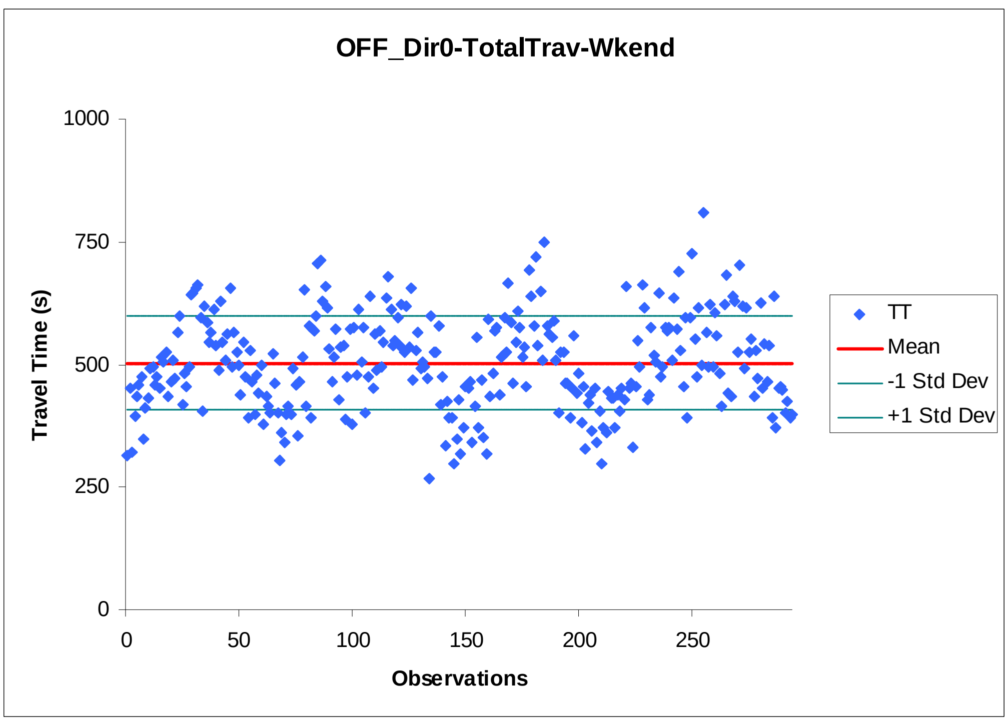


Figure A.12 Northbound Vehicle Travel Times, Weekend Total Study Period, TSP OFF

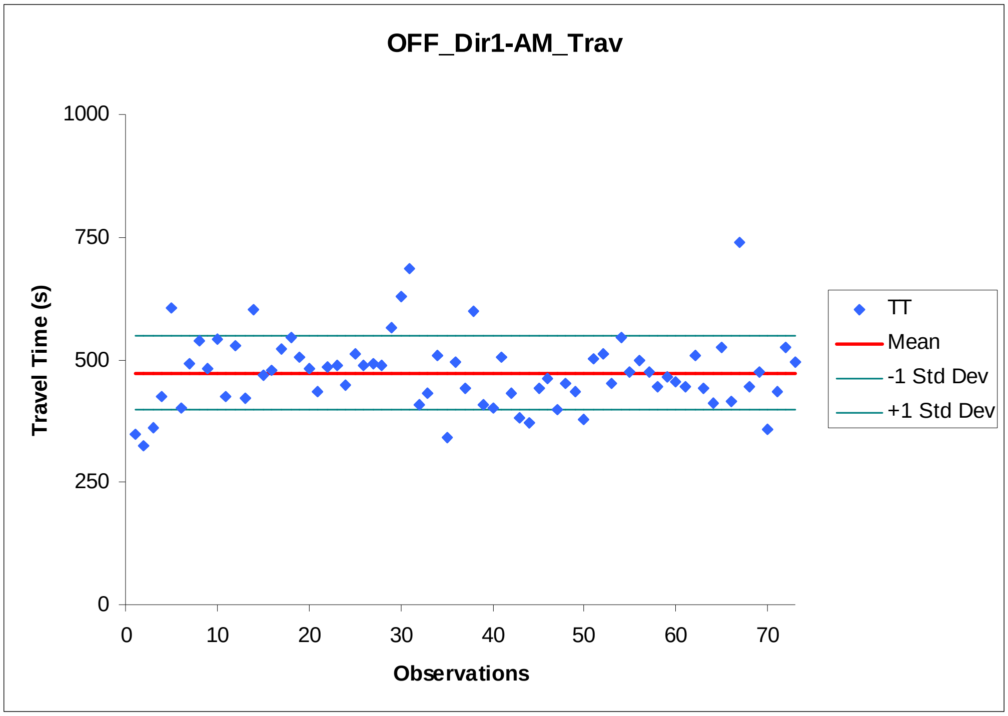


Figure A.13 Southbound Vehicle Travel Times, AM Peak Period, TSP OFF

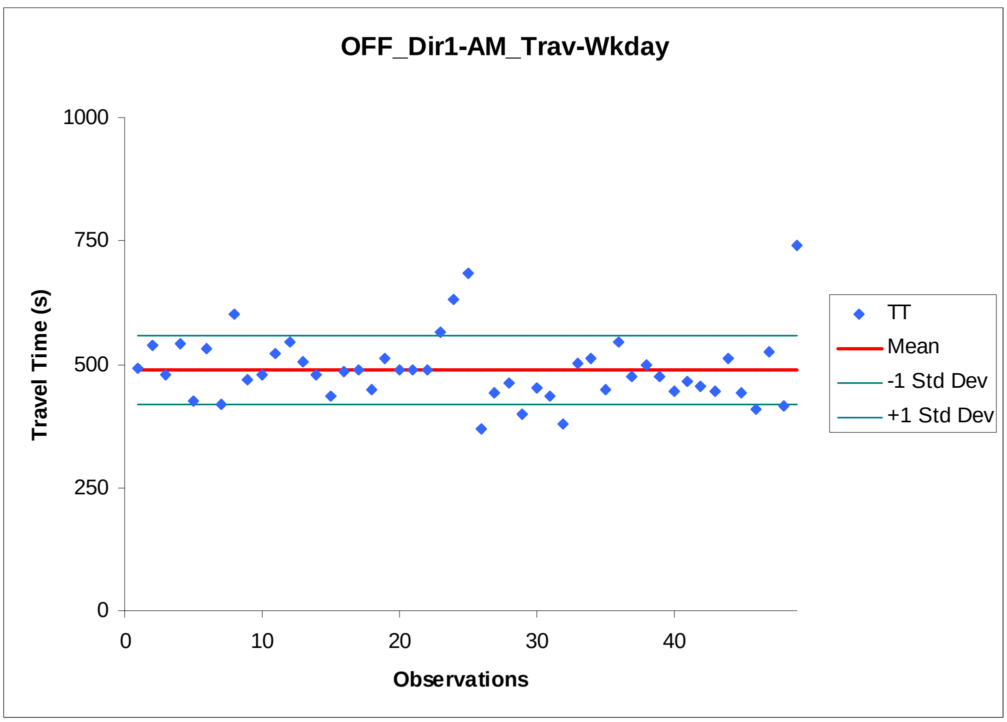


Figure A.14 Southbound Vehicle Travel Times, Weekday AM Peak Period, TSP OFF

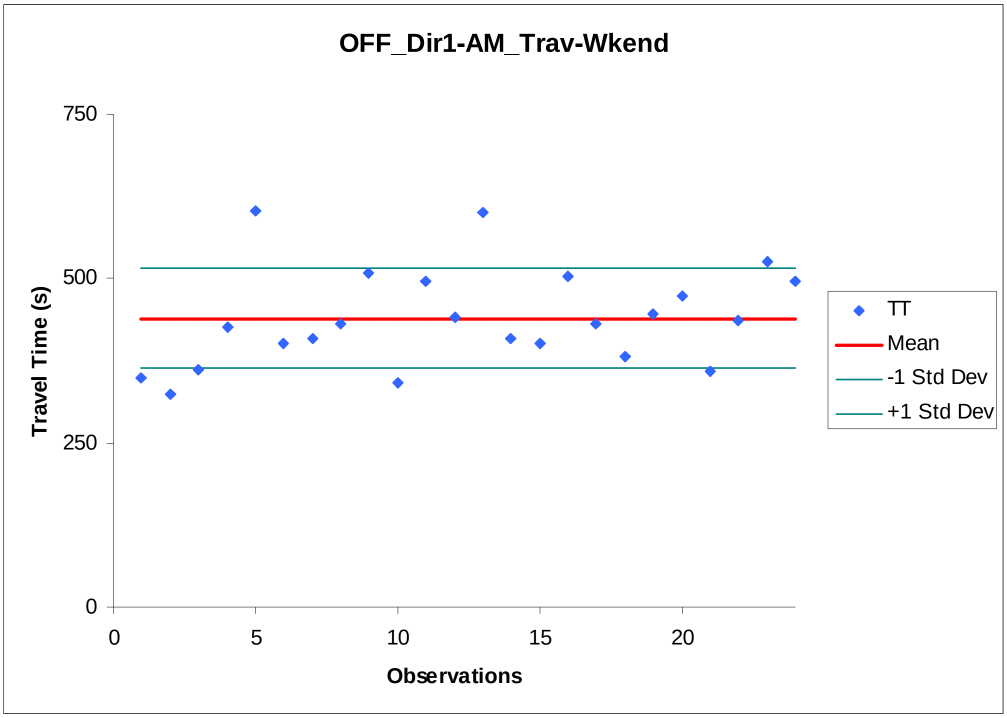


Figure A.15 Southbound Vehicle Travel Times, Weekend AM Peak Period, TSP OFF

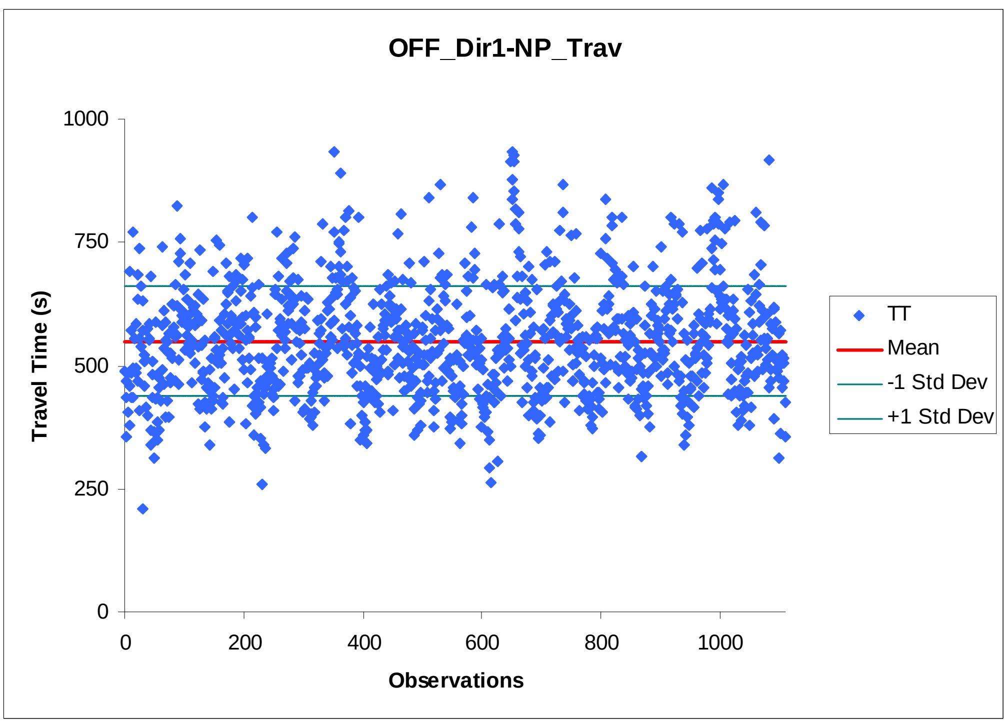


Figure A.16 Southbound Vehicle Travel Times, Non-Peak Period, TSP OFF

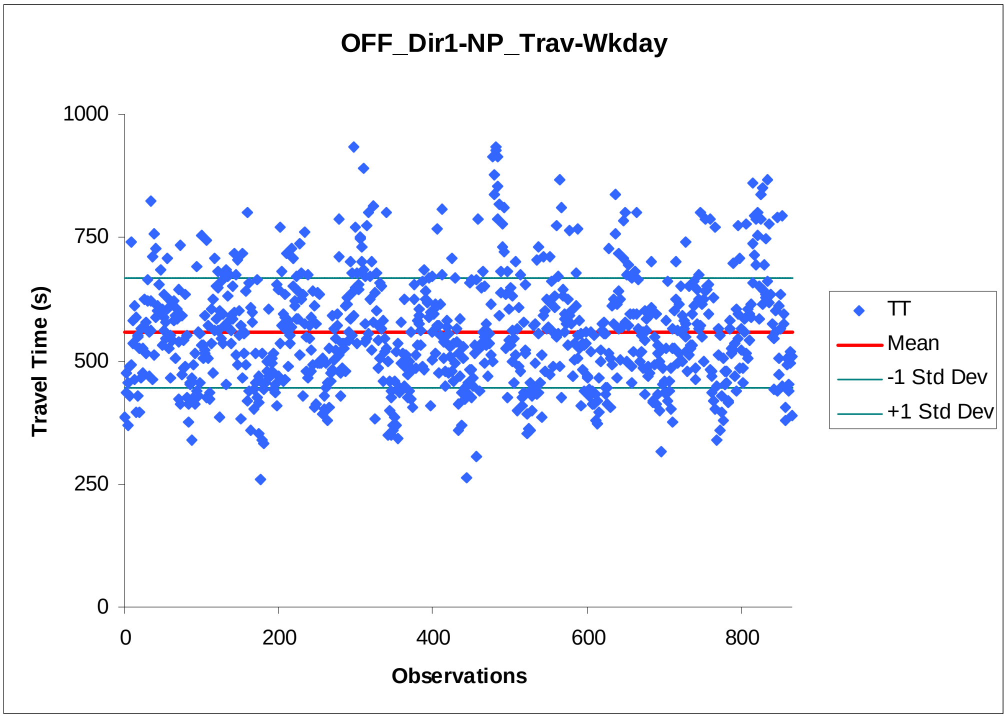


Figure A.17 Southbound Vehicle Travel Times, Weekday Non-Peak Period, TSP OFF

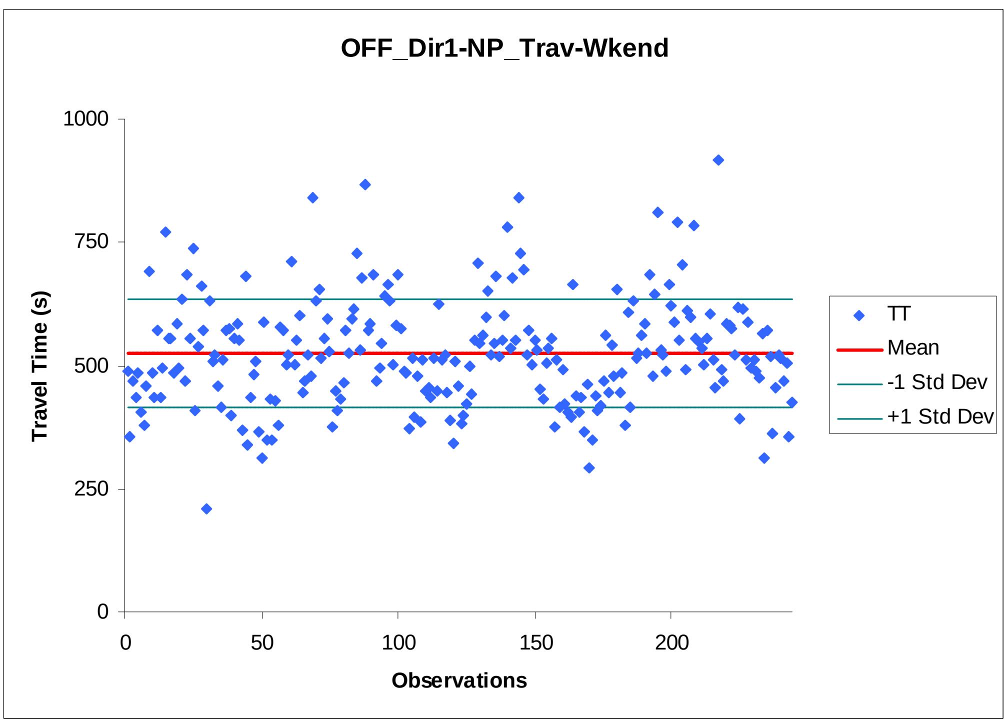


Figure A.18 Southbound Vehicle Travel Times, Weekend Non-Peak Period, TSP OFF

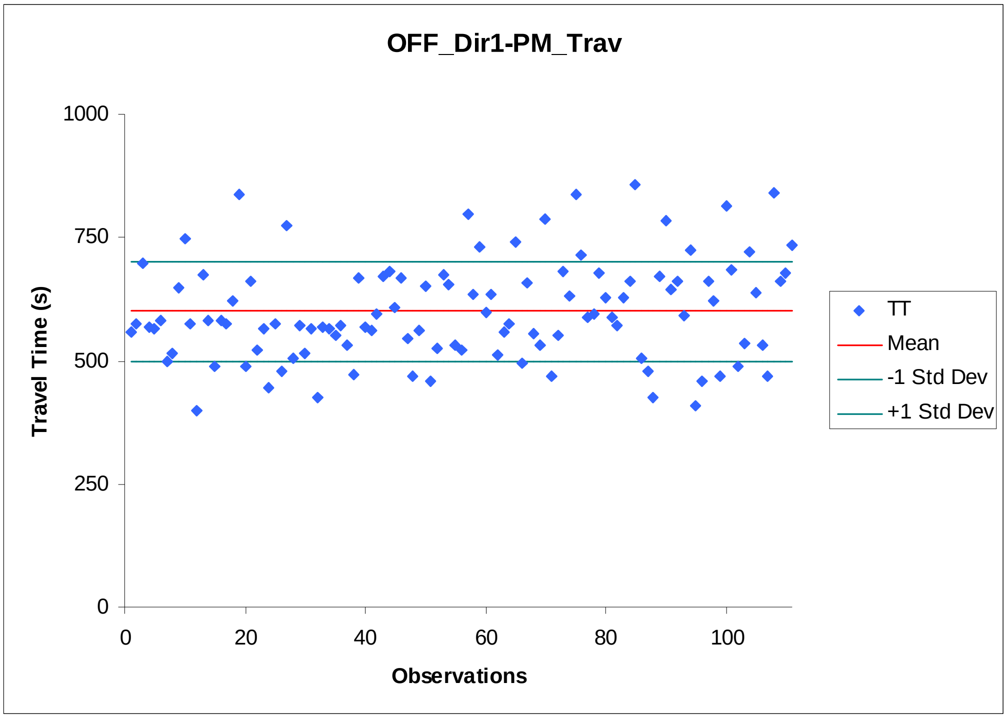


Figure A.19 Southbound Vehicle Travel Times, PM Peak Period, TSP OFF

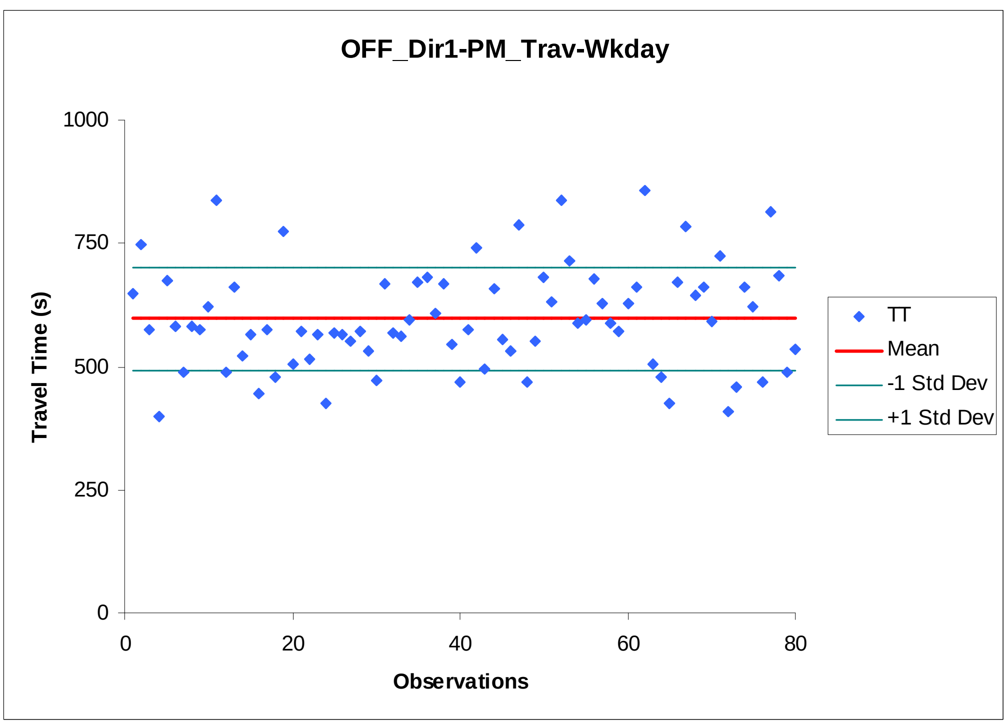


Figure A.20 Southbound Vehicle Travel Times, Weekday PM Peak Period, TSP OFF

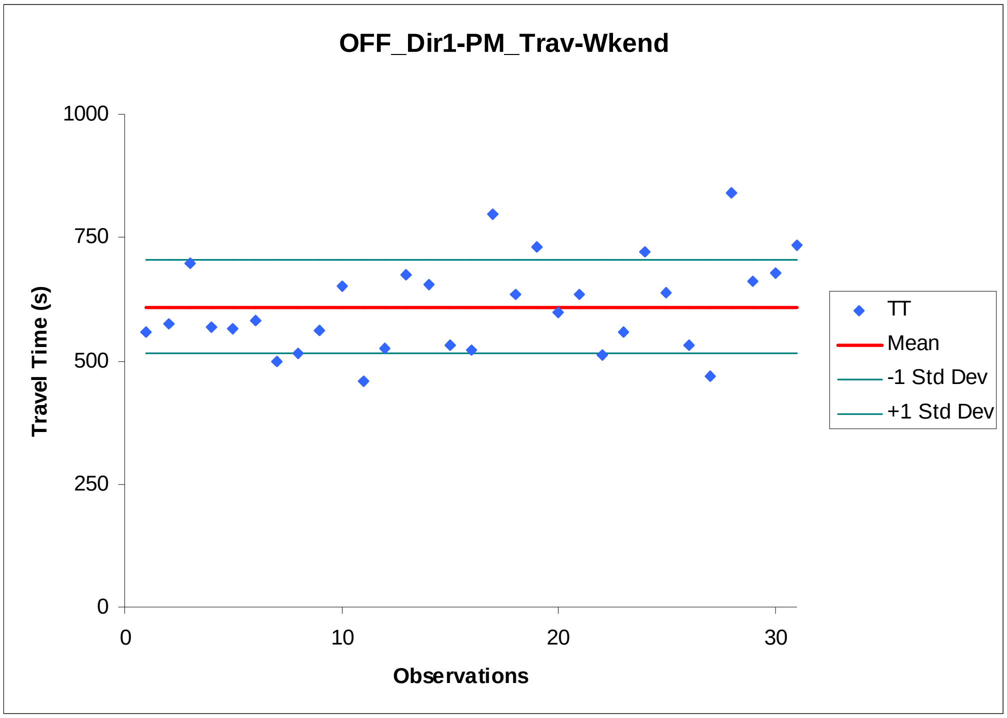


Figure A.21 Southbound Vehicle Travel Times, Weekend PM Peak Period, TSP OFF

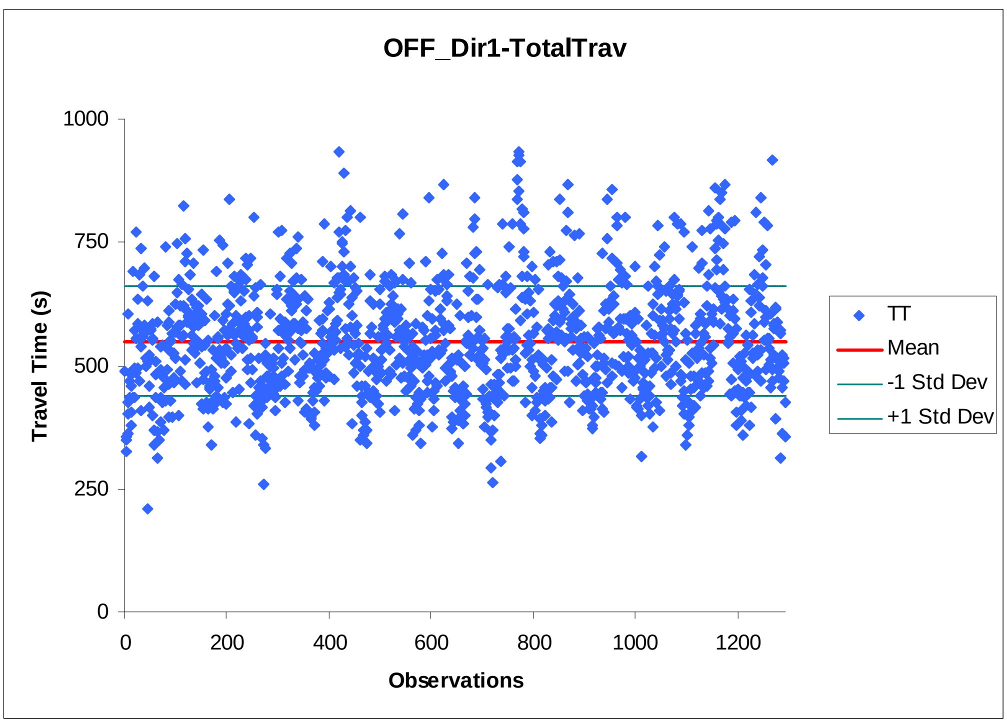


Figure A.22 Southbound Vehicle Travel Times, Total Study Period, TSP OFF

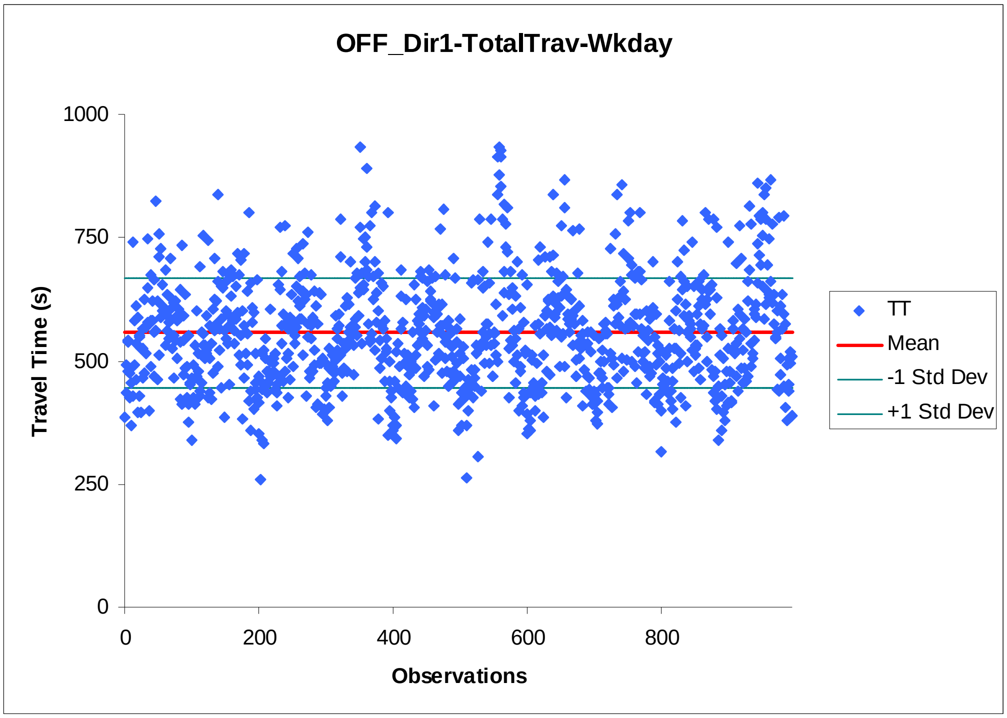


Figure A.23 Southbound Vehicle Travel Times, Weekday Total Study Period, TSP OFF

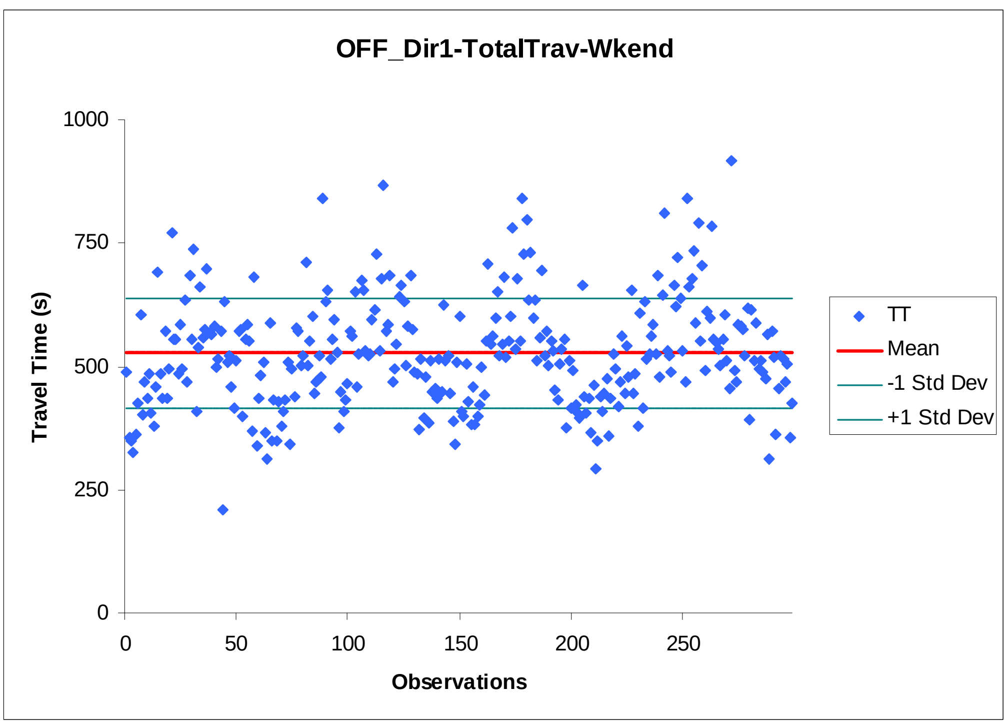


Figure A.24 Southbound Vehicle Travel Times, Weekend Total Study Period, TSP OFF

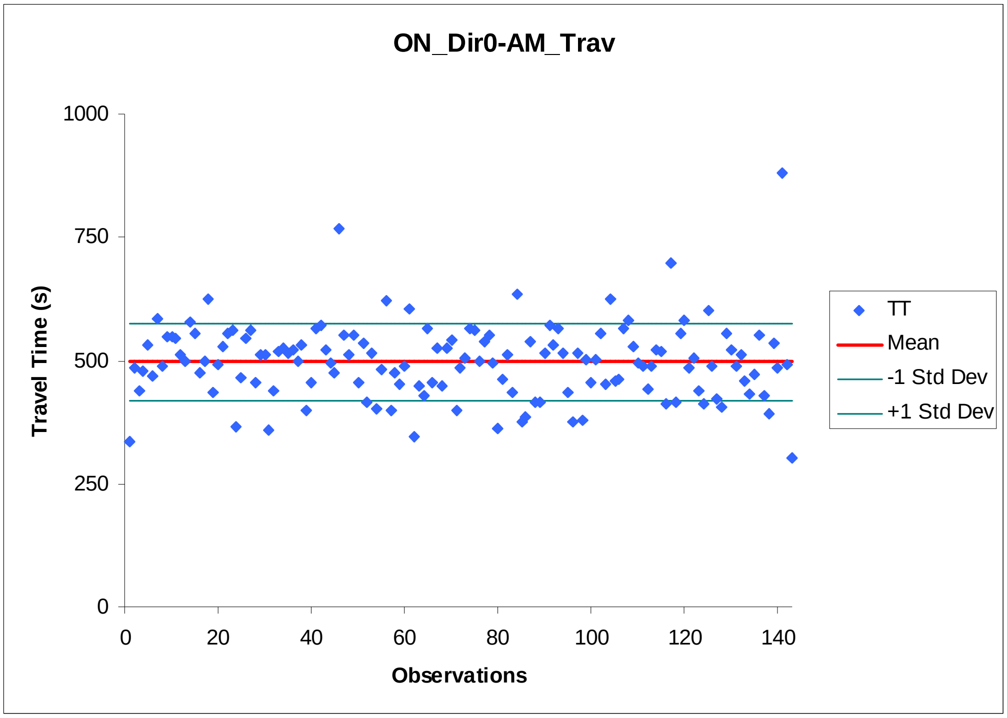


Figure A.25 Northbound Vehicle Travel Times, AM Peak Period, TSP ON

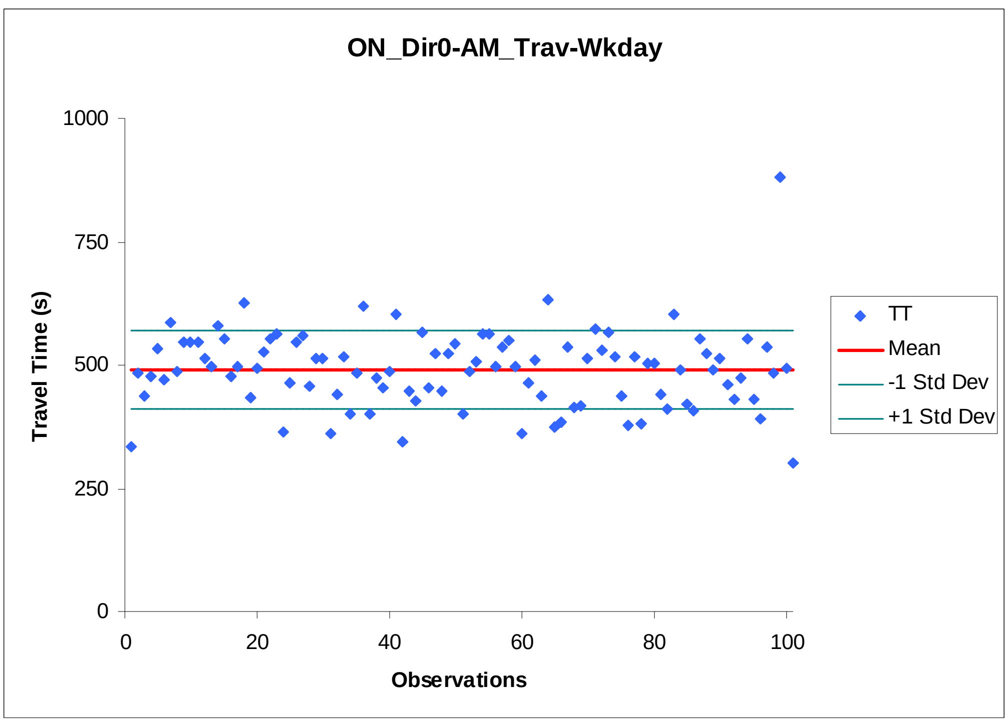


Figure A.26 Northbound Vehicle Travel Times, Weekday AM Peak Period, TSP ON

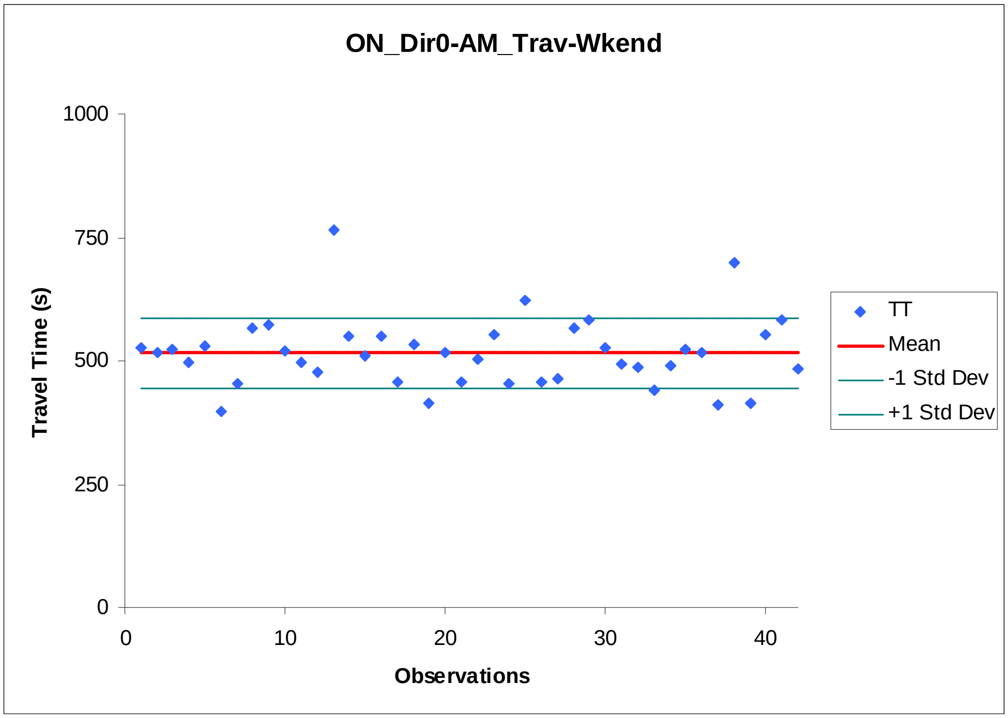


Figure A.27 Northbound Vehicle Travel Times, Weekend AM Peak Period, TSP ON

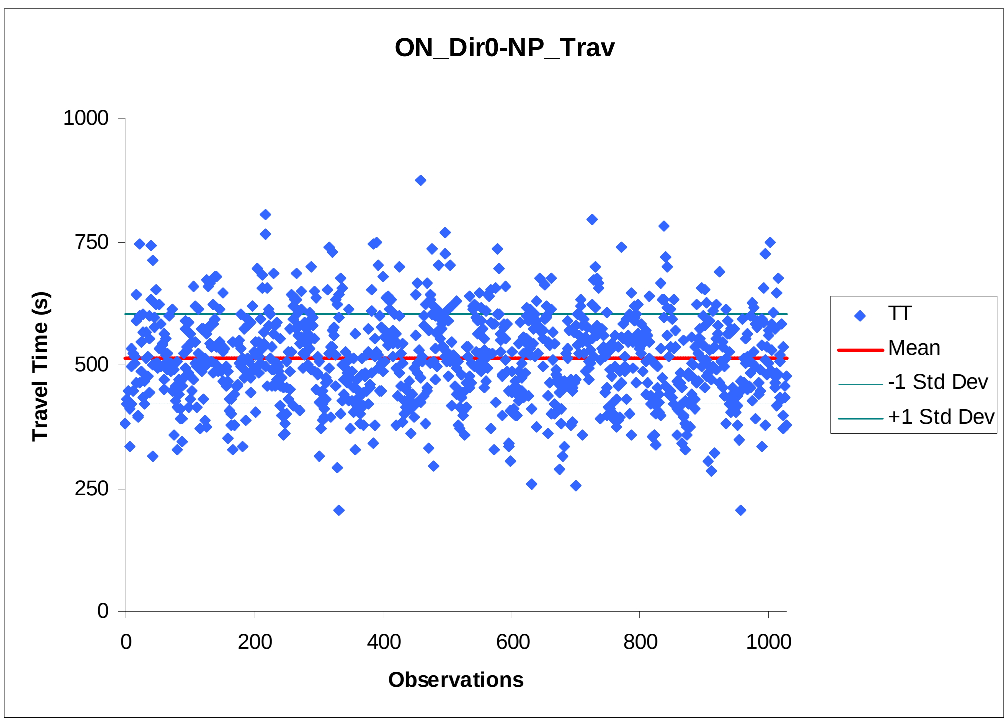


Figure A.28 Northbound Vehicle Travel Times, Non-Peak Period, TSP ON

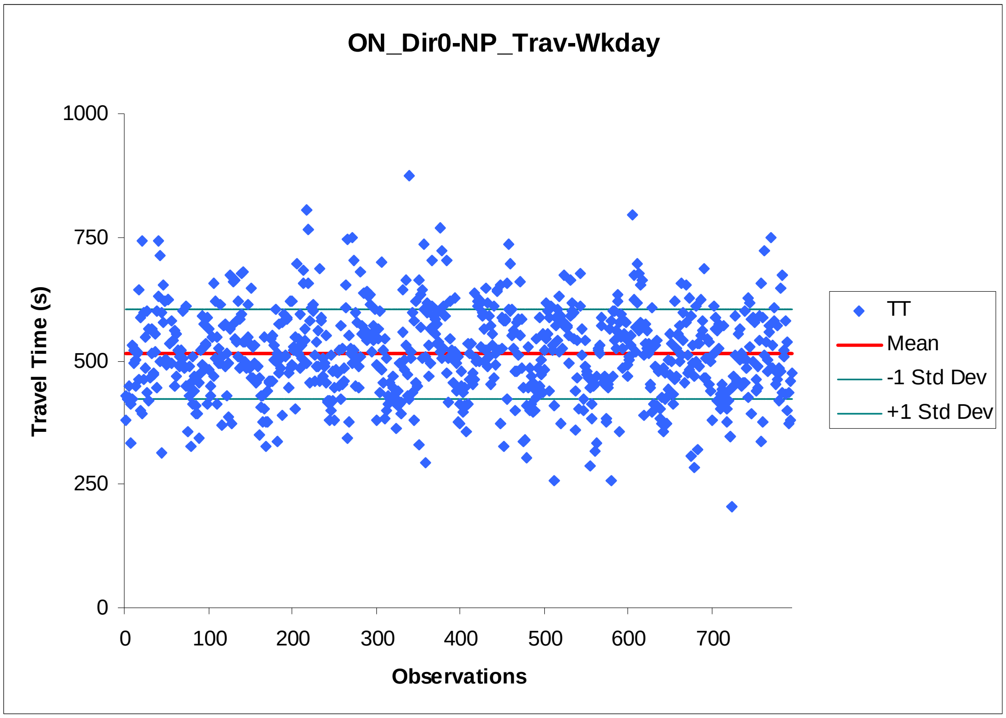


Figure A.29 Northbound Vehicle Travel Times, Weekday Non-Peak Period, TSP ON

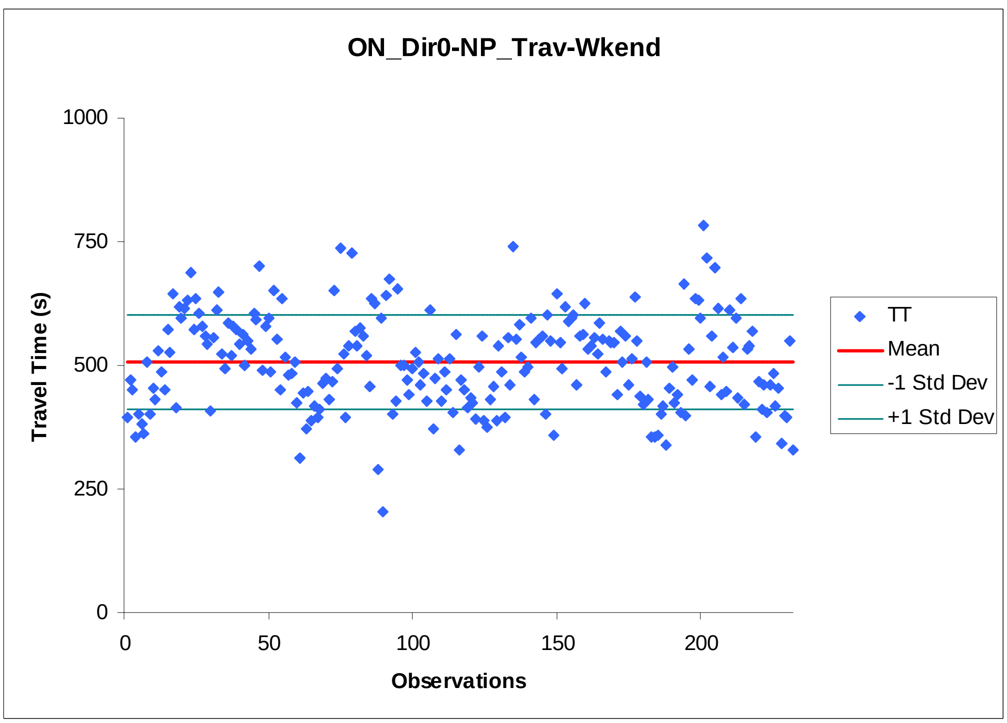


Figure A.30 Northbound Vehicle Travel Times, Weekend Non-Peak Period, TSP ON

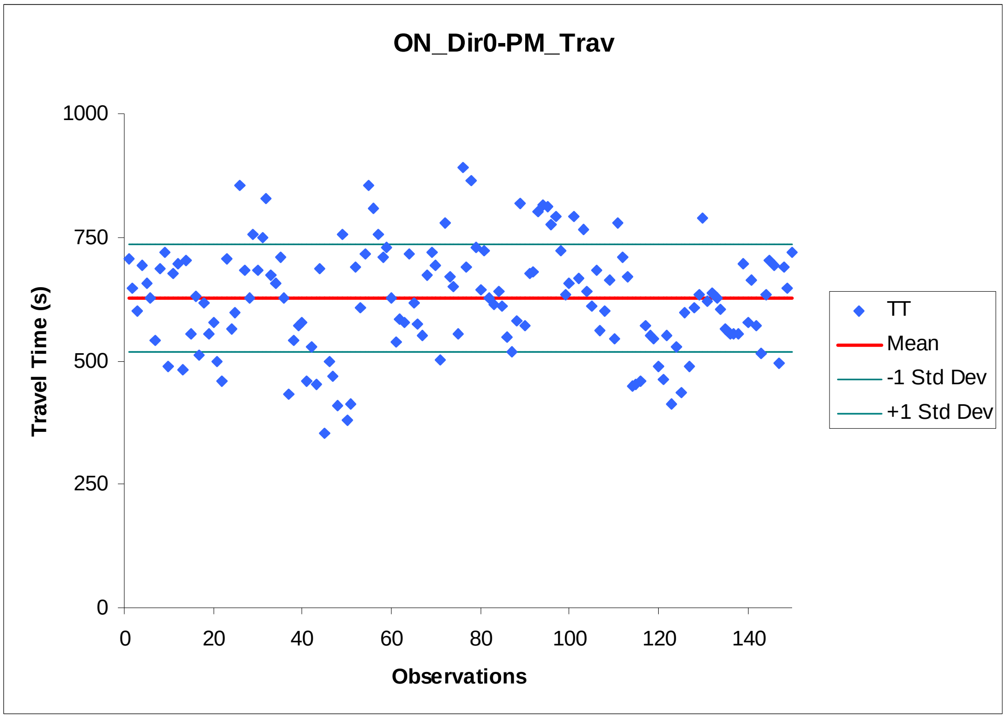


Figure A.31 Northbound Vehicle Travel Times, PM Peak Period, TSP ON

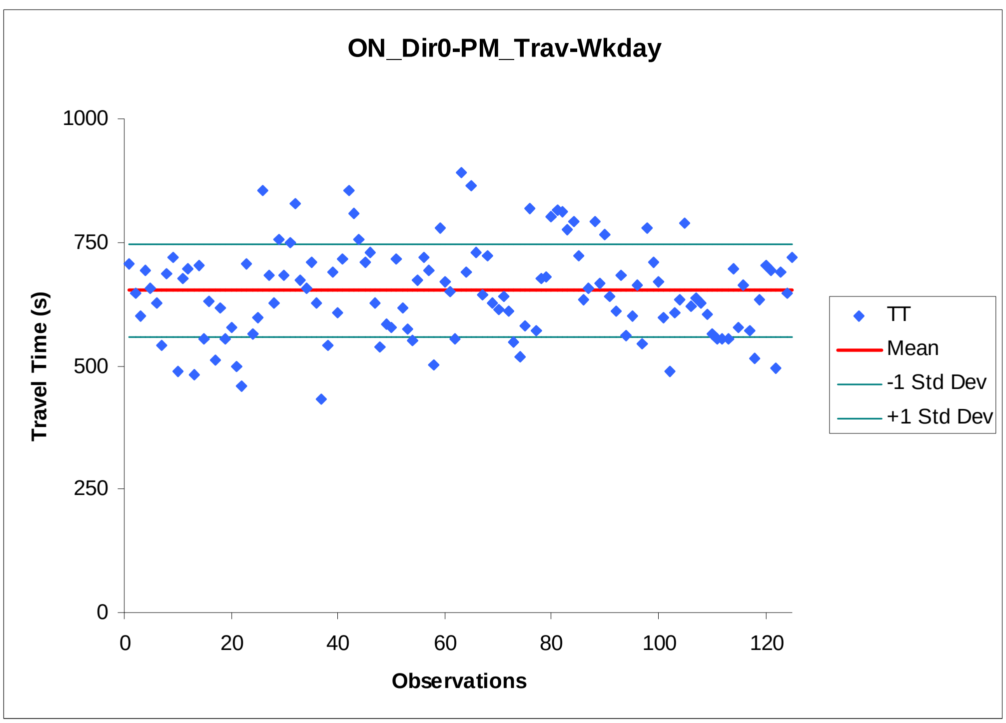


Figure A.32 Northbound Vehicle Travel Times, Weekday PM Peak Period, TSP ON

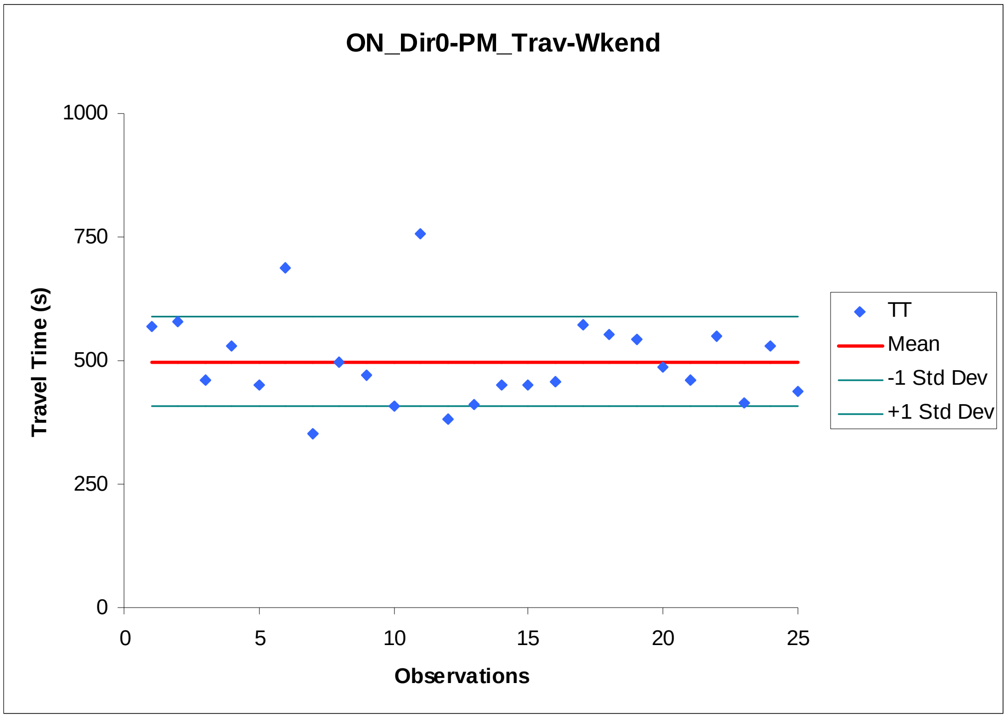


Figure A.33 Northbound Vehicle Travel Times, Weekend PM Peak Period, TSP ON

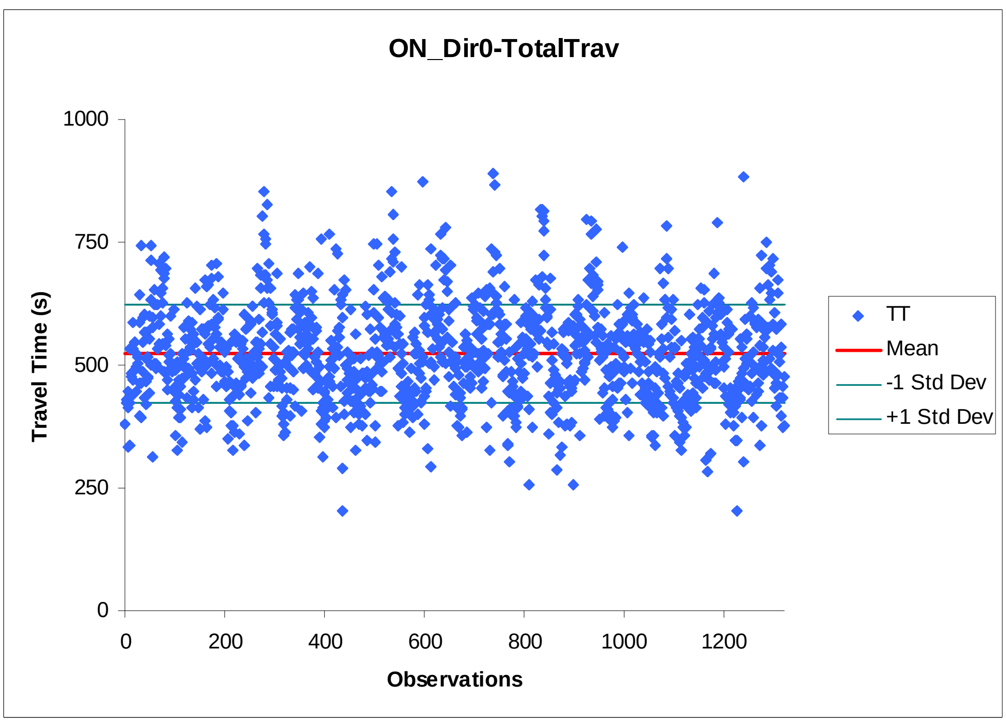


Figure A.34 Northbound Vehicle Travel Times, Total Study Period, TSP ON

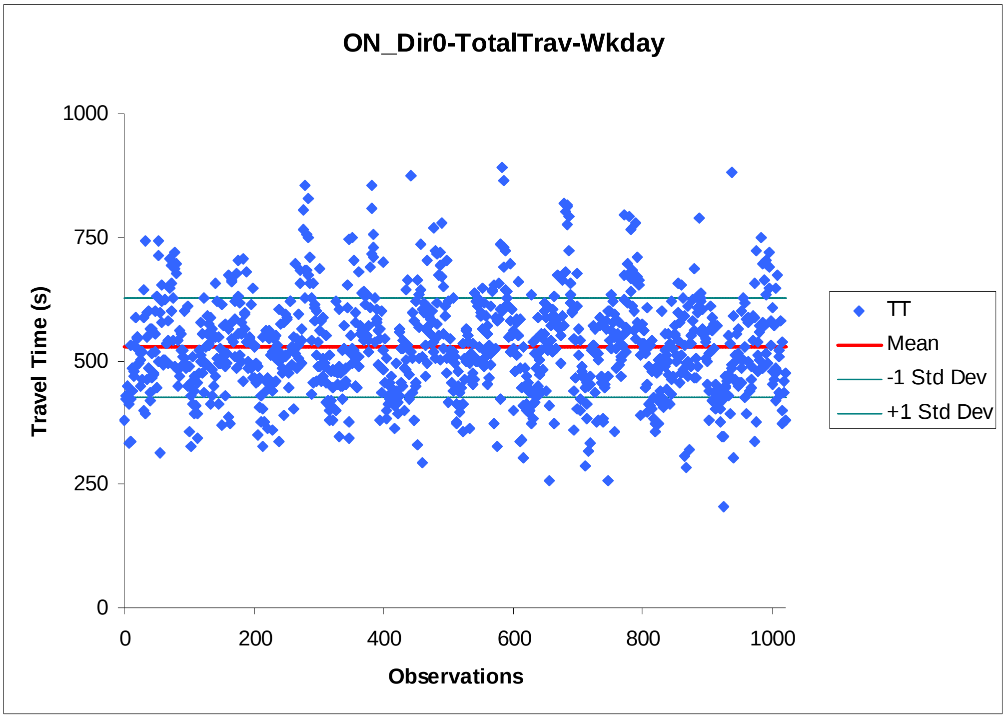


Figure A.35 Northbound Vehicle Travel Times, Weekday Total Study Period, TSP ON

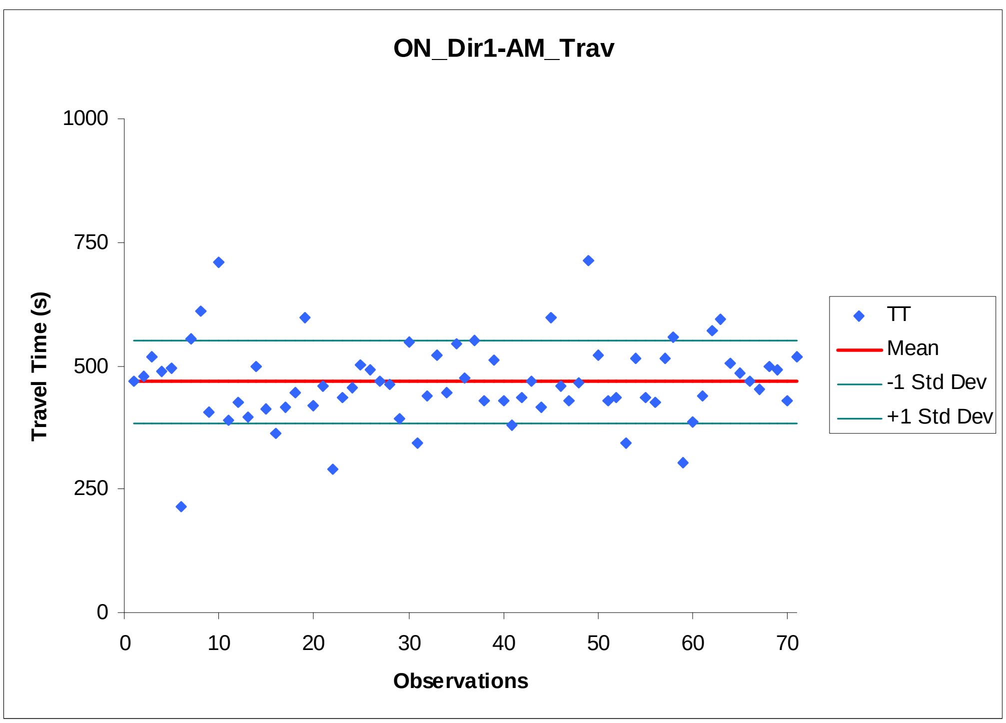


Figure A.36 Southbound Vehicle Travel Times, AM Peak Period, TSP ON

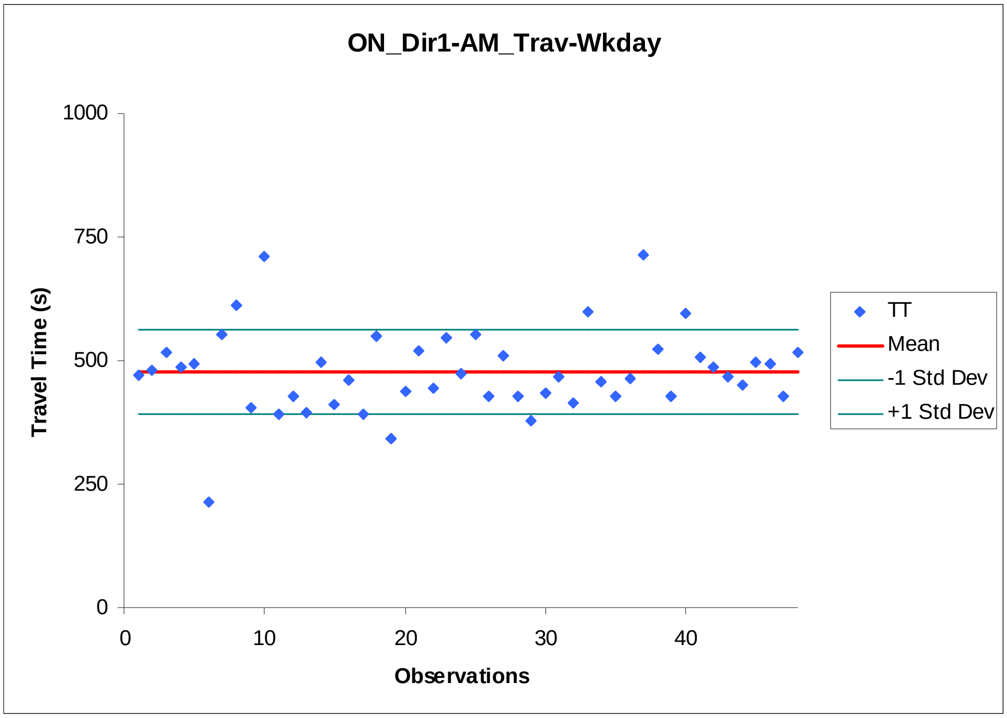


Figure A.37 Southbound Vehicle Travel Times, Weekday AM Peak Period, TSP ON

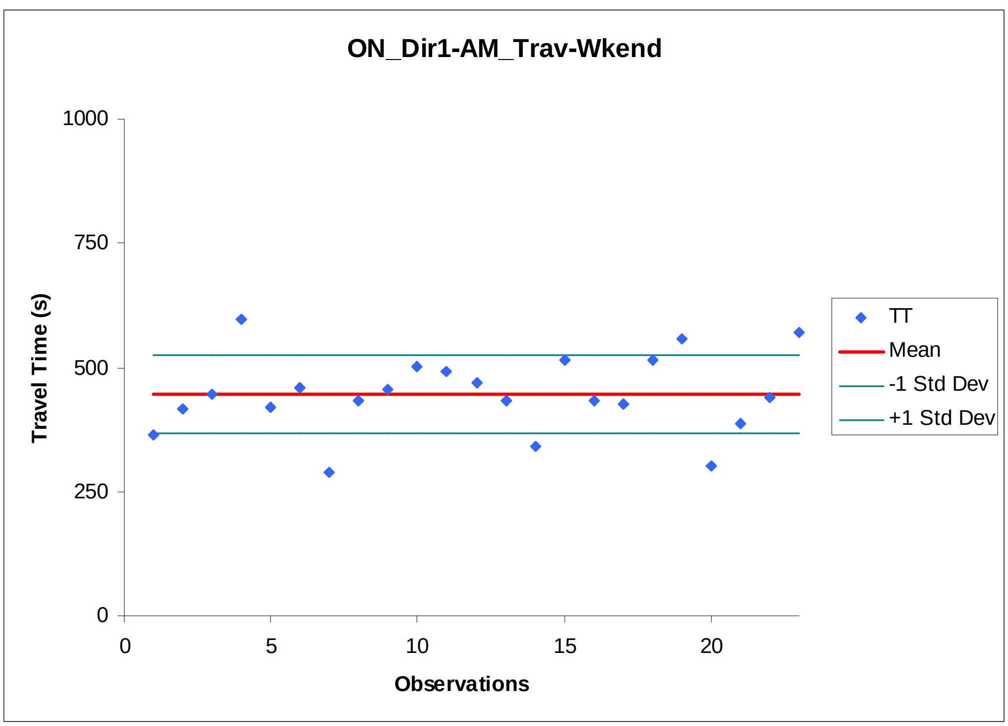
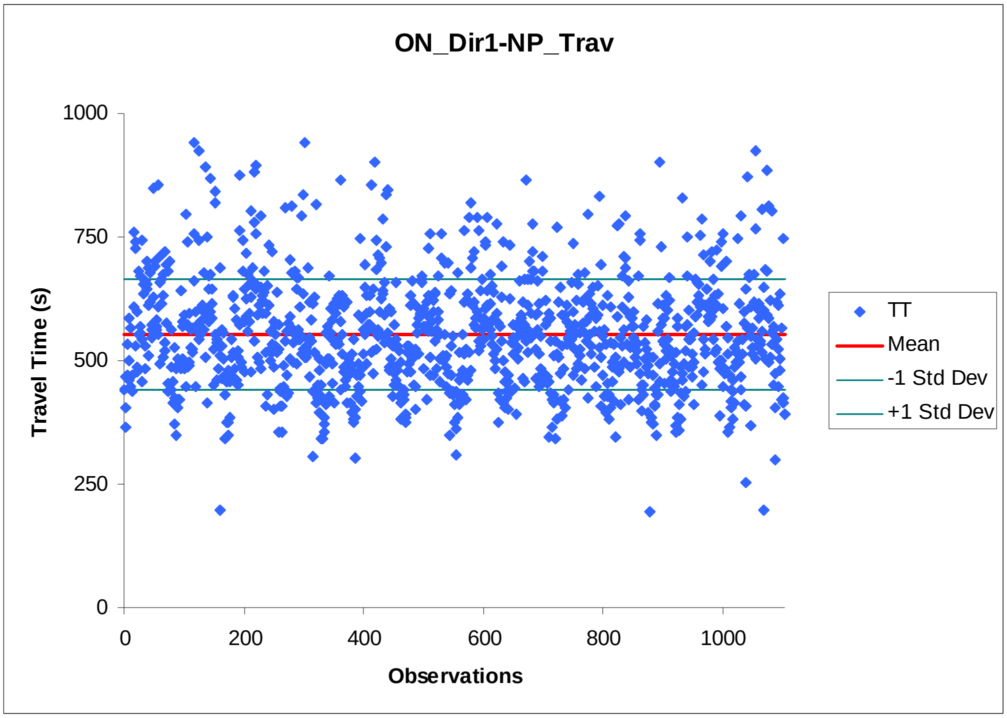


Figure A.38 Southbound Vehicle Travel Times, Weekend AM Peak Period, TSP ON



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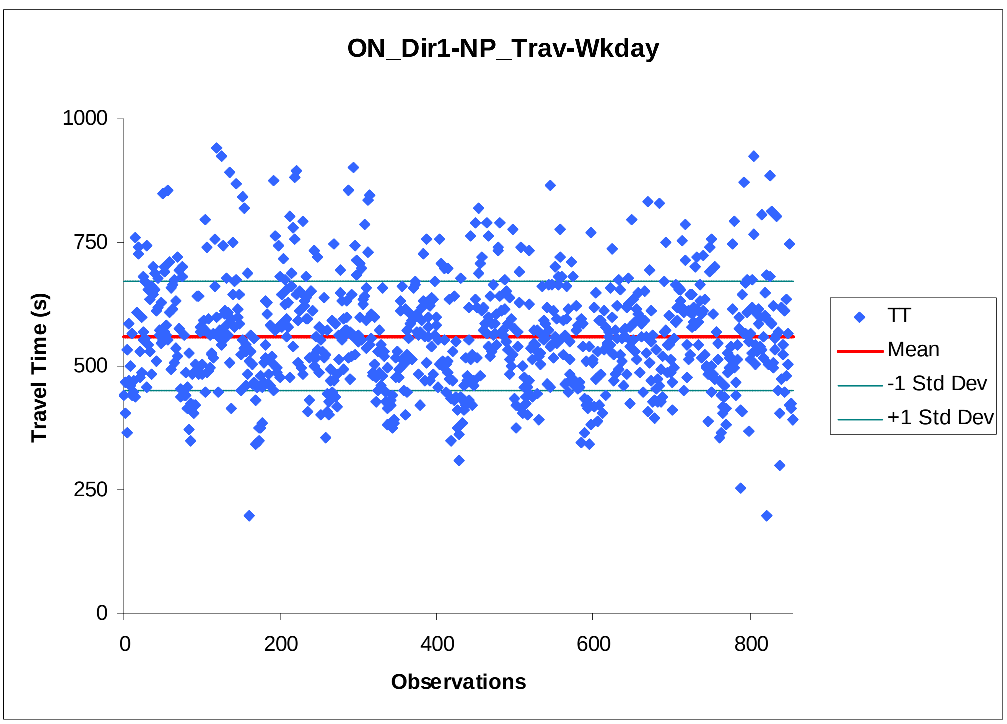

Figure A.40 Southbound Vehicle Travel Times, Weekday Non-Peak Period, TSP ON

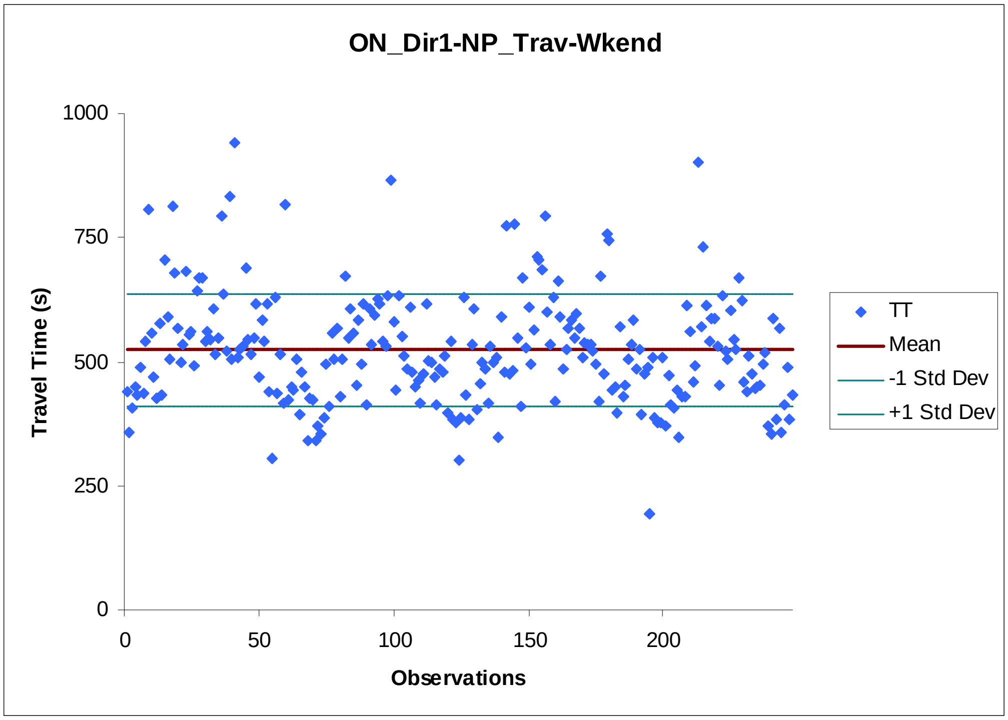

Figure A.41 Southbound Vehicle Travel Times, Weekend Non-Peak Period, TSP ON

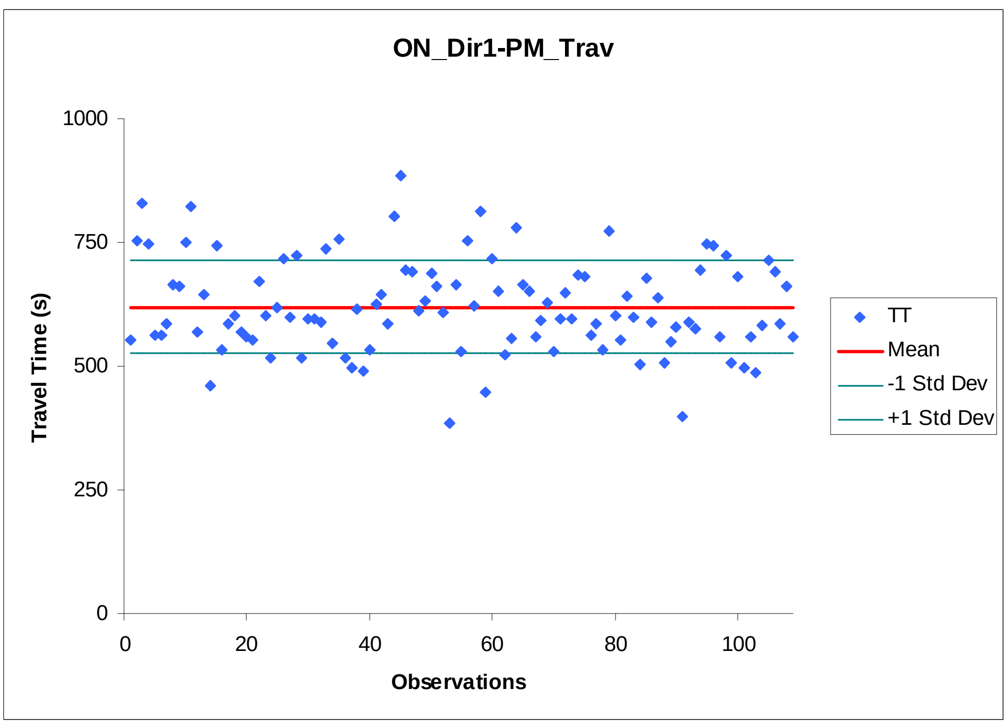

Figure A.42 Southbound Vehicle Travel Times, PM Peak Period, TSP ON

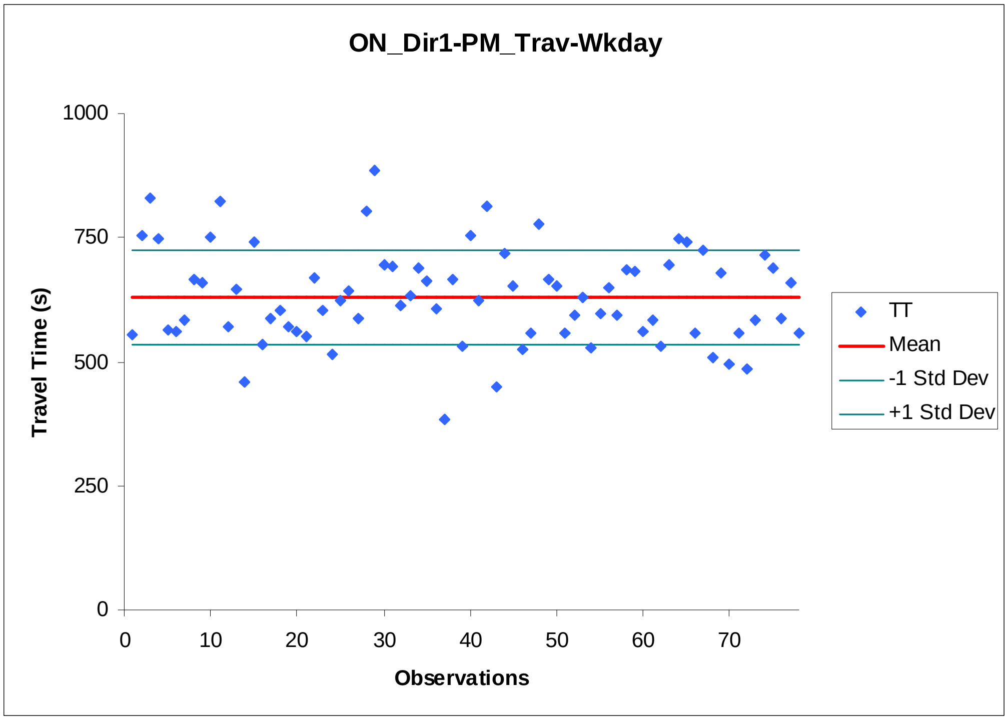

Figure A.43 Southbound Vehicle Travel Times, Weekday PM Peak Period, TSP ON

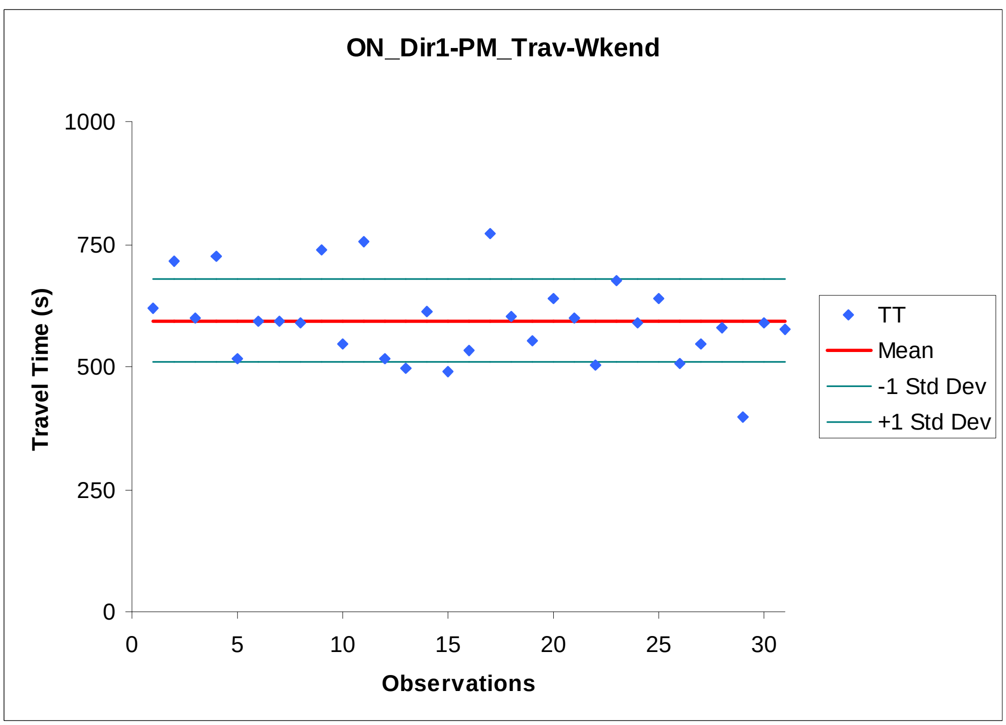

Figure A.44 Southbound Vehicle Travel Times, Weekend PM Peak Period, TSP ON

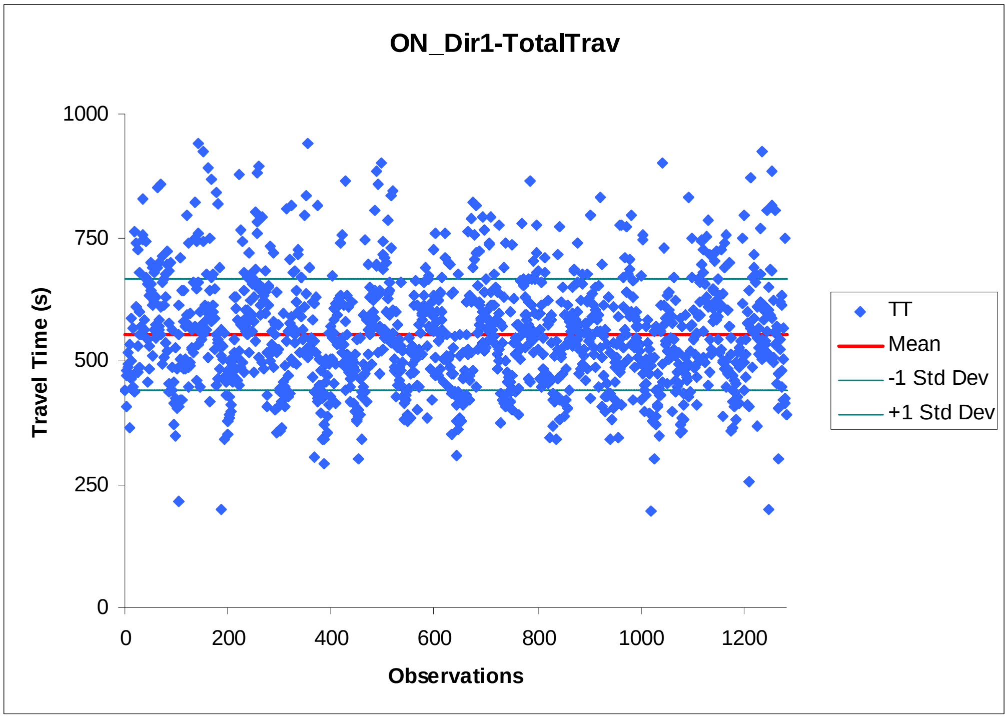

Figure A.45 Southbound Vehicle Travel Times, Total Study Period, TSP ON

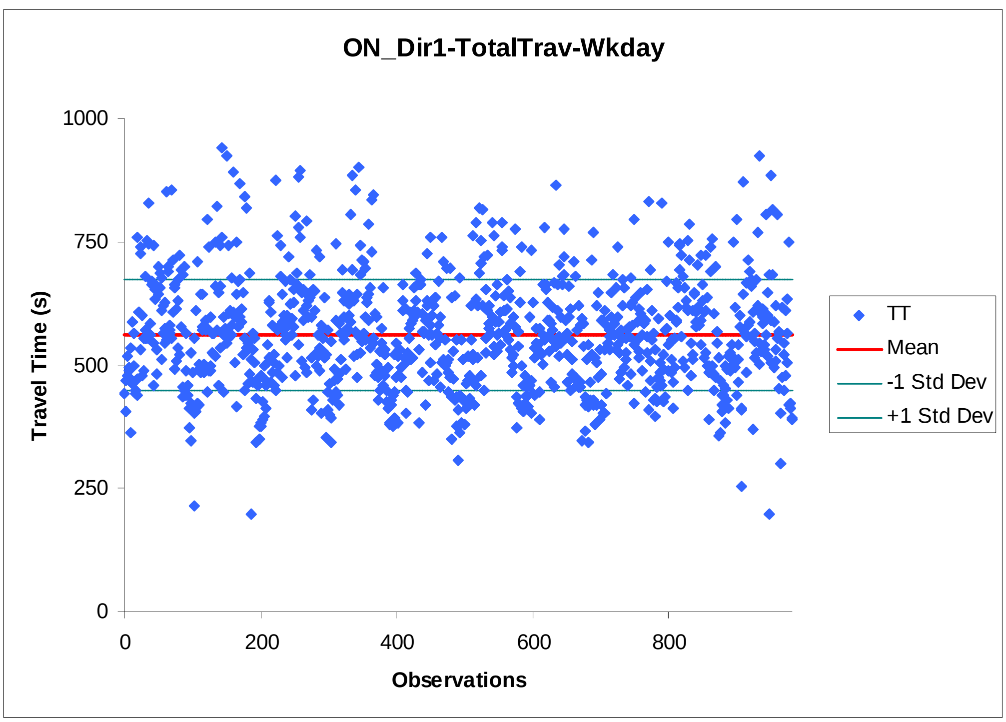

Figure A.46 Southbound Vehicle Travel Times, Weekday Total Study Period, TSP ON

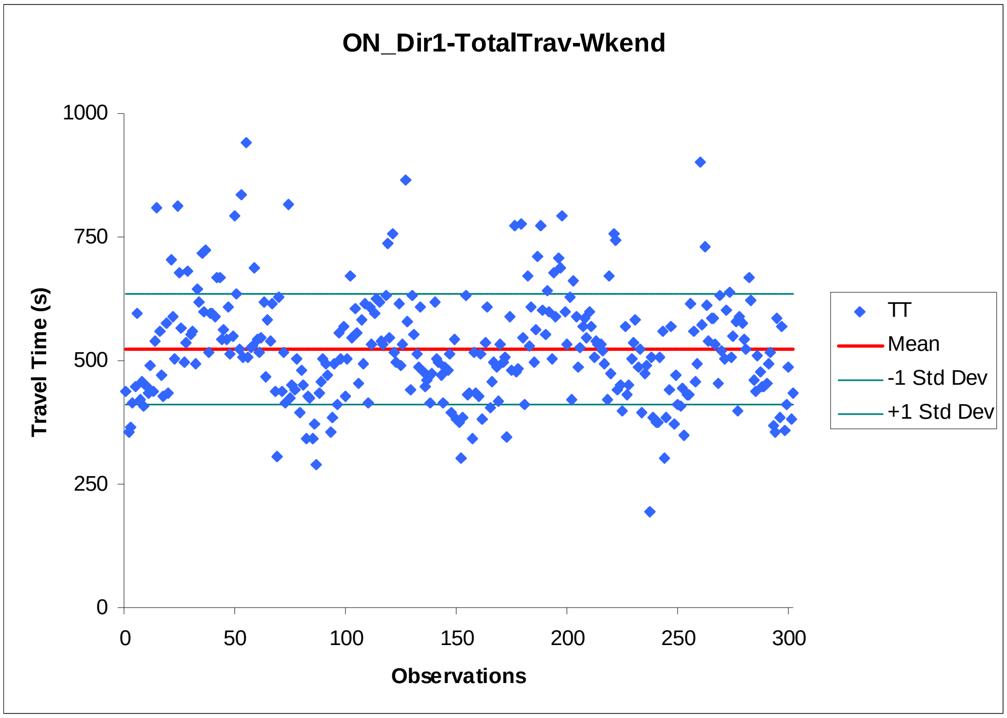

Figure A.47 Southbound Vehicle Travel Times, Weekend Total Study Period, TSP ON

APPENDIX B

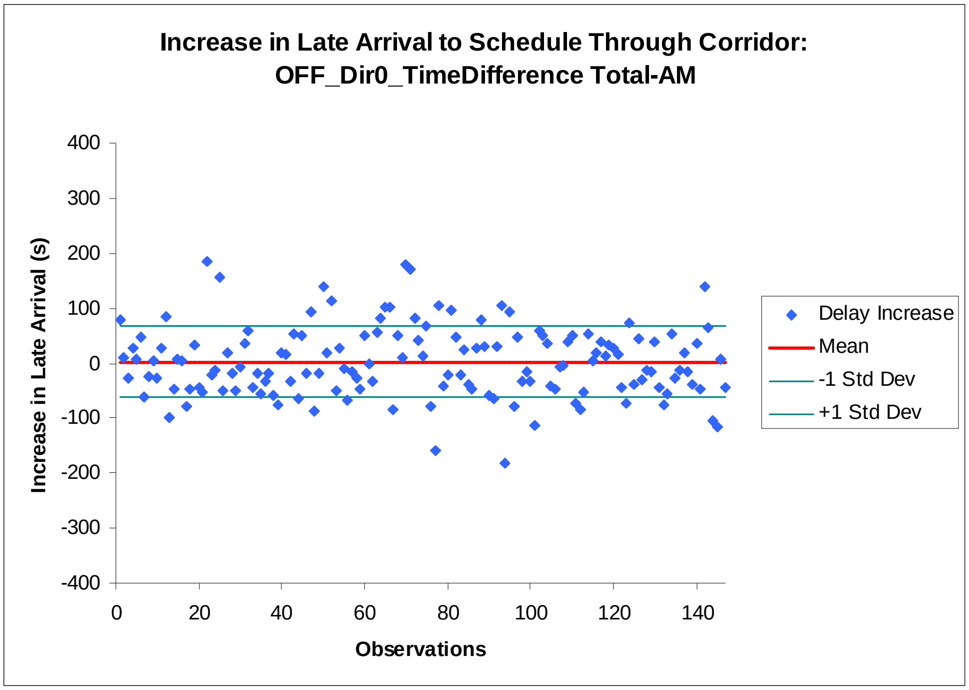

Figure B.1 Increase in Late Arrival to Schedule Through Corridor Northbound: AM Peak Period, TSP OFF

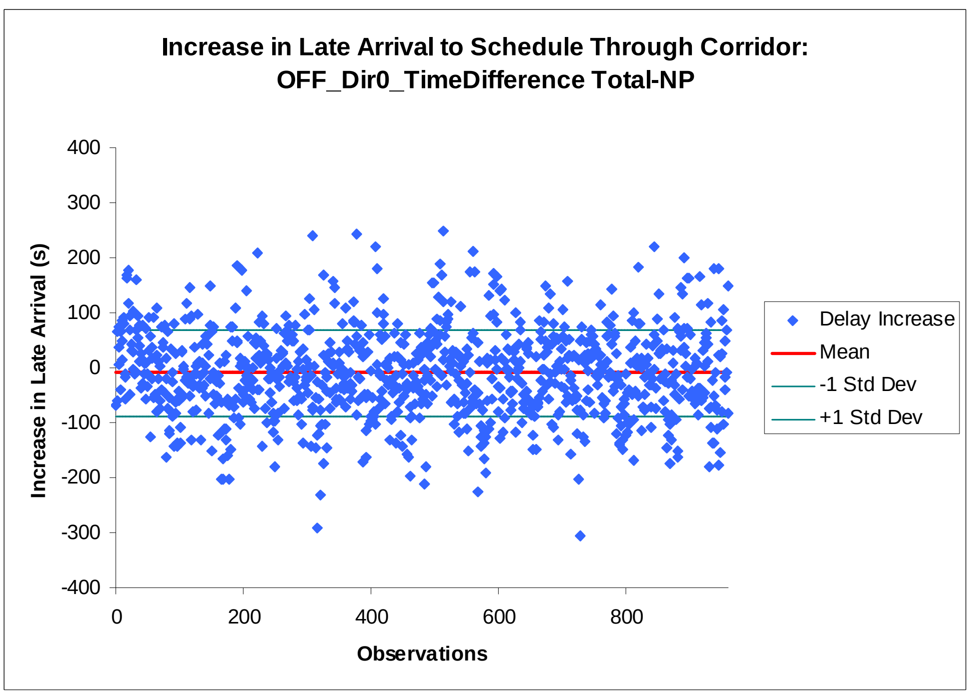

Figure B.2 Increase in Late Arrival to Schedule Through Corridor Northbound: Non-Peak Period, TSP OFF

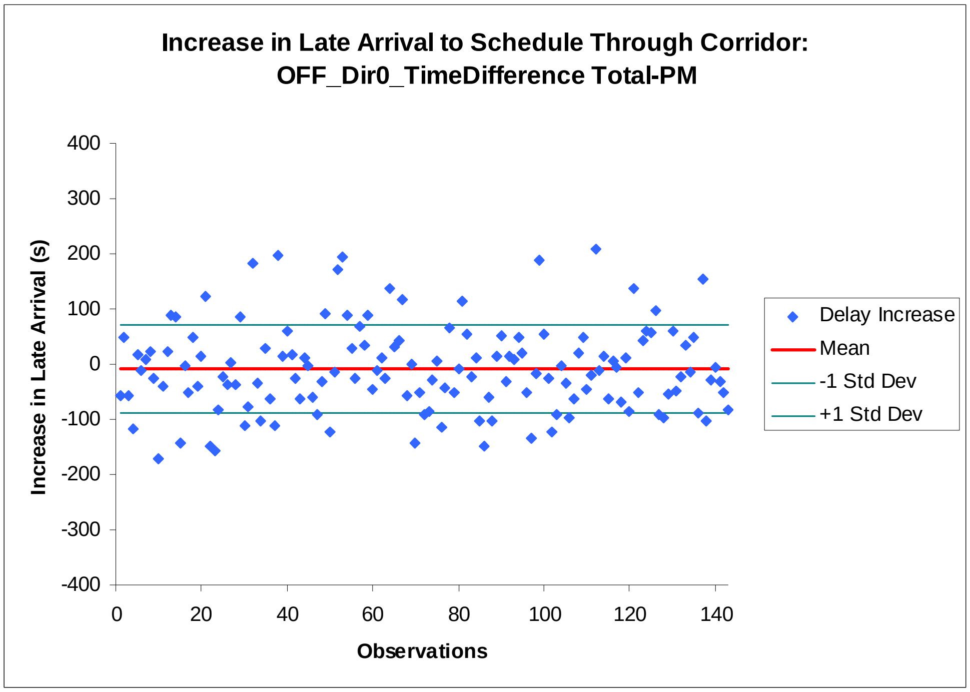

Figure B.3 Increase in Late Arrival to Schedule Through Corridor Northbound: PM Peak Period, TSP OFF

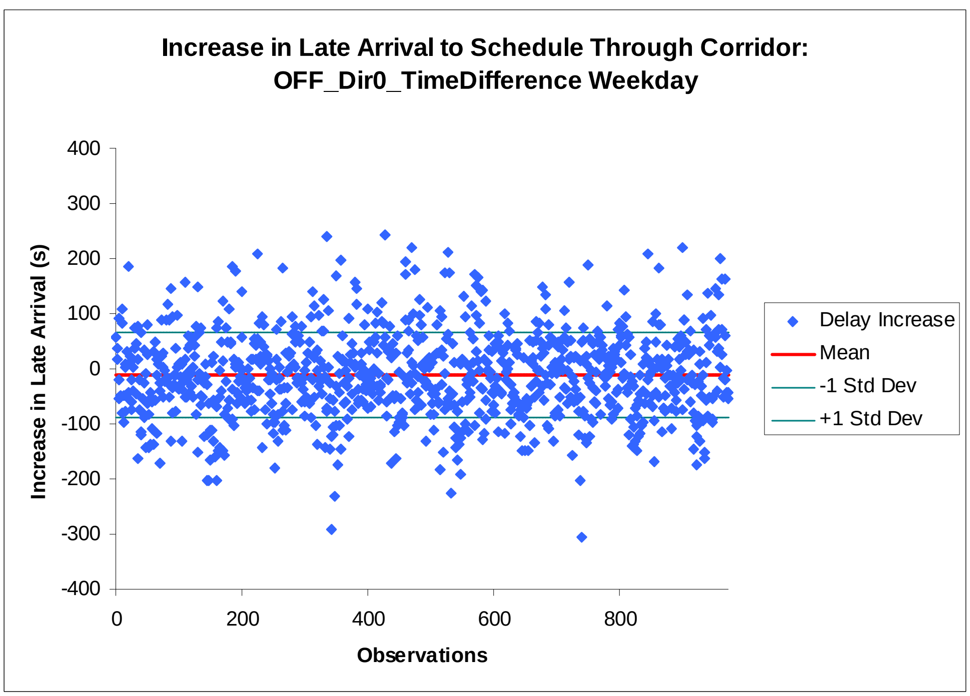

Figure B.4 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekday, TSP OFF

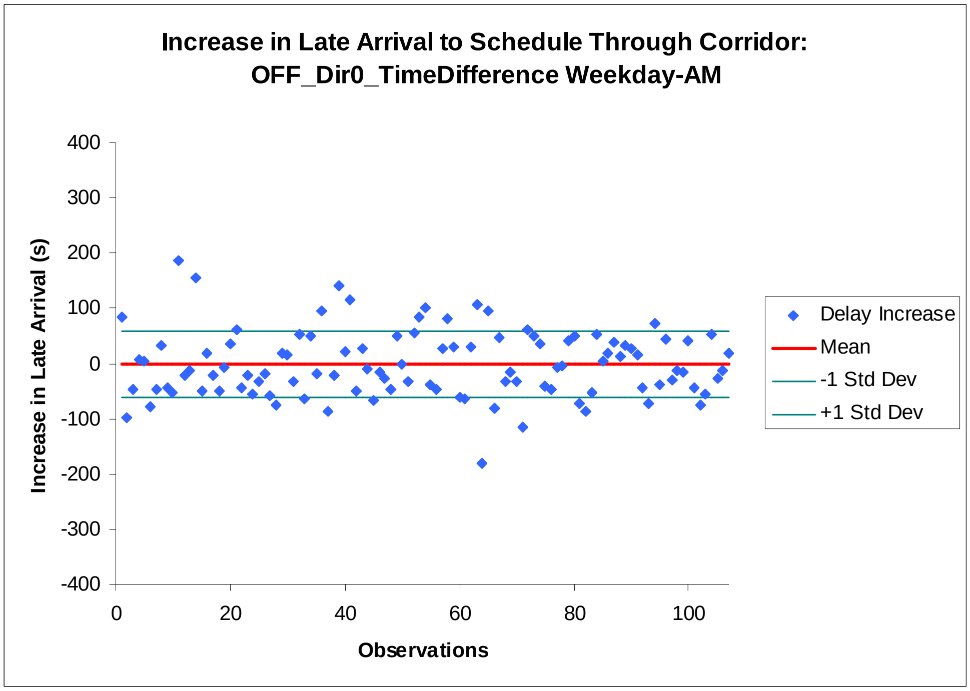

Figure B.5 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekday, AM Peak Period, TSP OFF

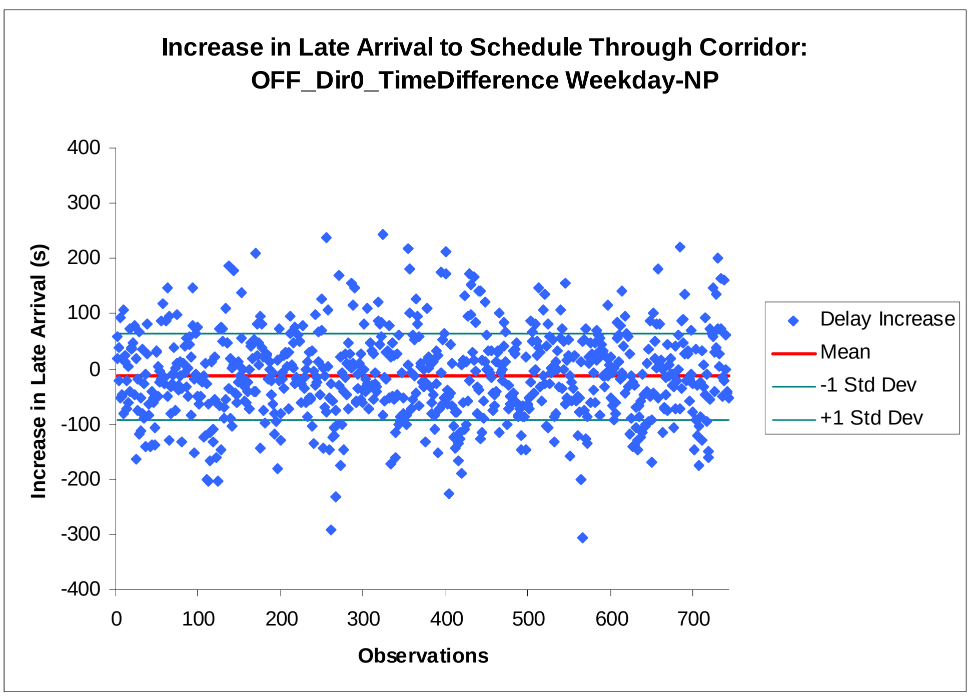

Figure B.6 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekday, Non-Peak Period, TSP OFF

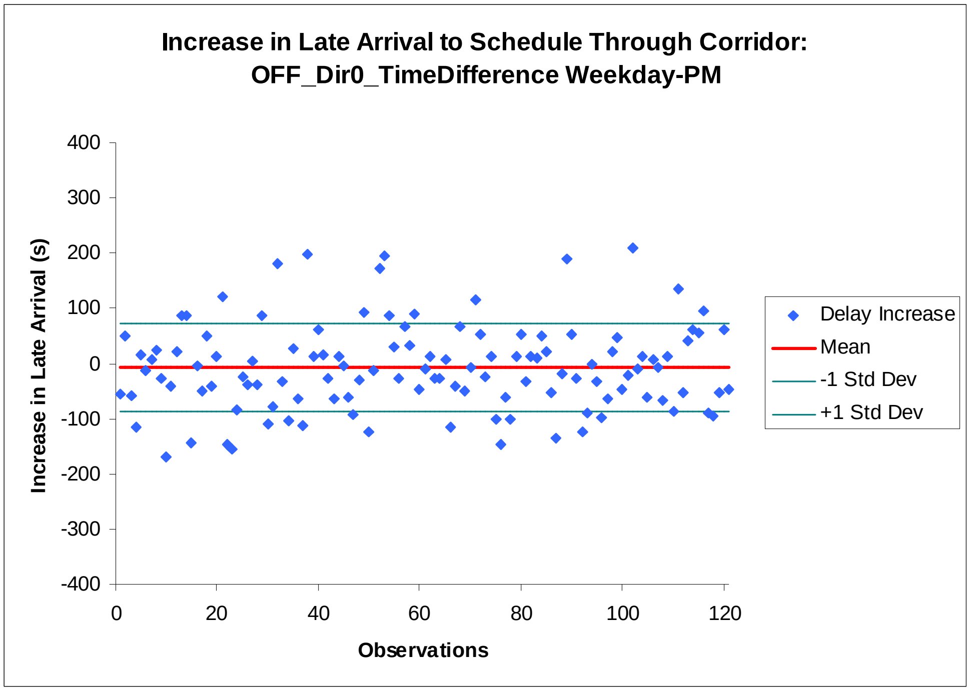

Figure B.7 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekday, PM Peak Period, TSP OFF

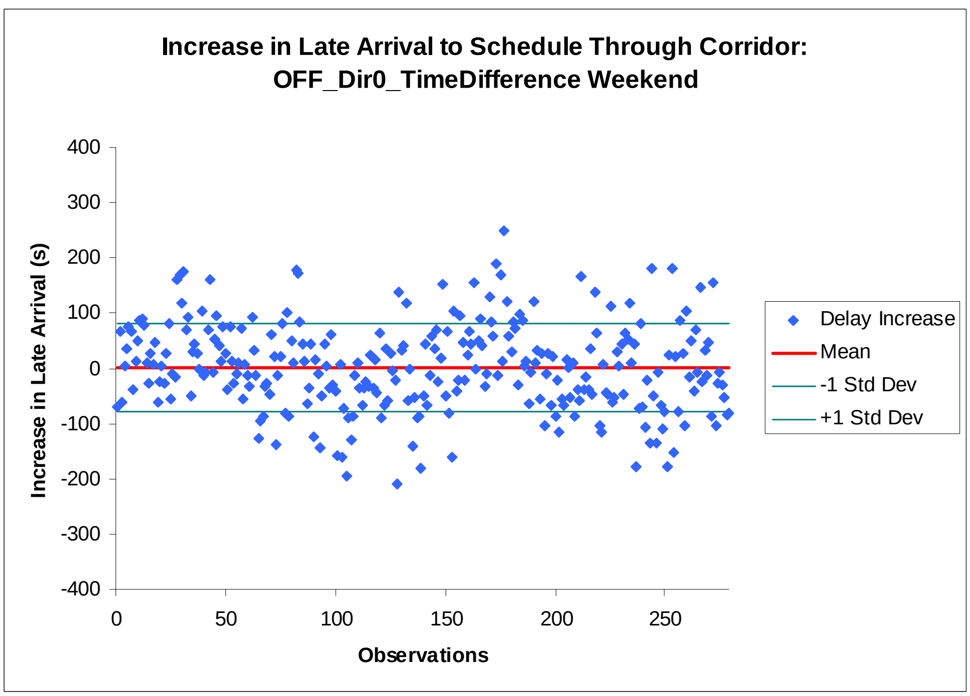

Figure B.8 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekend, TSP OFF

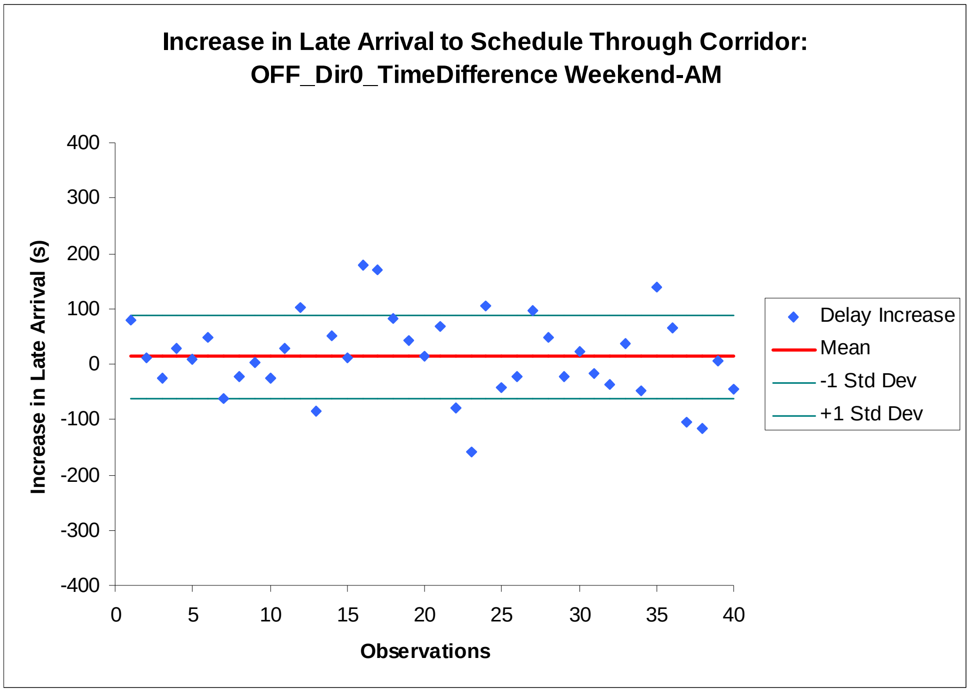

Figure B.9 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekend, AM Peak Period, TSP OFF

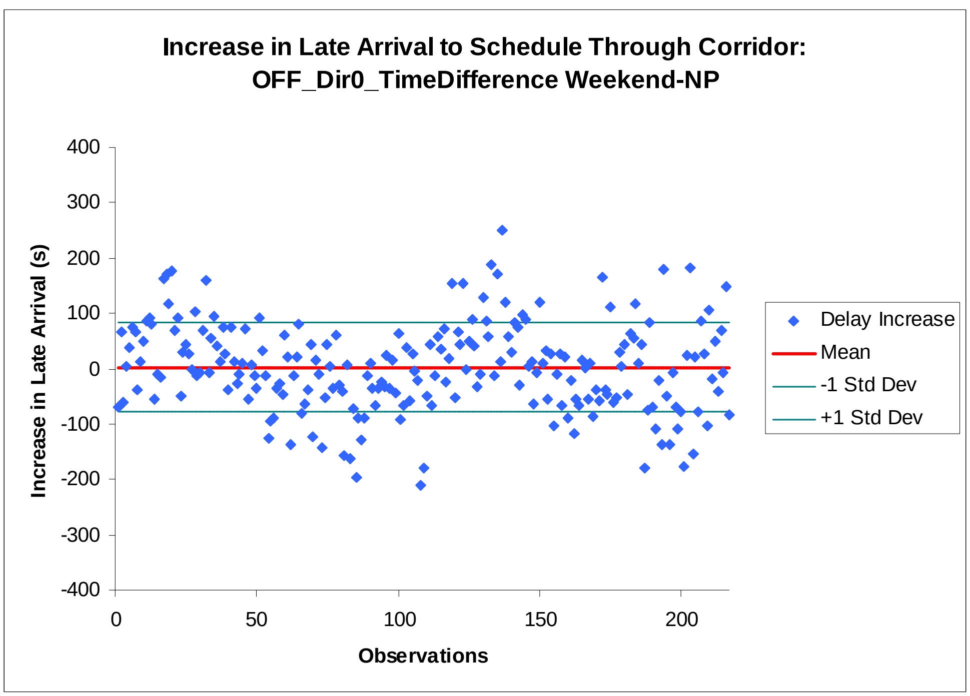

Figure B.10 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekend, Non-Peak Period, TSP OFF

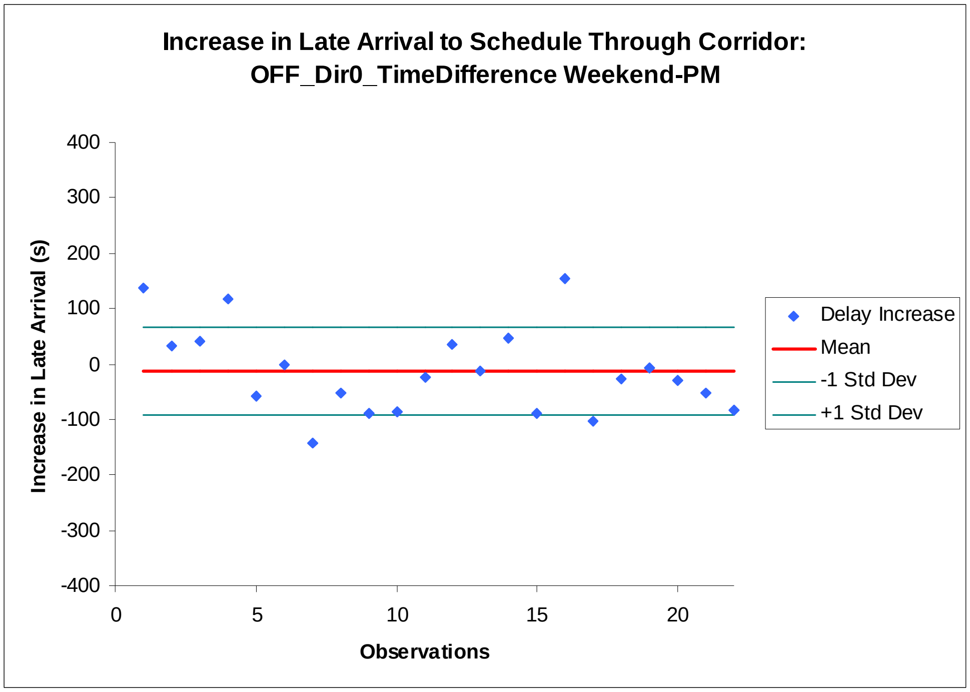

Figure B.11 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekend, PM Peak Period, TSP OFF

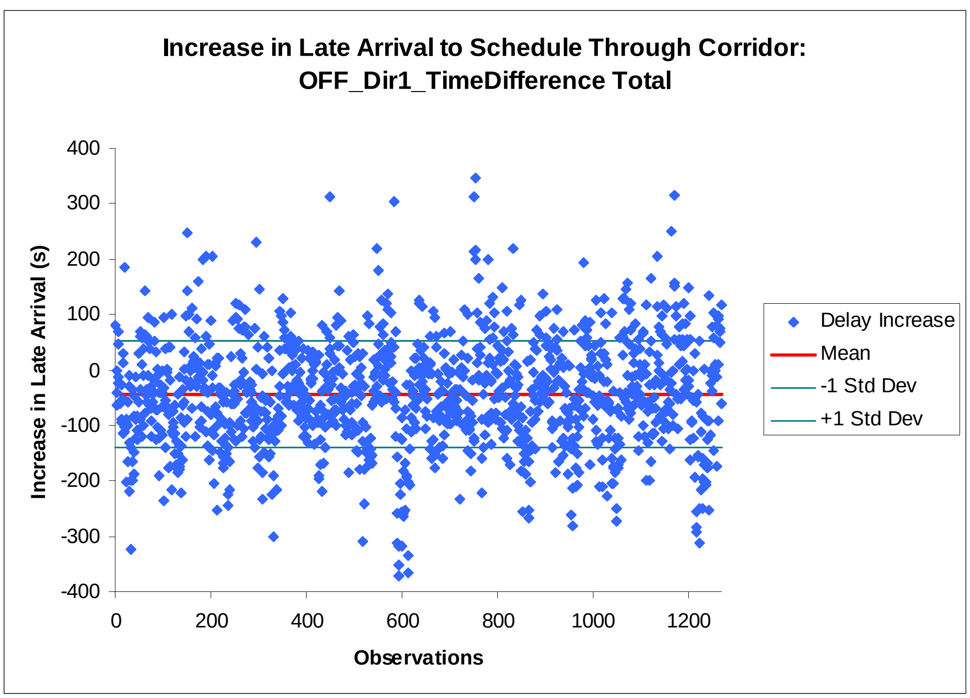

Figure B.12 Increase in Late Arrival to Schedule Through Corridor Northbound: Total Study Period, TSP OFF

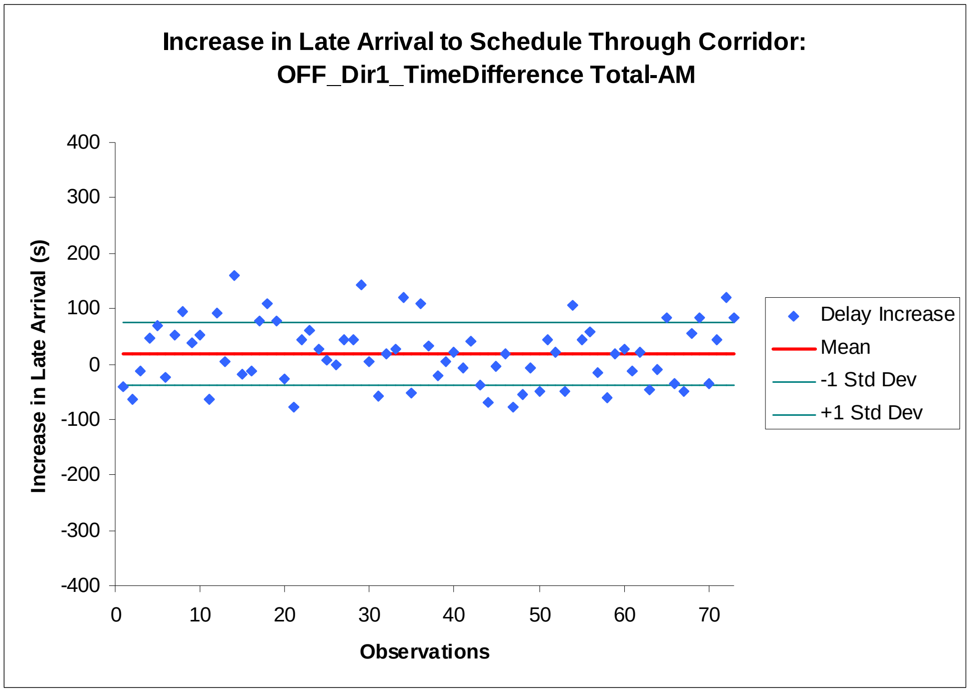

Figure B.13 Increase in Late Arrival to Schedule Through Corridor Northbound: Total Study Period, AM Peak Period, TSP OFF

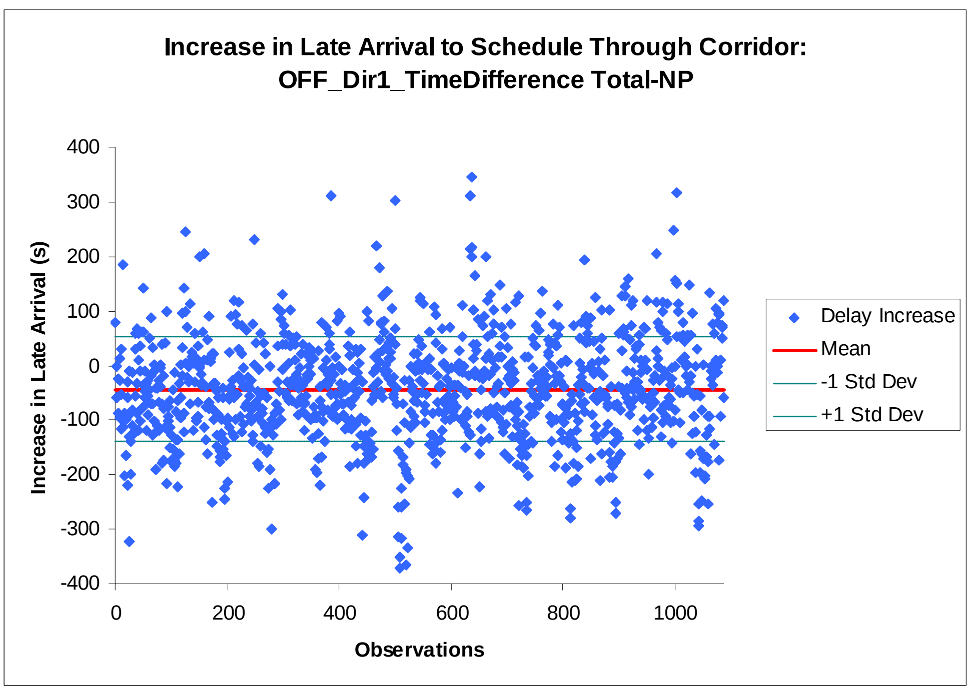

Figure B.14 Increase in Late Arrival to Schedule Through Corridor Northbound: Total Study Period, Non-Period, TSP OFF

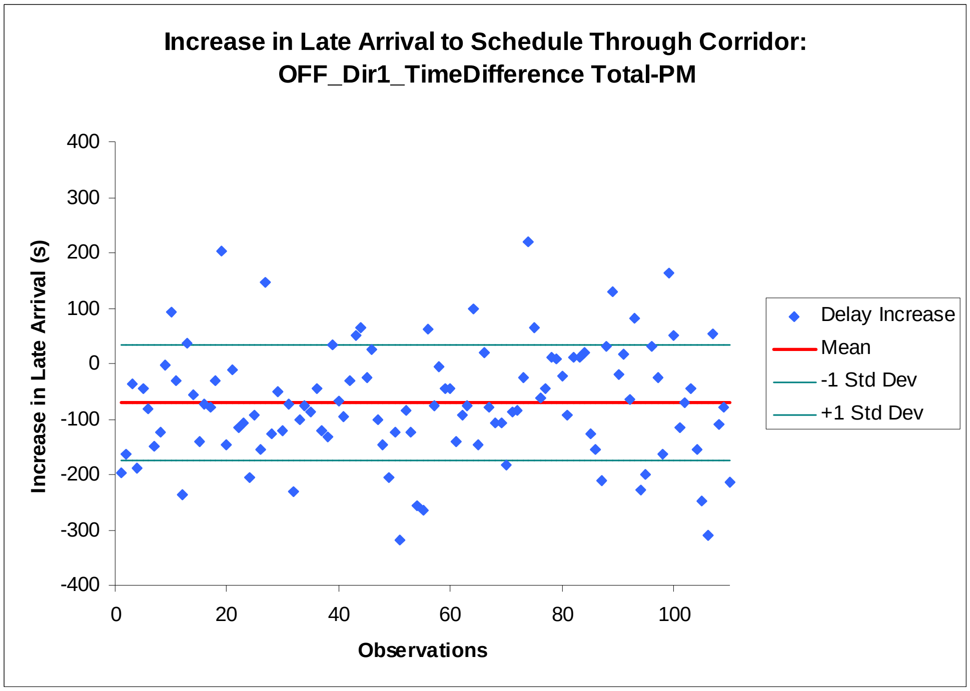

Figure B.15 Increase in Late Arrival to Schedule Through Corridor Northbound: Total Study Period, PM Peak Period, TSP OFF

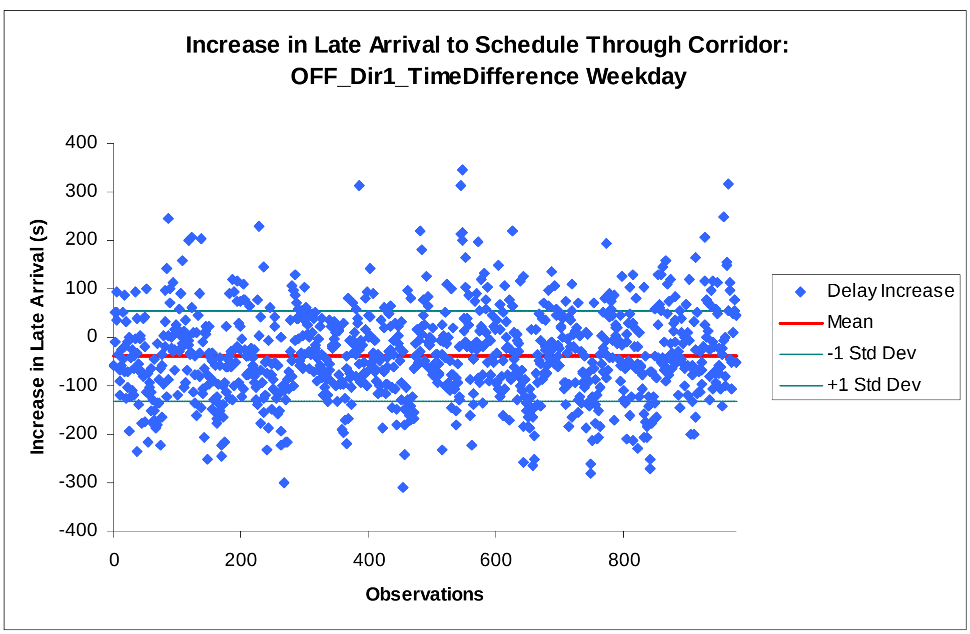

Figure B.16 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekday, TSP OFF

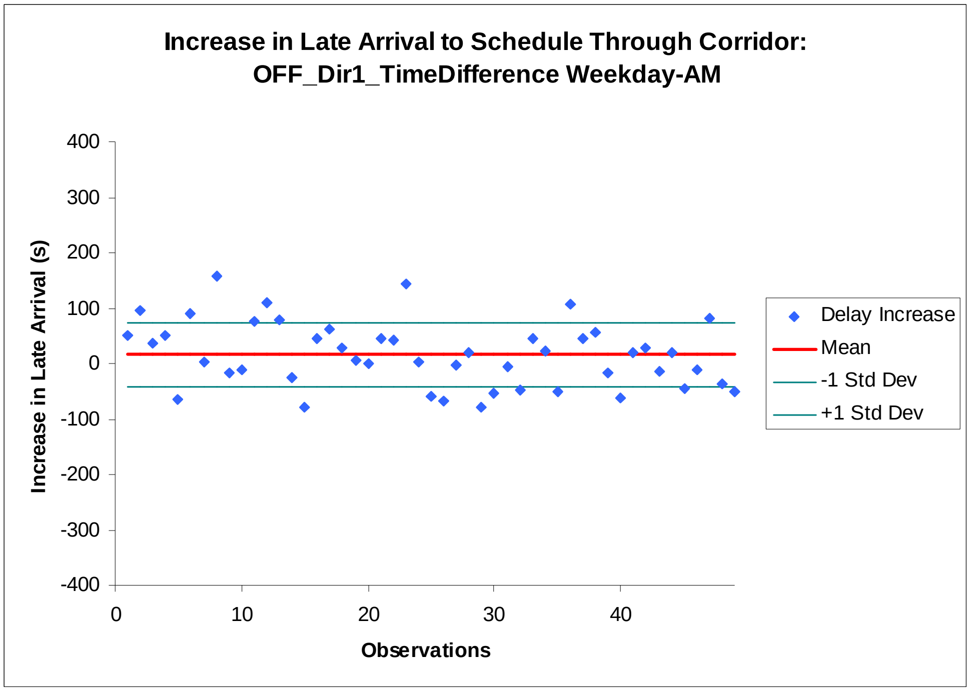

Figure B.17 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekday, AM Peak Period, TSP OFF

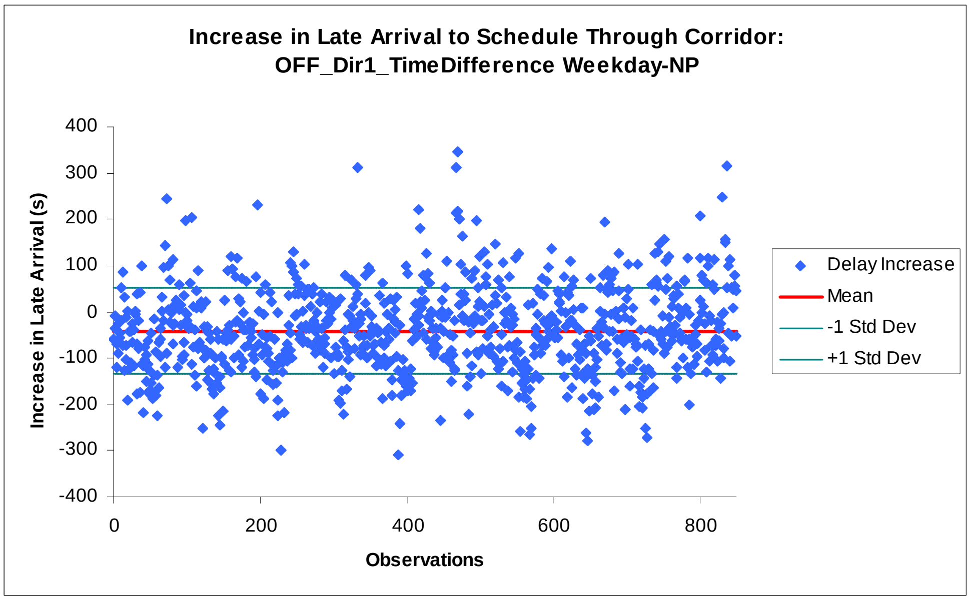

Figure B.18 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekday, Non-Peak Period, TSP OFF

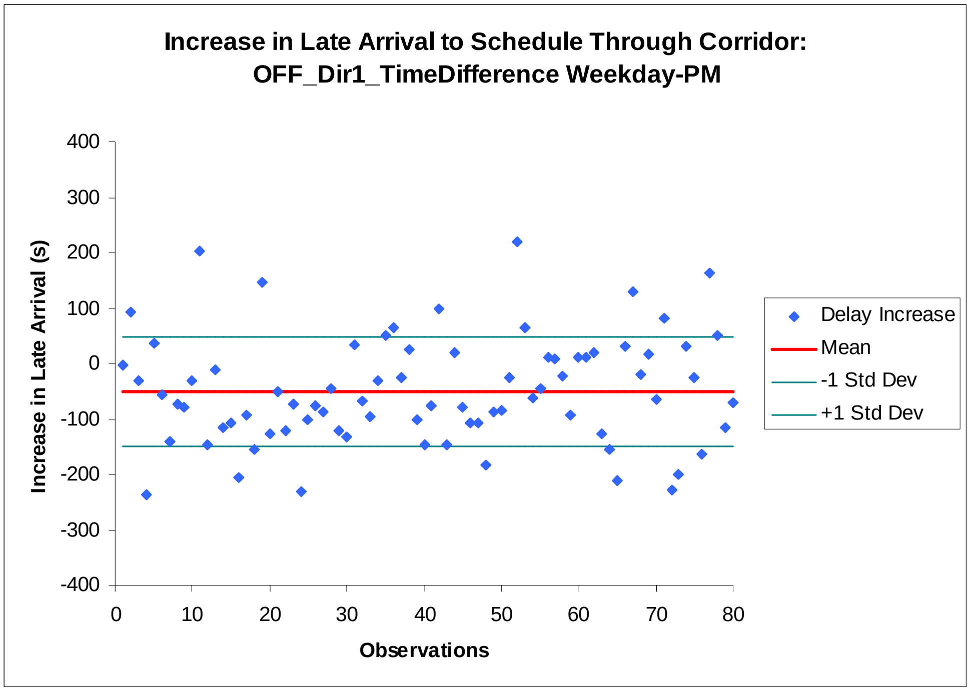

Figure B.19 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekday, PM Peak Period, TSP OFF

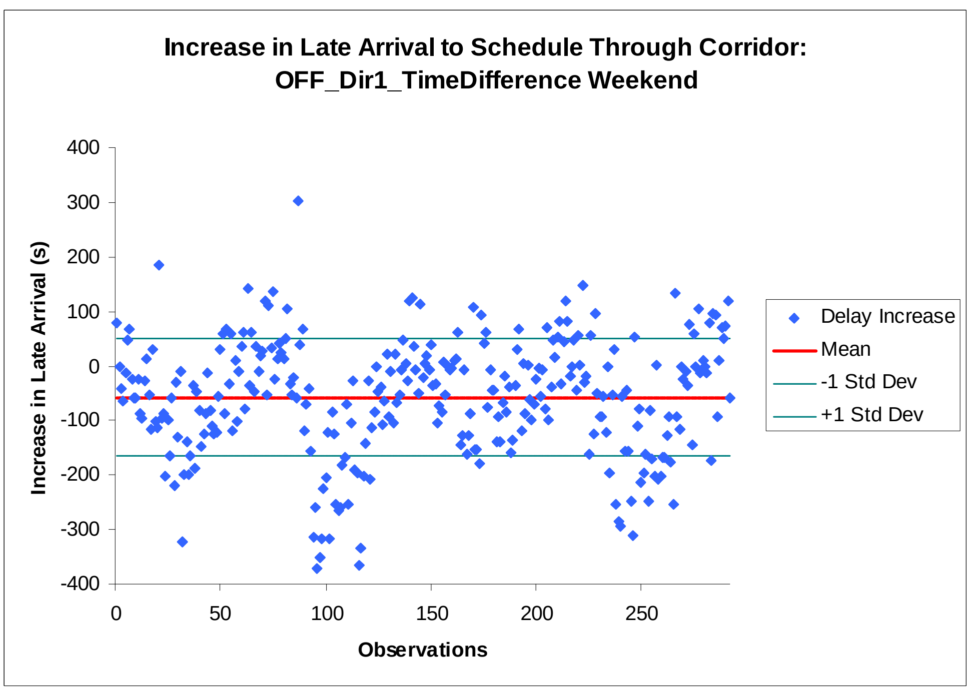

Figure B.20 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekend, TSP OFF

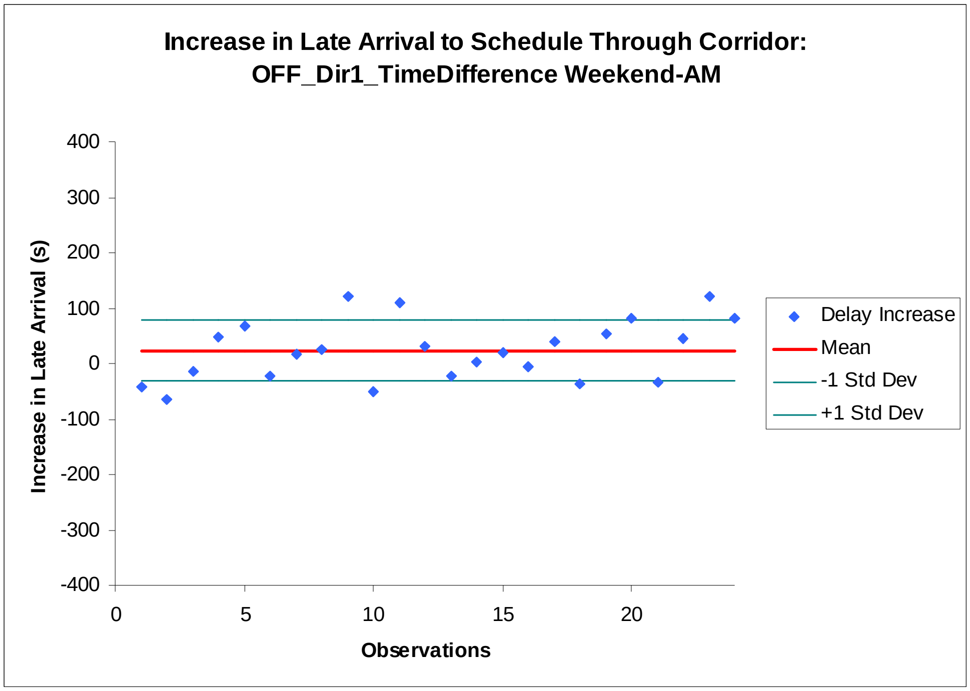

Figure B.21 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekend, AM Peak Period, TSP OFF

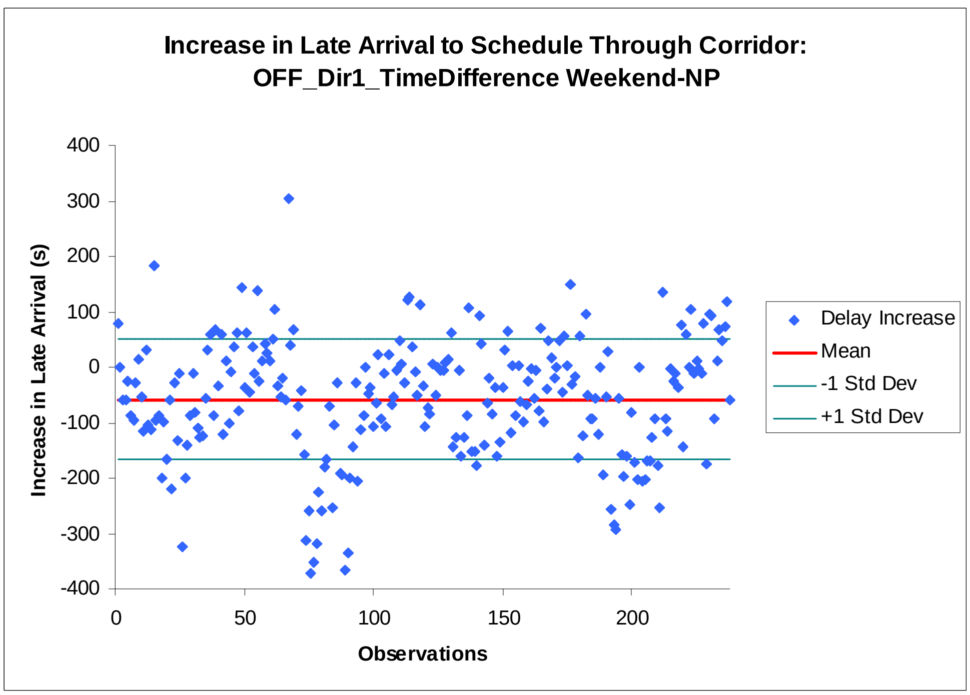

Figure B.22 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekend, Non-Peak Period, TSP OFF

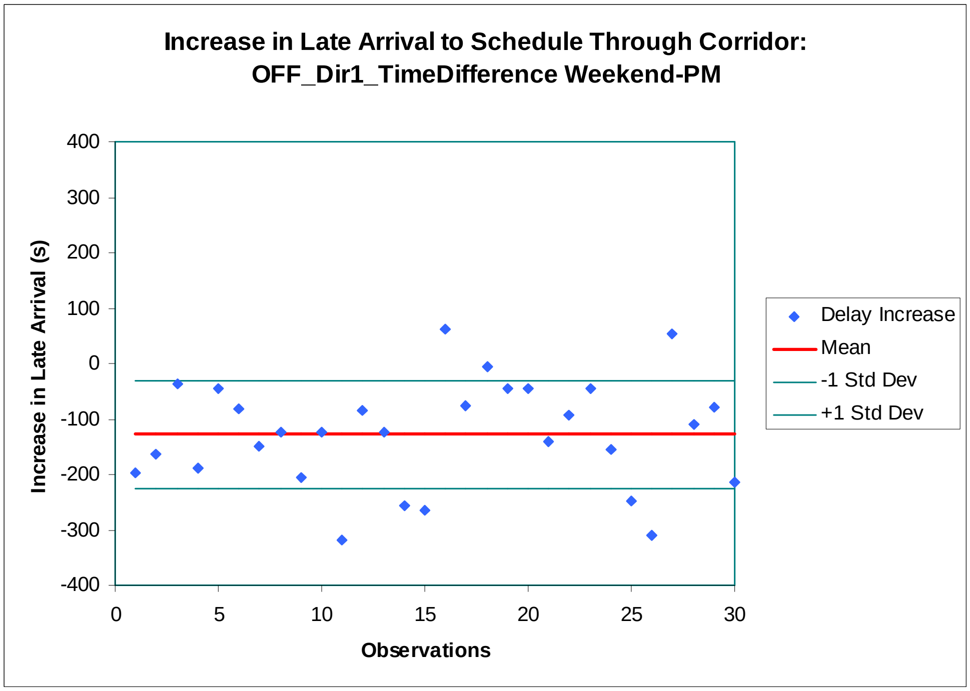

Figure B.23 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekend, PM Peak Period, TSP OFF

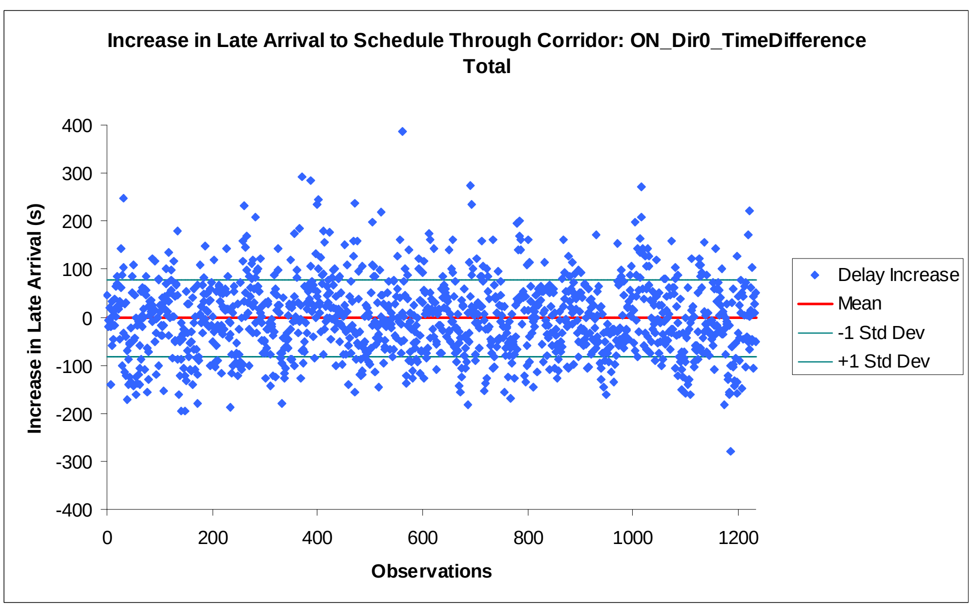

Figure B.24 Increase in Late Arrival to Schedule Through Corridor Southbound: Total Study Period, TSP OFF

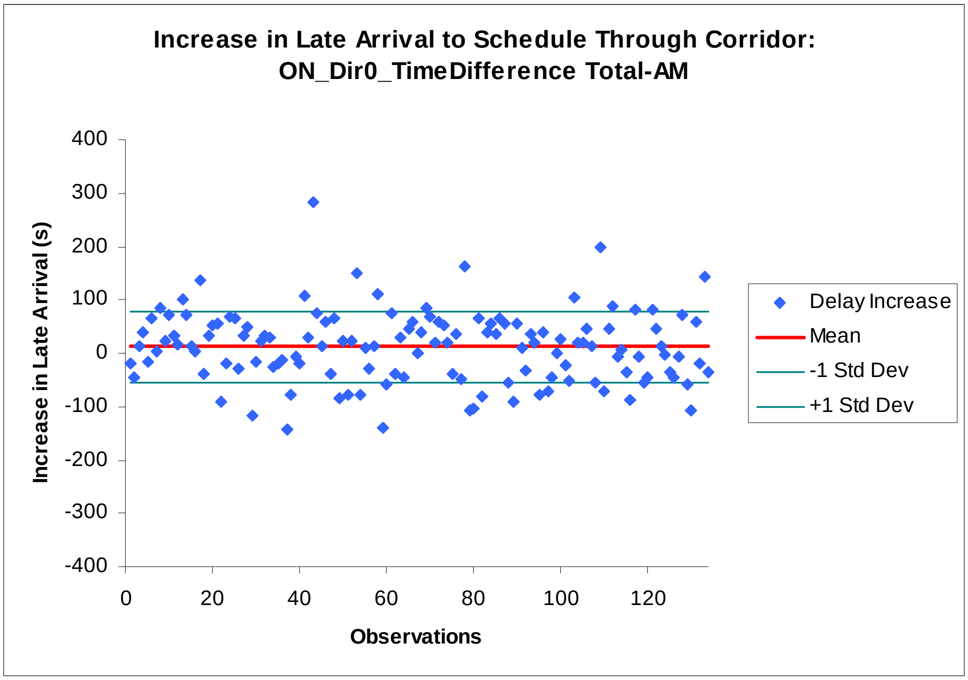

Figure B.25 Increase in Late Arrival to Schedule Through Corridor Southbound: Total Study Period, AM Peak Period, TSP OFF

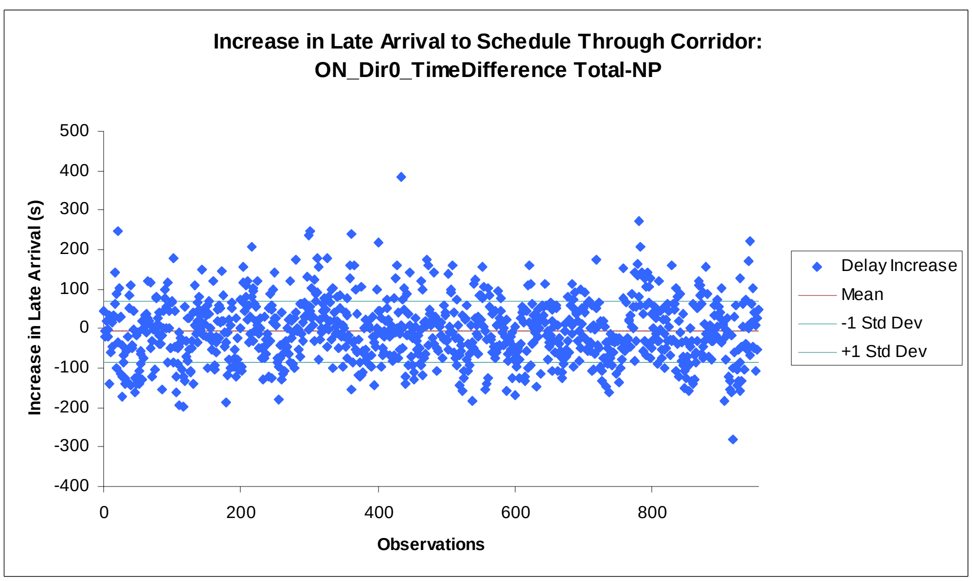

Figure B.26 Increase in Late Arrival to Schedule Through Corridor Southbound: Total Study Period, Non-Peak Period, TSP OFF

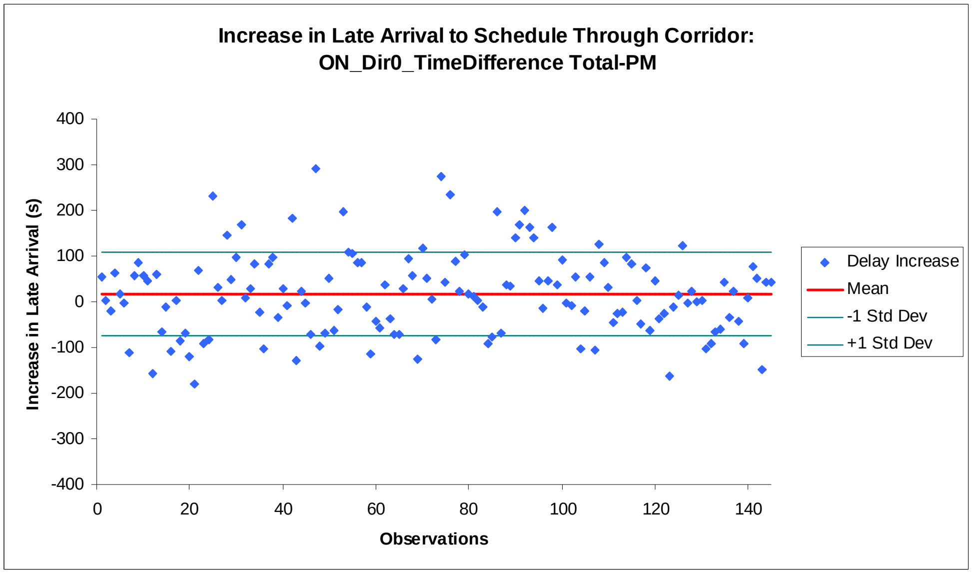

Figure B.27 Increase in Late Arrival to Schedule Through Corridor Southbound: Total Study Period, PM Peak Period, TSP OFF

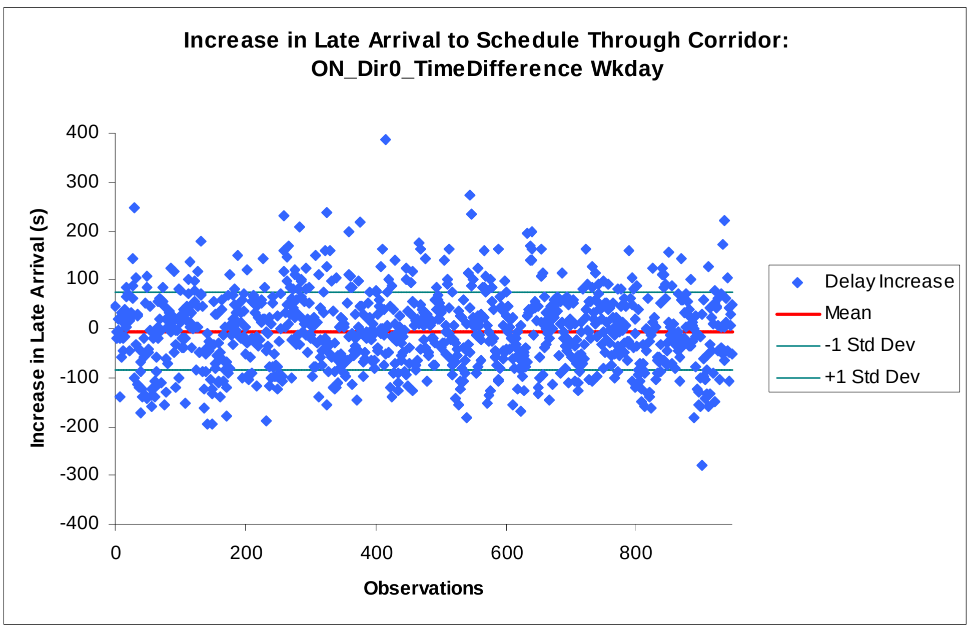

Figure B.28 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekday TSP ON

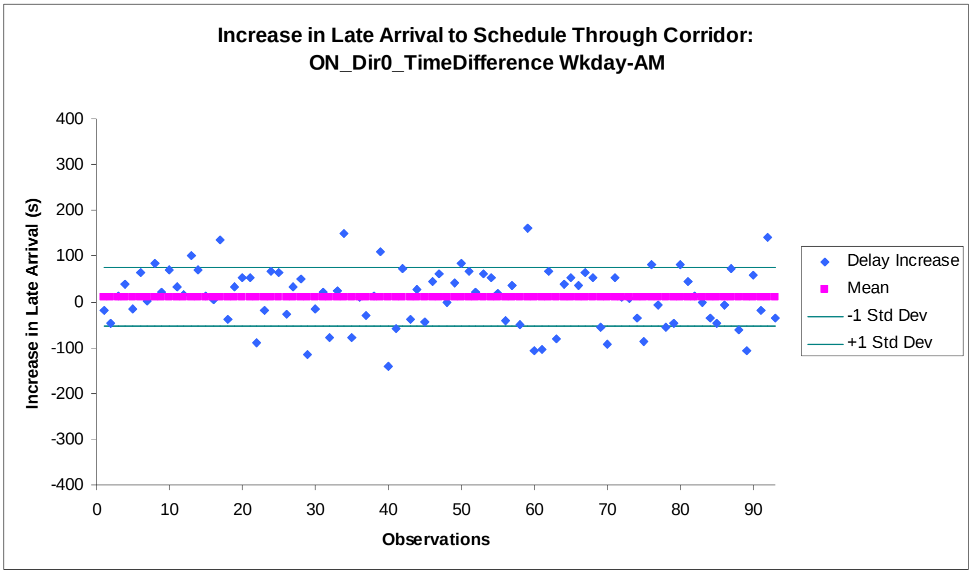

Figure B.29 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekday, AM Peak Period, TSP ON

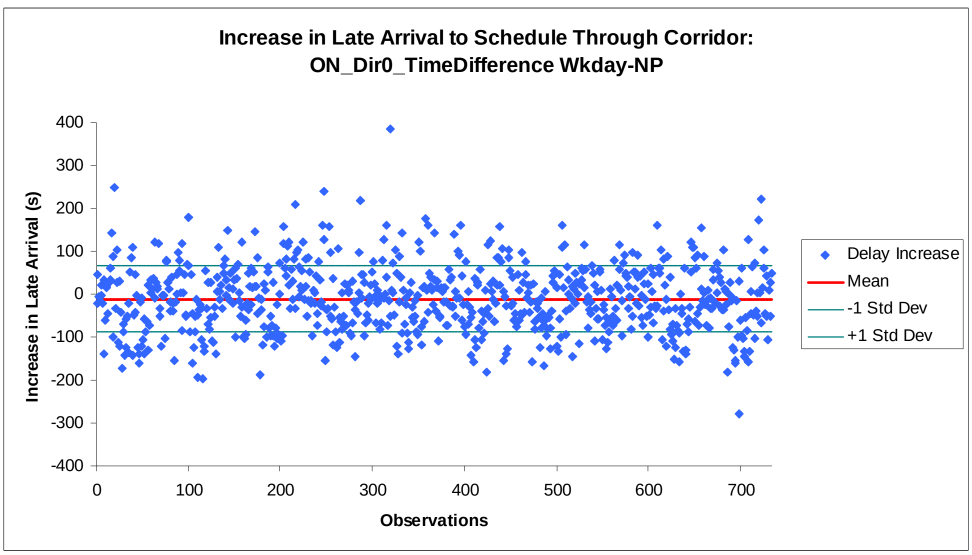

Figure B.30 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekday, Non-Peak Period, TSP ON

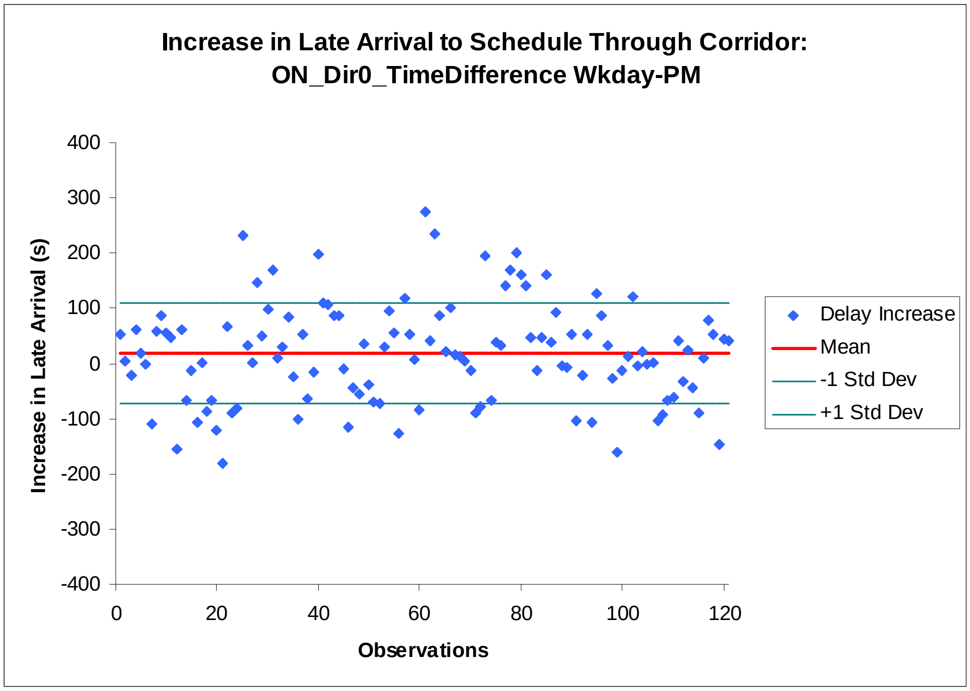

Figure B.31 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekday, PM Peak Period, TSP ON

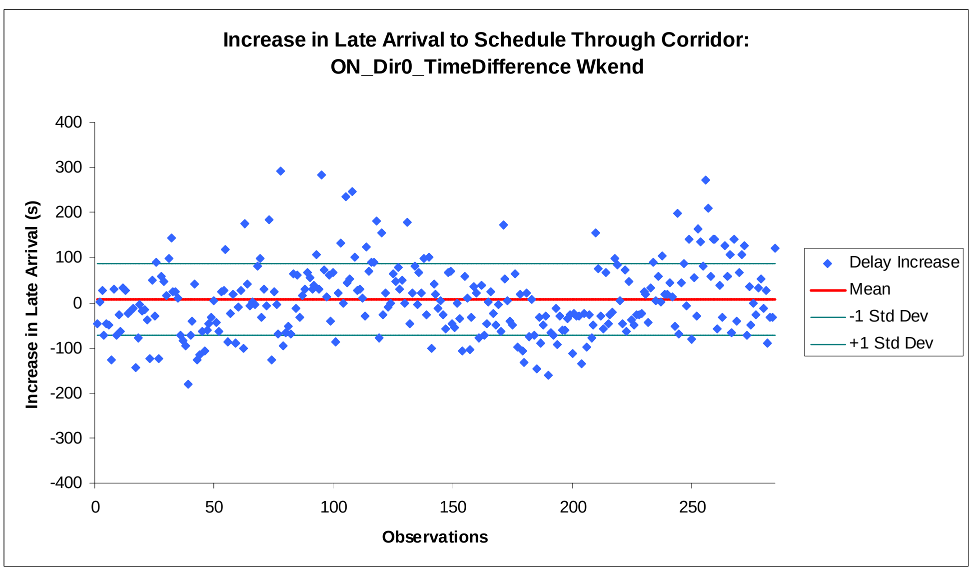

Figure B.32 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekend, TSP ON

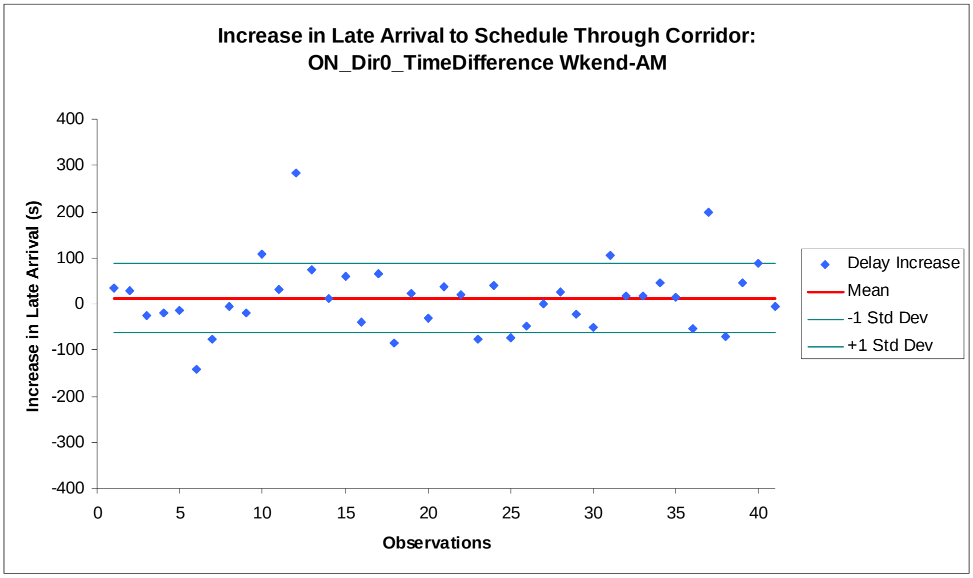

Figure B.33 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekend, AM Peak Period, TSP ON

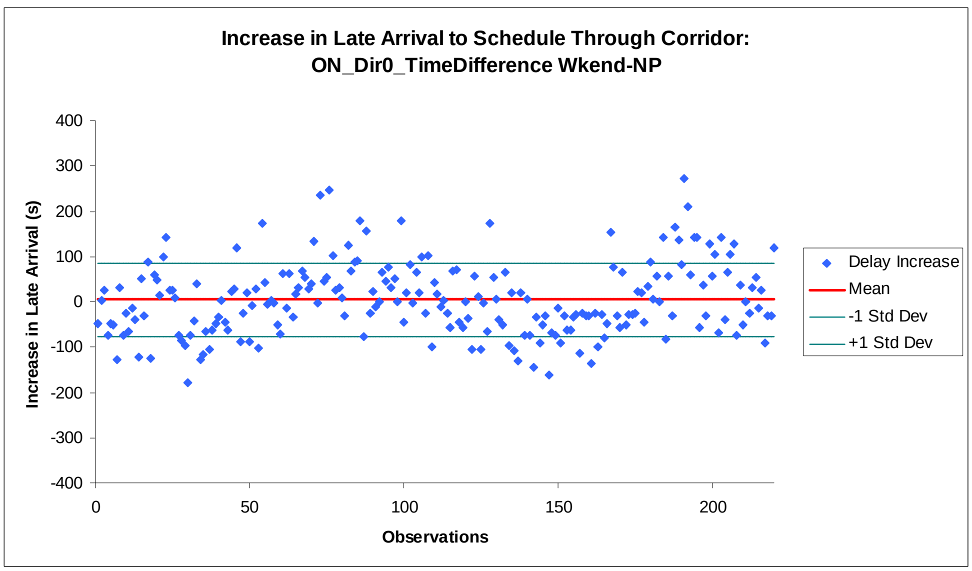

Figure B.34 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekend, Non-Peak Period, TSP ON

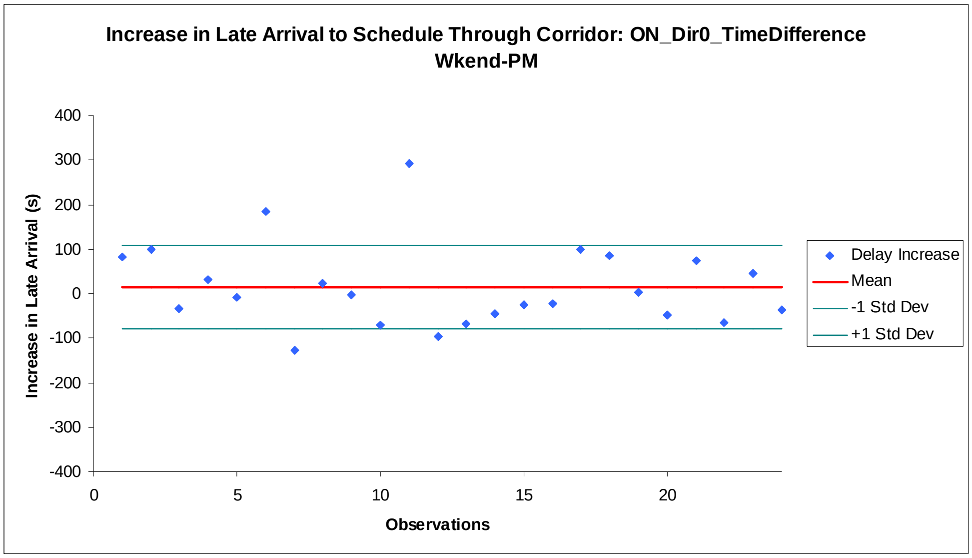

Figure B.35 Increase in Late Arrival to Schedule Through Corridor Northbound: Weekend, PM Peak Period, TSP ON

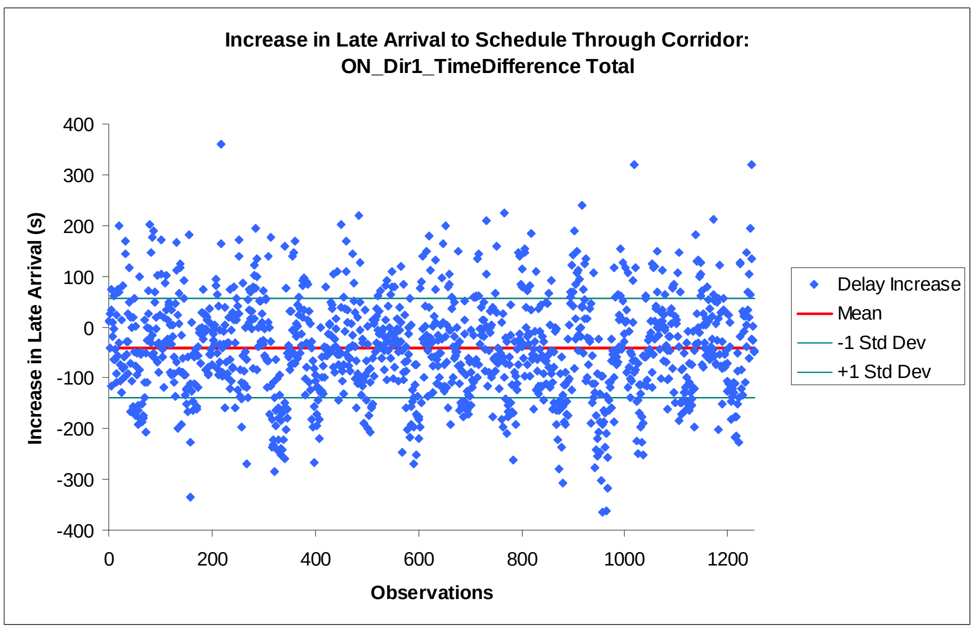

Figure B.36 Increase in Late Arrival to Schedule Through Corridor Southbound: Total Study Period, TSP ON

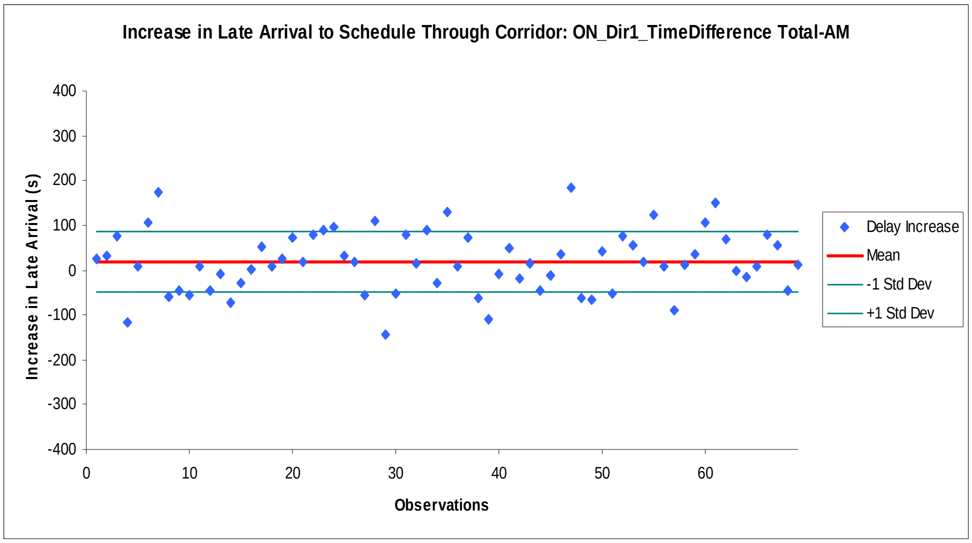

Figure B.37 Increase in Late Arrival to Schedule Through Corridor Southbound: Total Study Period, AM Peak Period, TSP ON

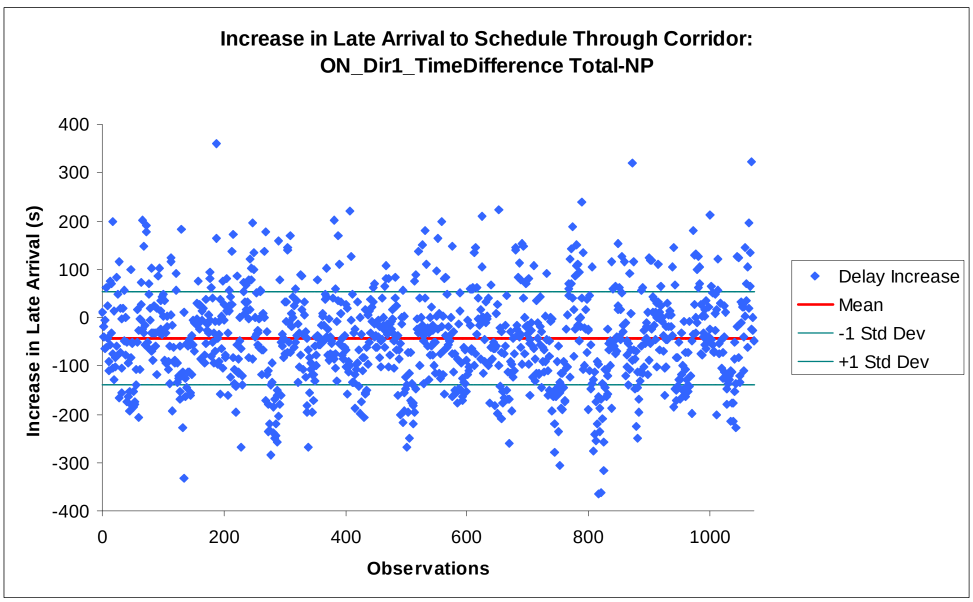

Figure B.38 Increase in Late Arrival to Schedule Through Corridor Southbound: Total Study Period, Non-Peak Period, TSP ON

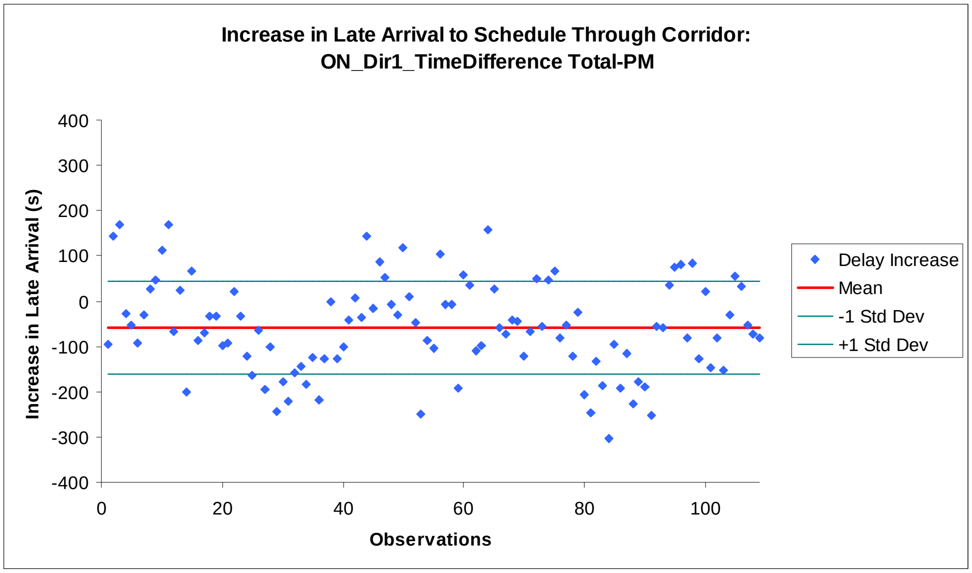

Figure B.39 Increase in Late Arrival to Schedule Through Corridor Southbound: Total Study Period, PM Peak Period, TSP ON

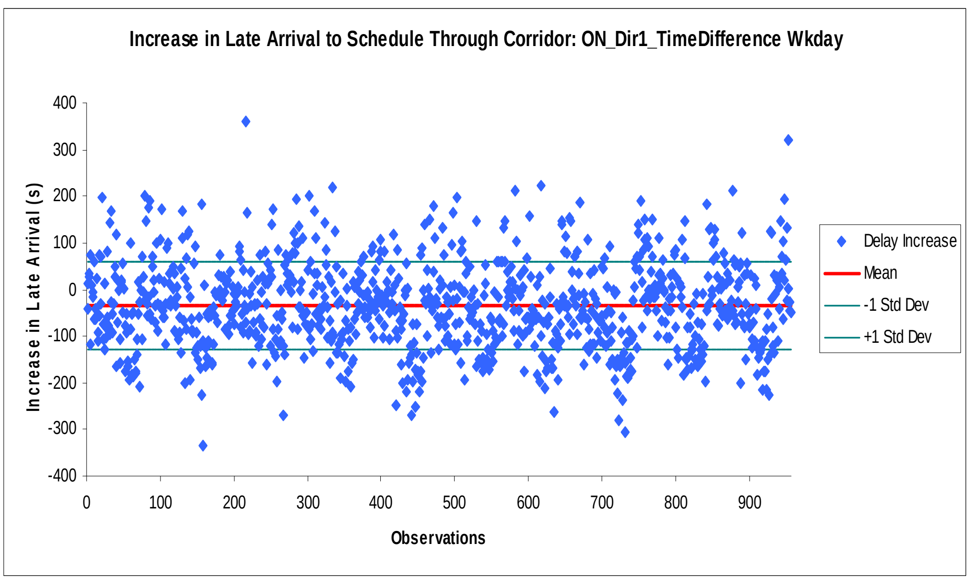

Figure B.40 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekday, TSP ON

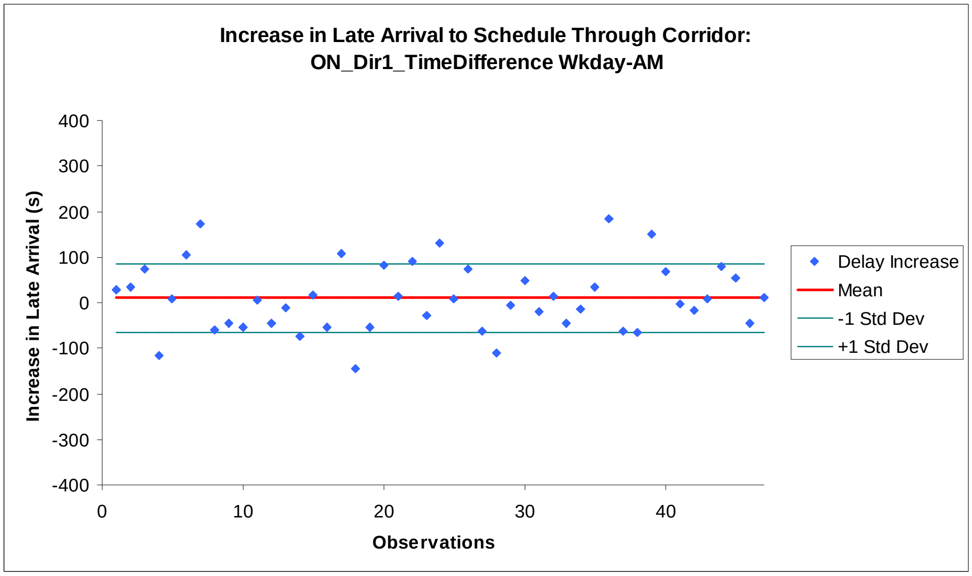

Figure B.41 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekday, AM Peak Period, TSP ON

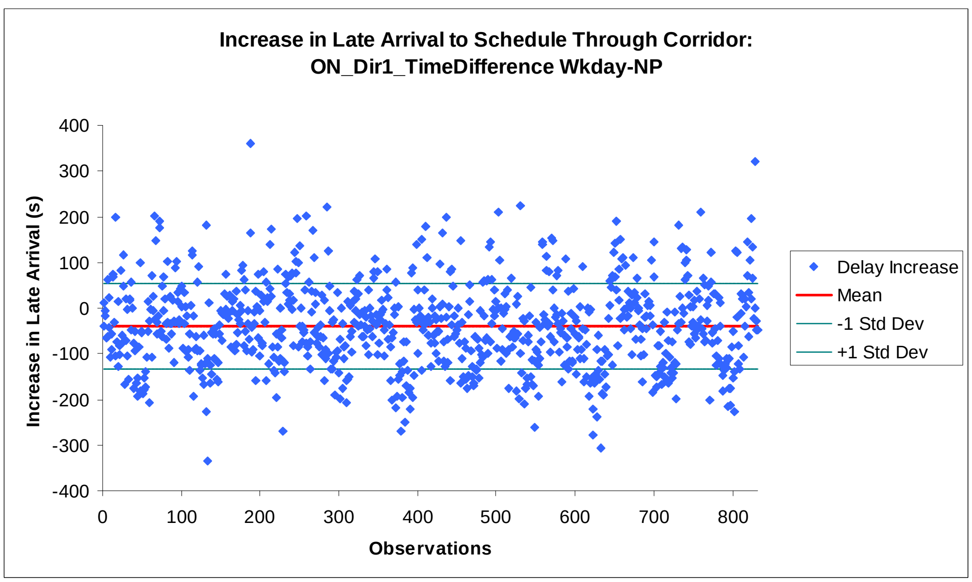

Figure B.42 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekday, Non-Peak Period, TSP ON

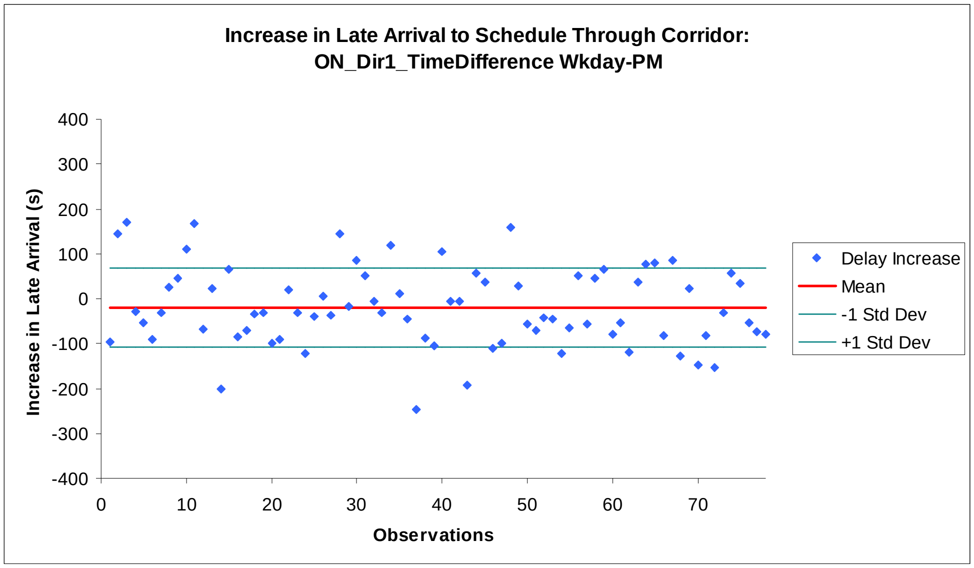

Figure B.43 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekday, PM Peak Period, TSP ON

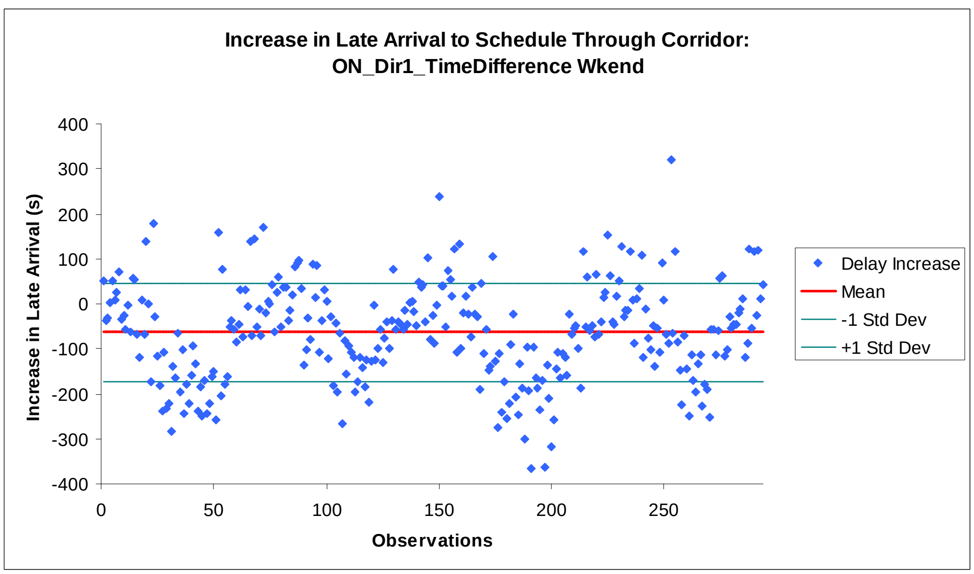

Figure B.44 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekend, TSP ON

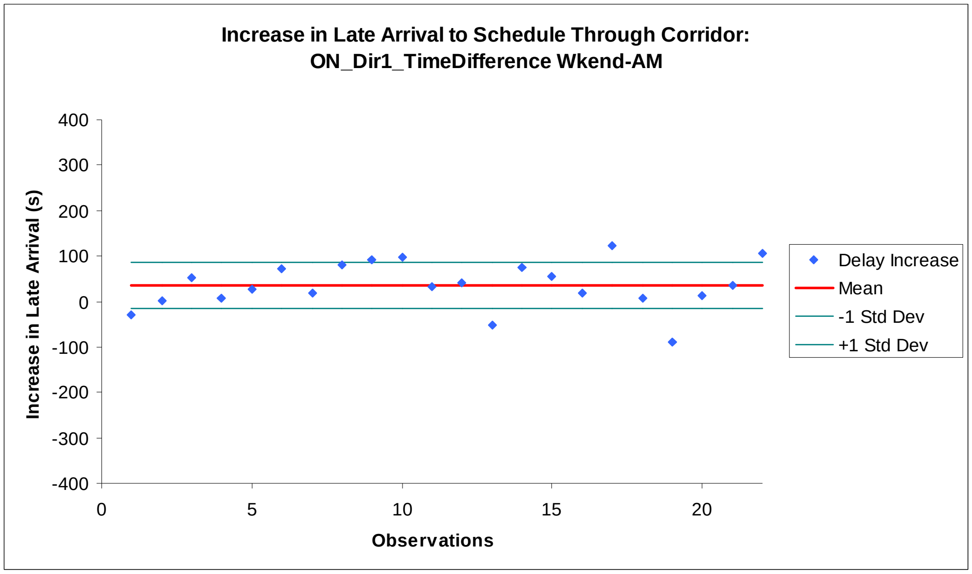

Figure B.45 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekend, AM Peak Period, TSP ON

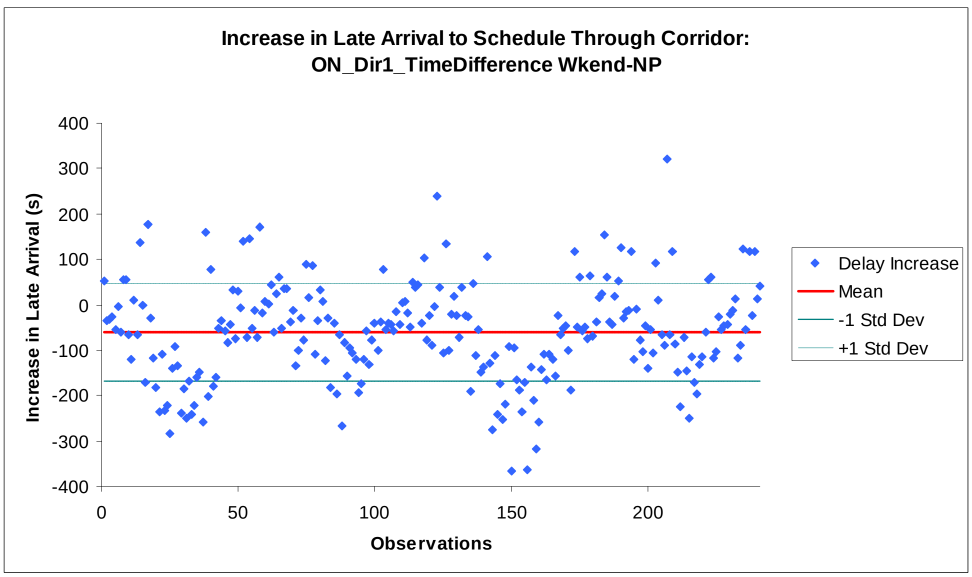

Figure B.46 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekend, Non-Peak Period, TSP ON

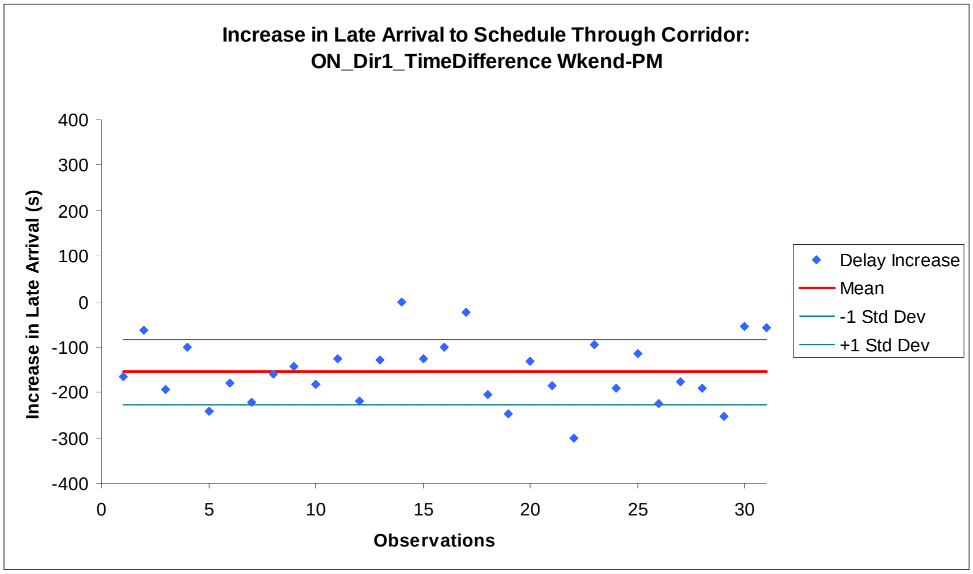

Figure B.47 Increase in Late Arrival to Schedule Through Corridor Southbound: Weekend, PM Peak Period, TSP ON

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