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IMPACTS OF CHANGING THE TRANSIT SIGNAL PRIORITY REQUESTING THRESHOLD ON BUS PERFORMANCE AND GENERAL TRAFFIC: A SENSITIVITY ANALYSIS

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16. Abstract A sensitivity analysis was performed on the transit signal priority (TSP) requesting threshold to evaluate its impact on bus performance and general traffic. Route 217, a conventional bus route, and the Utah Valley Express (UVX), a bus rapid transit line, utilize a dedicated short-range communication (DSRC)-based TSP system as part of their normal, day-to-day operations. Using field-generated data exclusively, bus performance and general traffic were evaluated over a seven-month period from February through August 2019. Bus performance was evaluated through on-time performance (OTP), schedule deviation, travel time, and dwell time, while the traffic analysis was performed by evaluating split failure, change in green time, and the frequency at which TSP was served. The requesting thresholds evaluated for Route 217 were 5, 3, 2, and 0 minutes, which stipulate how far behind schedule the bus must be in order to request TSP. For UVX, 5 minutes and 2 minutes, as well as always ON and always OFF scenarios were evaluated. A combination of observational and statistical analyses concluded with convincing evidence that OTP, schedule deviation, and travel time improve as the requesting threshold approaches zero with negligible impacts to general traffic. For Route 217, as the requesting threshold changed from 3, to 2, to 0 minutes, OTP increased 2.0 and 2.5 percent, respectively; mean schedule deviation improved 15.9 and 20.9 seconds, respectively; and travel time decreased at 72 percent of timepoints. Meanwhile, negative impacts to traffic occurred if an increase in split failure was measured after TSP was served, a phenomenon observed a maximum of once every 43 minutes. For UVX, as the requesting threshold changed from 5, to 2 minutes, to ON, OTP increased 7.6 and 4.7 percent, respectively; mean schedule deviation improved 24.3 and 15.0 seconds, respectively; and travel time decreased between 72 percent of timepoints. Thus, it is concluded that under the TSP system as implemented, bus performance improves as the requesting threshold approaches zero, with inconsequential impacts to general traffic.					
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UNIT CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ANPRM	Advanced Notice of Proposed Rulemaking
API	Application Programming Interface
ASTM	American Society for Testing and Materials
ATC	Advanced Transportation Controllers
ATSPM	Automated Traffic Signal Performance Measures
AVL	Automatic Vehicle Location
BRT	Bus Rapid Transit
BSM	Basic Safety Message
BYU	Brigham Young University
C-V2X	Cellular Vehicle-to-Everything
CV	Connected Vehicle
DSRC	Dedicated Short-Range Communication
EG	Early Green
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
GE	Green Extension
GPS	Global Positioning System
HCM	Highway Capacity Manual
IEEE	Institute of Electrical and Electronics Engineers
ITS	Intelligent Transportation Systems
LOS	Level of Service
MAP	Map Message
MDC	Mobile Data Computer
MOE	Measure of Effectiveness
MMITSS	Multi-Modal Intelligent Traffic Signal System
MMITSS-UT	Multi-Modal Intelligent Traffic Signal System: Utah Version
NEMA	National Electrical Manufacturers Association

NHTSA	National Highway Traffic Safety Administration
NPRM	Notice of Proposed Rulemaking
OBE	On-Board Equipment
OBU	On-Board Unit
OTP	On-Time Performance
PATH	Partners for Advanced Transportation Technology
PDU	Portable DSRC Unit
RFID	Radio Frequency Identification
RSE	Roadside Equipment
RSU	Roadside Unit
SAE	Society for Automotive Engineering
SD	Standard Deviation
SE	Standard Error
SIRI	Service Interface for Real-Time Information
SPaT	Signal, Phase, and Timing Message
SRM	Signal Request Message
SSM	Signal Status Message
TCQSM	Transit Capacity and Quality of Service Manual, 3rd Edition
TSP	Transit Signal Priority
UDOT	Utah Department of Transportation
UI	User Interface
USDOT	United States Department of Transportation
UTA	Utah Transit Authority
UVX	Utah Valley Express
v/c	Volume-to-Capacity
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

EXECUTIVE SUMMARY

A sensitivity analysis was performed on the transit signal priority (TSP) requesting threshold to evaluate its impact on bus performance and general traffic. Two distinct bus routes were evaluated to determine the optimal requesting threshold that would balance the positive impacts on bus performance with the negative impacts on general traffic.

Route 217, a conventional bus route, and the Utah Valley Express (UVX), a bus rapid transit line, utilize a dedicated short-range communication (DSRC)-based TSP system as part of their normal, day-to-day operations. Using field-generated data exclusively, bus performance and general traffic were evaluated over a 7-month period from February through August 2019. Bus performance was evaluated through on-time performance (OTP), schedule deviation, travel time, and dwell time, while the traffic analysis was performed by evaluating split failure, change in green time, and the frequency at which TSP was served.

The requesting thresholds evaluated for Route 217 were 5, 3, 2, and 0 minutes, which stipulate how far behind schedule the bus must be in order to request TSP. For UVX, 5 minutes and 2 minutes, as well as ON and OFF scenarios were evaluated; ON meant the buses were always requesting regardless of how late they were, while OFF meant that no requests were made, and operations would be as if there were no TSP at all. A combination of observational and statistical analyses concluded with convincing evidence that OTP, schedule deviation, and travel time improve as the requesting threshold approaches zero with negligible impacts to general traffic.

For Route 217, as the requesting threshold changed from 3, to 2, to 0 minutes, OTP increased 2.0 and 2.5 percent, respectively, mean schedule deviation improved 15.9 and 20.9 seconds, respectively, and travel time decreased at 72 percent of timepoints. Meanwhile, negative impacts to traffic occurred if an increase in split failure was measured after TSP was served, a phenomenon observed a maximum of once every 43 minutes. For UVX, as the requesting threshold changed from 5, to 2 minutes, to ON, OTP increased 7.6 and 4.7 percent, respectively, mean schedule deviation improved 24.3 and 15.0 seconds, respectively, and travel time decreased between 72 percent of timepoints. Thus, it is concluded that under the TSP

system as implemented, bus performance improves as the requesting threshold approaches zero with inconsequential impacts to general traffic.

1.0 INTRODUCTION

1.1 Background

Transit Signal Priority (TSP) is an operational strategy that facilitates the movement of transit vehicles through traffic-signal controlled intersections. The purpose of TSP is to reduce travel time and the variability in travel time of transit vehicles (Smith et al. 2005). The Utah Department of Transportation (UDOT) and the Utah Transit Authority (UTA) have partnered together to implement TSP and evaluate its impacts on bus performance and general traffic. The TSP system uses dedicated short-range communications (DSRC) technology for UTA buses to communicate with the signal controllers at the intersections along two bus routes: Route 217 in Salt Lake County, which is a conventional bus route, and the Utah Valley Express (UVX) in Utah County, a bus rapid transit (BRT) route. The TSP software for this deployment was based on the Multi-Modal Intelligent Traffic Signal System (MMITSS) developed for the Connected Vehicle Pooled Fund Study. It was adapted to match Utah's needs and is referred to as MMITSS-UT (Leonard et al. 2019).

Preliminary analysis conducted by Avenue Consultants measured the impact of TSP on bus performance and general traffic for Route 217 over a five-month period from April through August 2018. The primary metric for evaluating bus performance was on-time performance (OTP), which is the percentage of instances when a bus departed a timepoint behind schedule, defined by UTA as being 5 minutes or more behind schedule. The primary metric for evaluating general traffic was split failure, which occurs if the green time of a phase is unable to meet the demand for a given cycle. Split failure was evaluated for the 10 minutes before and after TSP was served. The research conducted by Avenue Consultants determined that general traffic was negatively impacted at an intersection if the percentage of cycles experiencing split fail for any conflicting phase was greater in the 10 minutes post-TSP than in the 10 minutes pre-TSP. Avenue Consultants also determined that equipped buses capable of requesting TSP when they were 5 minutes late or more were on time 3 percent more often than non-equipped buses, with an improvement of 1 percent or more considered a meaningful improvement. When TSP was served, general traffic was negatively impacted about 20 percent of the time, which was considered a limited negative impact (Avenue Consultants 2018).

Having established that TSP benefits the buses with minimal negative impact to general traffic, the need for optimization came next. While a TSP system has many parameters that can be optimized, this research will aid in optimization through field data exclusively by performing a sensitivity analysis of the TSP requesting threshold parameter. The requesting threshold is the point at which TSP is requested and is defined by how far behind schedule the transit vehicle must be in order to request TSP. Research on the impact of changing the requesting threshold is extremely limited, but one study demonstrated that a 3-minute requesting threshold would produce more favorable results than a 5-minute requesting threshold to balance benefits for buses and negative impacts on general traffic (Alomari et al. 2016). The results of this research can improve the efficiency of TSP on Route 217 and UVX, help other agencies understand the impact of changing the requesting threshold for their TSP deployments, and help UDOT and UTA meet their goal of improving mobility through optimization and innovation (UDOT 2015; UTA 2018).

1.2 Objectives

The purpose of this research was to conduct a sensitivity analysis of the TSP requesting threshold on bus performance and impacts to general traffic for Route 217. A systematic evaluation of this element of the TSP system allows the identification of the requesting threshold at which TSP will be most efficient. Using these results, a similar experiment and analysis was conducted for UVX. The primary objective of this research regarded Route 217, so no traffic analysis was performed for UVX and this report does not evaluate UVX to the depth at which Route 217 is analyzed.

Prior to this study, a 5-minute threshold for requesting TSP was used, meaning that an equipped bus could request TSP when it was 5 minutes late or more. On Route 217, 5-, 3-, 2-, and 0-minute thresholds were evaluated. For UVX, 5- and 2-minute thresholds were evaluated, in addition to ON and OFF scenarios; ON meant the buses were always requesting TSP regardless of how late they were, while OFF meant that no requests were made and operations would be as if there were no TSP at all.

Only 10 equipped buses run on Route 217, so four portable DSRC units (PDUs) were developed to accelerate data collection as each threshold was tested. A major part of this research was deploying the PDUs each day, which significantly increased the amount of data collected. Every UVX bus was equipped, so PDU deployment was not necessary to evaluate this route.

1.3 Organization

This report is organized as follows:

- Chapter 1 includes the background pertaining to this TSP deployment, research objectives, and the organization of the report.
- Chapter 2 contains a literature review, which summarizes the state of practice regarding TSP and identifies some knowledge gaps that were discovered.
- Chapter 3 discusses the experiment methodology by reviewing the TSP system, the data collected during the study, the two routes that were evaluated, and shortcomings of the experiment methodology.
- Chapter 4 contains the analysis methodology, which covers how the observational and statistical analyses were performed on bus performance and general traffic, and how the analysis differs between Route 217 and UVX.
- Chapter 5 covers the results of the analysis and discusses the various metrics evaluated for Route 217 and UVX.
- Chapter 6 concludes the report by summarizing the results obtained, making recommendations, and outlining future research opportunities.
- Following the main chapters are references and appendices.

2.0 LITERATURE REVIEW

2.1 Overview

TSP is an operational strategy that facilitates the movement of transit vehicles through traffic-signal controlled intersections (Smith et al. 2005). Transit vehicle delay can occur for many reasons, such as roadway congestion, acceleration and deceleration time, passenger boarding and alighting, traffic signal operations, reentry, transit vehicle's ability to pass, stop location, roadway design, or exposure to general traffic (Ryus et al. 2013). TSP, however, is specifically aimed at reducing delay caused by signal operations. If there is little existing transit vehicle delay along a route due to signal operations, TSP will likely provide insignificant reductions in transit vehicle delay. It is estimated that delay caused by signal operations counts for 10 to 20 percent of overall bus travel times and 50 percent or more of all delay (Danaher 2010).

Researchers have found that TSP is most effective at signalized intersections under level of service (LOS) D and E conditions with a volume-to-capacity (v/c) ratio between 0.8 and 1.0 (Danaher 2010; Ryus et al. 2013). Furthermore, "there is limited benefit in implementing [TSP] under LOS A through C conditions as the roadway is relatively uncongested and neither major bus travel time nor reliability increases can be achieved" (Danaher et al. 2007).

This chapter reviews TSP strategies and treatments, TSP by type of route, the components of TSP systems, how TSP is evaluated, optimizing TSP operations, and findings from previous TSP evaluations.

2.2 Transit Signal Priority Strategies and Treatments

TSP operations consist of one or more control strategies that determine the requirements of the TSP system. A TSP system may have passive, active, or adaptive priority that each have their own specific treatments, which are the implementation of the strategy itself. Treatments can be applied system-wide, by intersection, or by vehicle, depending on the capabilities of the TSP system. Passive, active, and adaptive priority strategies and their respective treatments are discussed further in this section.

2.2.1 Passive Priority

Passive TSP strategies operate continuously, regardless of whether a transit vehicle is present, and do not require detection or a TSP request. Thus, passive priority treatments are simpler and optimize the system for transit without requiring requests from individual vehicles. Common treatments of passive strategies include fixed signal timing that favors the movement of a transit vehicle, a predetermined green extension that occurs when the transit vehicle is scheduled to pass through the intersection, or a dedicated right-of-way for transit vehicles (Danaher 2010; Danaher et al. 2007; Ryus et al. 2013; Smith et al. 2005).

The literature shows disagreement regarding the inclusion of dedicated lanes as a passive priority treatment. Some sources agree that a change in signal timing is required to constitute a TSP treatment (Danaher 2010; Danaher et al. 2007; Ryus et al. 2013; Smith et al. 2005), but the *Transit Capacity and Quality of Service Manual, 3rd Edition* (TCQSM) contradicts itself by stating that “TSP treatment is a minor adjustment to signal phase split times” while including “buses use special reserved lanes” in a list of passive priority treatments (Ryus et al. 2013). The determining factor should simply be whether the dedicated lane provides priority treatment at a signalized intersection.

2.2.2 Active Priority

Active priority strategies require transit vehicle detection and a means to request TSP. Active TSP strategies can be classified as either conditional or unconditional. Unconditional priority means that TSP is requested whenever the transit vehicle is detected and does not consider other criteria. Conditional priority, on the other hand, means that certain conditions need to be met before generating the request, such as the transit vehicle being late, satisfying a minimum occupancy requirement, or time since the last request was granted.

Conditional strategies thus require additional information which is usually provided from the transit vehicle’s on-board computer or the signal controller. The additional information required for conditional priority complicates TSP deployments, yet it is “most commonly accepted as an initial TSP application...assuming that buses would be issued priority only if they are behind schedule or have a certain number of persons on board the bus” (Danaher 2010).

Any number of conditions can be in place before a TSP request is generated. For example, Portland's transit agency, TriMet, conditions priority requests on three things: the bus is on-route, the doors are closed, and the bus is more than 30 seconds late (Figliozzi 2016). Los Angeles limits the maximum additional green time to 10 percent of the cycle length (Levinson et al. 2003), which follows the TCQSM findings that state, "the additional time given to or taken away from a particular phase is usually no more than 10 percent of the signal cycle" (Ryus et al. 2013).

The most common active priority treatments are discussed in further detail in the following subsections. They include early green (EG), green extension (GE), and transit-only signals (Smith et al. 2005).

2.2.2.1 Early Green

The EG treatment, sometimes referred to as red truncation, is an active strategy that shortens the amount of red time of previous cycles in order to permit the phase that serves the transit vehicle to turn green earlier than normal. The benefits of early green are minimal because the transit vehicle must still wait at the red light and only profits by the number of seconds earlier that the light turns green.

2.2.2.2 Green Extension

GE is a strategy that lengthens the amount of green time allocated to the phase that serves the transit vehicle. Transit vehicles that benefit from GE are saved from having to wait at a red light for the green time allocated to all other conflicting movements to take place. Thus, GE, when served, offers a relatively large delay reduction, but only to the small fraction of buses that arrive at an intersection near the end of green (Altun and Furth 2009).

2.2.2.3 Transit-Only Signal

When transit vehicles operate on the same roadway as non-transit vehicles, a transit-only signal facilitates the movement of the transit vehicle through the intersection by eliminating conflicting movements. A transit-only signal treatment is usually implemented through phase insertion, which occurs when the special transit-only phase is inserted within the normal signal sequence (Smith et al. 2005). Common examples of a transit-only signal through phase insertion

include the insertion of a bus-only left-turn phase or a through movement phase to permit bus queue jumping, which is illustrated in Figure 2-1.

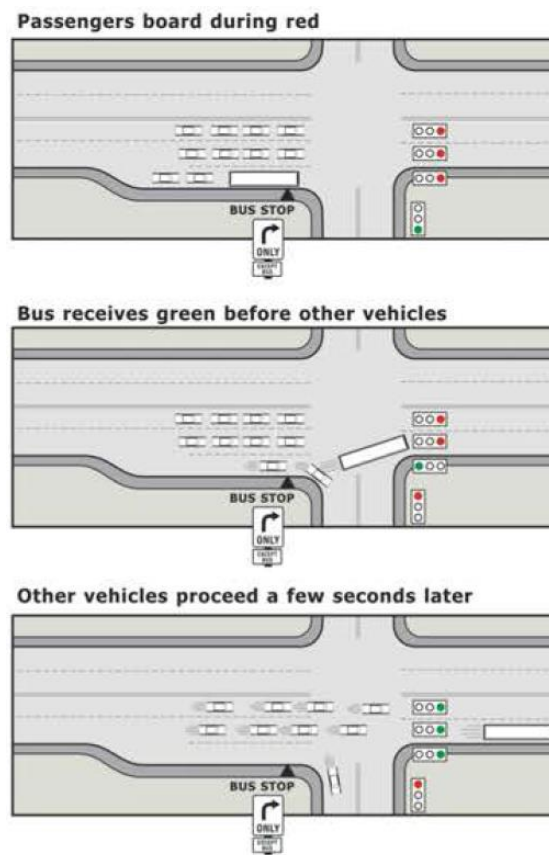


Figure 2-1: Transit-only signal for bus queue jumping (Ryus et al. 2013).

2.2.3 Adaptive Priority

Adaptive priority strategies are the most complex and grant TSP while “simultaneously trying to optimize given traffic performance criteria” (Smith et al. 2005). Adaptive, or real time, TSP strategies take into account both automobile and transit vehicle arrivals when considering granting TSP. Active priority treatments are then applied with the higher purpose of meeting specific measures of effectiveness (MOEs), such as minimizing person or vehicle delay. Thus, an adaptive strategy considers the trade-offs between transit and traffic vehicular delay or person delay and allows adjustments of signal timing based on prevailing conditions (Smith et al. 2005).

A TSP operation may have any number of treatments from different strategies. UVX, for instance, has dedicated bus lanes (passive), bus-only phases (active), EG (active), and GE (active), depending on the location of the bus and other circumstances, while Route 217 has EG and GE treatments only.

2.3 Transit Signal Priority by Type of Route

Commuter rail, light rail, BRT lines, and conventional bus routes are the most likely candidates for TSP implementation. While TSP should be applied to each of these types of transit differently in order to maximize efficiency, only TSP as it relates to BRT and conventional bus routes will be discussed in this report.

Conventional bus routes are typically part of the normal traffic stream, have many stops, and can have large amounts of delay from boarding, alighting, and re-entry to the traffic stream. BRT on the other hand, is a flexible, rubber-tired form of rapid transit that combines stations, vehicles, services, running ways, and intelligent transportation systems (ITS) elements into an integrated system. It is often referred to as light rail on wheels and offers greater flexibility over light rail with generally lower capital and operating costs (Levinson et al. 2003). The Federal Transit Administration (FTA) says that BRT is a “high-quality bus-based transit system that delivers fast and efficient service that may include dedicated lanes, busways, traffic signal priority, off-board fare collection, elevated platforms, and enhanced stations” (FTA 2017).

In 2003, *TCRP Report 90: Bus Rapid Transit* reported the results from a survey on the current state of practice for BRT lines and included responses from 26 cities for a total of 36 individual facilities. It reported that over 80 percent of the systems profiled have dedicated running ways, more than 75 percent provide frequent, all-day service, and about 67 percent have stations rather than stops (Levinson et al. 2003). Dedicated running ways make predicting the intersection arrival time of the bus much easier, which enables TSP to have a greater influence on minimizing bus delay caused by signalized intersections.

2.4 Transit Signal Priority System Components

Technological advancements have complicated an otherwise simple concept of providing transit vehicles with extra green time. This complication is not unwarranted, however, as the technological advancements are incorporated to make the TSP system as efficient as possible. These advancements place TSP operations at the forefront of implementing new technologies that are disrupting the transportation industry. This section will briefly discuss traffic signal controller hardware, software, transit vehicle detection systems, and communication systems, the four main components of a TSP system (Smith et al. 2005).

2.4.1 Controller Hardware

Traffic control devices have evolved from simple roadway signs directing travelers, to stop signs, to three-color traffic signals, to the traffic signals of today that can dynamically alter the amount of green time allocated to each phase based on current traffic volumes.

Most electromechanical traffic signal controllers of the past have been replaced with modern ones that enable customized software, more flexible intersection configurations, and communication with other controllers. Generally speaking, there are three types of modern signal controllers available today: National Electrical Manufacturers Association (NEMA) controllers, Type 170 controllers, and advanced transportation controllers (ATC) [specifically, Type 2070] (Gordon et al. 2005). NEMA controllers specify that software is included with the controller as firmware, but the specifications for Type 170 and 2070 controllers include hardware only. Type 2070 controllers have a more powerful processor and allow more advanced signal control than NEMA and Type 170 controllers (Smith et al. 2005).

Depending on the complexity of the TSP system, general traffic detection may be required as is the case for adaptive TSP strategies, which take into account both automobile and transit vehicle arrivals. Methods for detecting general traffic can typically be the same methods used for detecting transit vehicles and are discussed in more detail in Section 2.4.3.

2.4.2 Software

The software capabilities required for a TSP system vary considerably and are based on the complexity of the system. Many controller manufacturers offer TSP-capable software, but there are third-party TSP software packages that generally provide more flexibility (Smith et al. 2005), such as MMITSS, which is discussed in more detail in Section 3.3.

2.4.3 Transit Vehicle Detection

Detecting transit vehicles can be done through a variety of methods but must be able to differentiate between transit vehicles and general traffic. The most common transit vehicle detection systems utilize optical and inductive loop detectors (Danaher 2010; Ryus et al. 2013; Smith et al. 2005), but are limited in the information they can provide to a single identification code (Li et al. 2008). Other technologies used for detection are radio frequency identification (RFID) tags and global positioning system (GPS), although they are not as common. In 2013, the TCQSM stated, “the combination of GPS and wireless technology are emerging technologies for TSP application” (Ryus et al. 2013). This illustrates the delay that occurred in adopting GPS to improve traffic operations despite its widespread deployment for navigational purposes (Skog and Handel 2009).

Some vehicle detection systems are driver-activated and require the operator to manually turn the transmitter on and off as needed. This is not desirable because it increases the workload of the operator, can be left on when priority is not needed, and may not be appropriately activated due to human error. UTA buses on route 35M have a driver-activated optical detection system where the infrared emitter located on the bus is turned on manually by the operator when the bus begins service on the route (Zlatkovic et al. 2010). This avoids placing additional responsibility on the operator, but also causes TSP requests to be made when the bus is early.

The location at which transit vehicles are detected is an important element of a TSP system that should be given much consideration. It is important that transit vehicles be detected far enough from the signal they are approaching to allow enough time for the signal to adjust its timing as necessary. Advanced detection complements a TSP operation most effectively when transit vehicles have dedicated rights-of-way. When a transit vehicle with dedicated rights-of-

way passes the detection point, it is easy to determine the time at which it is expected to arrive at the next downstream intersection, thus facilitating the ability of the vehicle to achieve uninterrupted progress through intersections. If the transit vehicle is in the normal traffic stream, the travel time to the next downstream intersection will vary considerably based on current congestion levels. Furthermore, additional detection at the far end of the intersection should occur so that the signal can return to its normal operation as soon as possible (Smith et al. 2005).

2.4.4 Communication System

The TSP communication system is primarily the provision of detection and priority-request information to the local intersection and/or traffic management centers. A combination of technologies may be used to provide this information and frequently involves a physical connection between the receiver, signal controller, and traffic management center, such as fiber optic or copper cable (Smith et al. 2005). Transit vehicle detection and the communication system are closely intertwined and collectively determine the information about the transit vehicle that is available. Although not necessary for TSP functionality, an important part of the communication system is a backhaul network for data logging purposes. This subsection specifically discusses the communication system DSRC.

DSRC is a wireless communication technology that operates in the 5.9 GHz band with 75 MHz of spectrum, from 5.850-5.925 GHz (FCC 1999). This specific technology is being pursued by the United States Department of Transportation (USDOT) because of its low-latency and high-reliability performance that can be used to reduce fatalities while supporting close-range communication requirements (Perry et al. 2017). DSRC radios inside vehicles are called on-board units (OBUs) while those at intersections or along other segments of the road are called roadside units (RSUs). If a vehicle or intersection has an OBU or RSU it is considered “equipped.” Often, additional equipment is used along with the OBU and RSU so on-board equipment (OBE) and roadside equipment (RSE) can be used as well.

DSRC can be used to enable vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Collectively, these communications are referred to as vehicle-to-everything (V2X). If a cellular network is used rather than DSRC, cellular V2X (C-V2X) is the acronym used to describe the type of communication. The Society for Automotive Engineering (SAE) created a DSRC message-set dictionary standard, SAE J2735, that outlines the content and format for V2X messages to promote interoperability (SAE 2016). There are several kinds of messages, including basic safety message (BSM); signal request message (SRM); signal status message (SSM); signal, phase, and timing message (SPaT); and a map message providing information about the layout and geometry of an intersection (MAP). Table 2-1 contains a list of each DSRC message, the frequency at which they are sent, and the origin and destination of the message. The following subsections will discuss the purpose and select content of BSMs, SRMs, SSMs, and SPaT and MAP messages, as well as a brief history of DSRC.

Table 2-1: DSRC Messages (University of Arizona et al. 2016)

Message	Frequency (per second)	From	To
BSM	10	OBU	RSU, OBU
SRM	1	OBU	RSU
SSM	1	RSU	OBU
SPaT	10	RSU	OBU
MAP	1	RSU	OBU

2.4.4.1 Basic Safety Message

The BSM is the primary message set for safety applications and is the most important message for V2V and V2I communication. Although BSMs were developed for safety applications, the information they contain can be used in mobility, weather, and real-time situational awareness applications (Harding et al. 2014). BSMs are sent 10 times per second by equipped vehicles and are comprised of mandatory Part I data and optional Part II data, as shown in Table 2-2 and Table 2-3, respectively (SAE 2016).

Table 2-2: BSM Mandatory Part I Content (SAE 2016)

Content	Description and Data Elements
Message Count	This data element provides a sequence number used to determine if all messages are received.
Temporary ID	A randomized string that periodically changes to ensure the overall anonymity of the vehicle
Timestamp	Timestamp with millisecond granularity
Location	Includes latitude, longitude, elevation, and positional accuracy
Transmission State	States whether the transmission is in neutral, park, a forward gear, or a reverse gear
Vehicle Movement	Includes vehicle speed, heading, steering wheel angle, longitudinal, lateral, and vertical acceleration, and yaw rate
Brake Status	Describes the status of the brakes, ABS brakes, traction, and stability control systems
Vehicle Size	States the length and width of the vehicle

Table 2-3: BSM Optional Part II Content (SAE 2016)

Content	Description and Data Elements
Vehicle Event Flags	Permits specific safety-critical messages to be broadcasted, such as ABS brake activation, hard braking, airbag deployment, or loss of traction control
Travel Path	Provides a breadcrumb trail of vehicular and location data for the last 10 minutes and a prediction of future travel path
Exterior Lights	Conveys the status of the exterior lights, such as low- and high-beam headlights, turn signals, hazards, or parking light
Emergency Response	For an emergency response vehicle, this indicates the status of the sirens, light bar, response type, and the direction of travel this message applies to
Trailer Data	Allows vehicles pulling a trailer to describe the trailer, including dimensions, mass, and pivot angle
Supplemental Information	Broadly provides information about the vehicle and its operating conditions, such as vehicle class, whether it is disabled, average speed of oncoming traffic, and weather-related information

2.4.4.2 Signal Request Message

SRMs are sent by equipped vehicles to make a priority or preemption request at a signalized intersection. Granting this request typically results in providing extra green time in some form or another to the vehicle requesting priority. A personal automobile would not send an SRM, but rather transit vehicles, emergency response vehicles, or snowplows. Although the RSU will know the transit vehicle is present through the reception of BSMs, SRMs are requisite to grant TSP. Several data elements of the SRM require the OBE to first interpret the MAP

message and determine to which intersection the SRM applies and the lane ID and approach ID in which the transit vehicle is traveling. Table 2-4 describes the content of SRMs.

Table 2-4: SRM Content (SAE 2016)

Content	Description and Data Elements
Timestamp	Timestamp with millisecond granularity
Message Count	This data element provides a sequence number used to determine if all messages are received
Request Package	This contains the intersection ID, request type, request ID, and lane and approach IDs for the incoming vehicle
Vehicle Information	Describes the vehicle role and type, what level of priority the request is, and if it is a transit vehicle, its route, occupancy, and schedule adherence

2.4.4.3 Signal Status Message

SSMs are sent by an RSU to relate the current status of the signal and the collection of pending or active priority or preemption requests acknowledged by the controller (SAE 2016). It acts as a confirmation message indicating that the SRM was received and communicates to all approaching equipped vehicles that a request has been made. Table 2-5 describes the content of SSMs.

Table 2-5: SSM Content (SAE 2016)

Content	Description and Data Elements
Timestamp	Timestamp with millisecond granularity
Message Count	This data element provides a sequence number used to determine if all messages are received
SRM Content	Relays back much of the information received in the SRM
Priority Status	Indicates the general status of a prior request, such as requested, processing, watch for other traffic, granted, rejected, or unable to serve at this time

2.4.4.4 Signal, Phase, and Timing Message

The SPaT message is used to convey the current status of one or more signalized intersections and the state of signal phasing by sending the current movement state of each active phase. This message requires a corresponding MAP message to understand it properly (SAE 2016). Table 2-6 contains a description of select content contained within the SPaT message.

Table 2-6: SPaT Message Content (SAE 2016)

Content	Description and Data Elements
Timestamp	Timestamp with millisecond granularity
Message Count	This data element provides a sequence number used to determine if all messages are received
Intersection ID	Contains the intersection ID and a reference to the entity with authority over the intersection
Controller Status	Conveys whether the controller is off, in failure, controlled manually, has fixed or actuated timing, and if preemption or priority is being granted
Enabled Lanes	Conveys which lanes are open to travel, which may change depending on the time of day without requiring a new MAP message
Intersection Movements	Describes, for each movement, the state of signal phasing for that movement, timing details (start of phase, estimated end time, and time when phase will next occur), and an advisory speed
Connection Maneuvers	Describes, for each lane or group of lanes, queue length, available storage length, and if any pedestrians or bicycles are crossing the lane or group of lanes

2.4.4.5 MAP Message

The MAP message primarily conveys one or more intersection-lane geometry maps within a single message (SAE 2016). The creation of a MAP message with the level of detail outlined in SAE J2735 is an arduous and complex process. The USDOT has spent considerable effort designing a tool to create a MAP message from aerial imagery. This tool greatly facilitates the creation of MAP messages, but it is not very user friendly and only scratches the surface with the amount of detail that can be provided through its use (USDOT 2016). Table 2-7 contains a description of select content contained within the MAP message and Figure 2-2 contains an example of a graphically displayed MAP message from the California Connected Vehicle (CV) Test Bed.

Table 2-7: MAP Message Contents (SAE 2016)

Content	Description and Data Elements
Timestamp	Timestamp with millisecond granularity
Message Count	This data element provides a sequence number used to determine if all messages are received
Intersection ID	Contains the intersection ID and a reference to the entity with authority over the intersection
General Lane Information	Conveys the lane ID, the approach it belongs to, and its direction of travel

Table 2-7 (continued)

Lane Type	Describes whether the lane is a vehicle lane, bike lane, crosswalk, sidewalk, tracked lane (trains or trolleys), striping, or parking
Lane Sharing	Describes the type of traffic that may share this lane and its direction of travel, such as individual motor vehicles, buses, taxis, cyclists, trains, or pedestrians
Allowed Maneuvers	Lists allowed maneuvers from the lane, such as straight, left or right turn, left or right turn on red, U-turn, or proceed after making a full stop
Lane Nodes	A sequence of two or more nodes are used to denote the lane centerline, among other things
Node Attributes	Conveys node-specific information, such as stop line, merge or diverge point, curb is present, or hydrant is present
Segment Attributes	Conveys information relevant to the space between one or more nodes, such as merging abilities, presence of adjacent loading zones, parking spots, bike lanes, or transit stops, and pedestrian support attributes, such as the presence of curb intrusion, low curb, rumble strips, audible pedestrian signal, or a call request button



Figure 2-2: MAP message aerial view of Page Mill Rd. and El Camino Real in Mountain View, CA (California CV Test Bed et al. 2020).

2.4.4.6 History of Dedicated Short-Range Communication

Although DSRC has been around for decades, widespread deployment has been slow with relatively few deployments utilizing this technology. In 2014, the American Association of State Highway and Transportation Officials (AASHTO) reported that all CV infrastructure deployments to date have occurred in test beds or pilot projects (Wright et al. 2014). In fact, the TSP system in Utah deployed in November 2017 may be the first DSRC V2I deployment in the nation to function as a fully-operational, day-in-day-out part of the transportation system (Leonard et al. 2019). This slow adoption is seemingly due to the need for standards and technical experience as this technology matures.

To illustrate, in 1999 the Federal Communications Commission (FCC) allocated 75 MHz of spectrum for intelligent transportation services to improve highway safety and efficiency. In this announcement, the FCC stated that DSRC could be used for a variety of uses, such as “traffic light control, traffic monitoring, travelers’ alerts, automatic toll collection, traffic congestion detection, emergency-vehicle signal preemption of traffic lights, and electronic inspection of moving trucks through data transmissions with roadside inspection facilities” (FCC 1999).

Shortly thereafter, the Federal Highway Administration (FHWA) and the American Society for Testing and Materials (ASTM) began work on an ASTM-DSRC standard to promote interoperability as it is deployed. Years of researching DSRC took place before the FCC adopted a Notice of Proposed Rulemaking (NPRM) regarding DSRC service rules in November 2002, which, among other things, recommended the incorporation of the ASTM-DSRC standard. In June 2003 the ASTM-DSRC standard was approved for DSRC operations, and in December 2003 the FCC adopted updated rules for DSRC licensing and service (FCC 2004).

In 2005, the USDOT initiated a program to develop and test a DSRC vehicle infrastructure integration proof-of-concept with one of the primary objectives to validate Institute of Electrical and Electronics Engineers (IEEE) 1609 and 802.11p standards for V2I and V2V communications (Kandarpa et al. 2009). This led to the development of the SAE J2735 Recommended Practice in 2006, which specified standard message sets, data frames, and data elements for DSRC-based communication systems (SAE 2016). Simultaneously, the USDOT

Cooperative Intersection Collision Avoidance Systems initiative began and focused on developing DSRC V2I applications such as Signal Violation Warning, Stop Sign Assist, and Signalized Left-Turn Assist. These applications, and others, were tested at CV test beds in California and Michigan (FHWA 2007).

The Final Report for the vehicle infrastructure integration proof-of-concept was published in February 2009 and concluded, among other things, that “some refinements are required to the DSRC standards implemented for the [proof-of-concept] (e.g., SAE J2735, IEEE 1609.2, 1609.3, 1609.4, and IEEE 802.11p) based on lessons learned during the [proof-of-concept] testing” (Kandarpa et al. 2009). It is worth noting that SAE J2735 and the IEEE standards have undergone many revisions since their first draft, often for further refinement of several existing messages due to deployment experience (SAE 2016).

In July 2009, the National Highway Traffic Safety Administration (NHTSA) published their *Vehicle Safety Rulemaking and Research Priority Plan: 2009-2011* (NHTSA 2009), which only lists rulemaking and research areas that are priorities, listed V2V and V2I vehicle communication, and stated that they intend to make the next agency decision in 2013. From 2010 to 2012 research continued to address the technical issues that were discovered in the previous deployments related to interoperability, scalability, security, and data integrity of DSRC (Bettisworth et al. 2015).

From August 2012 to February 2014, the USDOT sponsored the largest to date real-world test of CV technology in Ann Arbor, Michigan with nearly 2,800 vehicles and 24 RSUs using updated equipment to meet current technology standards (Auer et al. 2016; Bettisworth et al. 2015). In the midst of this large-scale CV deployment, the FCC published an NPRM on April 10, 2013 indicating that they would revise their rules to permit the sharing of the DSRC-allocated spectrum to unlicensed devices so long as they operated on a secondary and non-interfering basis (Bettisworth et al. 2015).

Nearing the conclusion of the model CV deployment in Ann Arbor, NHTSA announced on February 3, 2014 that it would begin working on a regulatory proposal to require V2V devices in new vehicles in a future year (NHTSA 2014a). On August 20, 2014 NHTSA released an advanced notice of proposed rulemaking (ANPRM) proposing to establish a new Federal

Motor Vehicle Safety Standard to mandate DSRC V2V equipment on new light-duty vehicles beginning in 2020 (NHTSA 2014b).

In September 2015, the USDOT announced that New York City, Wyoming, and Tampa, FL will be the locations of the three CV pilot deployments. In December 2015, the USDOT launched the Smart City Challenge, ultimately won by Columbus, OH, to create an integrated, first-of-its-kind smart transportation system that would use data, applications, and technology to help people and goods move faster, cheaper, and more efficiently (ITSJPO 2020).

Finally, on January 12, 2017, nearly two and a half years after the ANPRM mandating DSRC on new light-duty vehicles, NHTSA publishes its NPRM proposing to mandate DSRC on all new light-duty vehicles in 2021 (NHTSA 2017). Shortly thereafter on January 30, 2017, President Donald Trump signed an Executive Order stating that “for every one new regulation issued, at least two prior regulations be identified for elimination” (Trump 2017). Some believe that this has caused NHTSA to refrain from moving forward on the DSRC mandate and makes it unlikely that they will for the duration of the current administration (Abuelsamid 2018).

Then, on December 12, 2019 and sparking considerable controversy, the FCC adopted an NPRM to make the lower 45 MHz of the band available for unlicensed operations and to permit C-V2X in the upper 20 MHz (FCC 2019). Nevertheless, CV deployments using the 5.9 GHz band continue to rise with current estimates as of January 2020 showing that there are 57 operational projects with 15,506 OBUs and 6,182 RSUs. An additional 40 projects are planned and will include 3,371 OBUs and 1,991 RSUs. In total, 97 projects across the nation are either planned or operational with 18,877 OBUs and 8,173 RSUs (Volpe 2020), a far cry from the 2014 AASHTO report that all connected-vehicle infrastructure deployments to that date had occurred in test beds.

2.5 Evaluating Transit Signal Priority Operations

Evaluation of a TSP operation can be performed on the transit vehicle, general traffic, or system itself, each with its own set of MOEs. This section examines MOEs related to bus performance and general traffic.

2.5.1 Bus Performance Measures of Effectiveness

When evaluating bus performance, the term “reliability” is frequently used. Reliability is broadly defined by the TCQSM simply as how often transit service is provided as promised or how well the transit service can keep to its schedule (Ryus et al. 2013). This is confusing because reliability based on schedule and headway are two different things and might be more applicable on one route versus another. Furthermore, if all transit vehicles are running equally late, reliability regarding headway would be perfect while schedule reliability would be poor. In lieu of the term reliability, which can be defined differently between agencies and from one route to the next, the specific metrics themselves will be referenced throughout this paper. Measuring adherence to the “promised service” is most commonly done through OTP and headway adherence (Ryus et al. 2013). In addition to OTP and headway adherence, schedule deviation and travel time are discussed in the following subsections.

2.5.1.1 On-Time Performance

The most widely used measure of reliability and schedule adherence in North America is OTP, the percent of schedule deviations that fall within a defined range. This defined range indicates when a transit vehicle is considered on time. Defining “on time” varies widely by agency and whether the perspective of the passenger or operator is considered. One minute early to 5 minutes late is a definition of on time that reflects passenger and operator perspectives and is common practice among many U.S. transit agencies (Ryus et al. 2013). Although the TCQSM provides this definition of on time, a widely adopted standard does not exist. Each transit agency independently sets their own on-time parameters. UTA, for example, defines on time as being between 0 and 5 minutes late for conventional bus routes and between 1 minute early and 2 minutes late for UVX.

OTP can be applied to any transit service that operates according to a published timetable, but it is best applied to routes with headways longer than 10 minutes. At shorter headways, passengers arrive at random, whereas at longer headways, passengers arrive based on the published schedule (Ryus et al. 2013).

2.5.1.2 Headway Adherence

Headway is a measurement of the time, or distance, between successive vehicles, measured from some common reference point on the vehicles (Smith et al. 2005). Thus, headway adherence measures how well transit vehicles maintain the scheduled frequency and is the best metric to measure the bunching effect. Measuring headway adherence is most appropriately applied to routes with headways of 10 minutes or less. The TCQSM recognizes that additional research is required to develop procedures to estimate the effect of TSP on headway adherence (Ryus et al. 2013).

2.5.1.3 Schedule Deviation

Another way to measure schedule adherence is by schedule deviation, or actual departure minus scheduled departure (Liao and Davis 2011; Ryus et al. 2013). Schedule deviation is an MOE that allows for more detailed analysis of schedule adherence that OTP will inherently overlook.

For instance, an agency may define on time as being 0 to 5 minutes behind schedule. If a bus is always 4 minutes behind schedule, its OTP would be 100 percent. TSP is implemented and this bus is now always 1 minute behind schedule. The OTP metric indicates that TSP did not improve schedule adherence—OTP was 100 percent for both scenarios—but the schedule deviation of the bus was reduced by 3 minutes, from 4 minutes to 1 minute behind schedule.

This is likely one of the main reasons that Portland’s TriMet has seen little impact on OTP as they have implemented and refined their TSP deployments over the years. While TriMet’s TSP has only marginally impacted OTP, smaller variations in travel time were realized as they changed the requesting threshold from 30 seconds late to 0 seconds late (Lutterman and Yand 2019).

2.5.1.4 Travel Time

Measuring bus performance based on travel time is an important metric to passengers and transit agencies alike. From the perspective of a passenger, travel time is an important value when evaluating different modes of transportation. Transit agencies rely on travel time to determine, for example, the block schedule for a bus or how many buses should be used for a

route. Travel time can be measured cumulatively (from the beginning of the route to the end) or incrementally (in between stops) and may or may not include dwell time at stops along the route.

2.5.2 General Traffic Measures of Effectiveness

General traffic references the vehicles on the road that are not transit vehicles. It is important to analyze the impact of TSP on general traffic to determine the extent of the negative impacts associated with providing transit vehicles with extra green time. The lack of post-deployment and non-simulated traffic analyses for TSP operations is perhaps the most astounding shortcoming discovered from the literature review. Instead of obtaining analytical results from actual field data and live deployments, the results of simulations are relied upon to draw conclusions about the impact of TSP. While there are exceptions, most studies that rely exclusively on field data use data from a short time period to draw their conclusions.

Evaluating the impact of a TSP operation on general traffic is a complex and data-intensive undertaking. It is common for model-based evaluations to take place before implementing TSP, but their complicated nature has consequently led few agencies to conduct evaluations post-implementation. *TCRP Synthesis 83: Bus and Rail Transit Preferential Treatments in Mixed Traffic* accordingly concluded that there is less documentation on the impact of TSP on general traffic and more of a focus on transit-travel time savings and improved OTP (Danaher 2010).

A 2004 survey of agencies and cities with TSP was conducted to provide a broad background of the current status of TSP systems in North America (Smith et al. 2005). When asked about measuring the success of their TSP operation, several agencies said that they lack the resources to perform such analyses while several others reported that the measure of success for their TSP programs was simply that it was implemented and operated effectively without any complaints from motorists.

In fact, conducting TSP evaluations on general traffic using field data exclusively is so unusual that *Transit Signal Priority: A Planning and Implementation Handbook* states, “two types of software are required to study TSP: simulation software to evaluate different transit

signal priority scenarios, and optimization software to optimize traffic signal operations” (Smith et al. 2005).

An important and recent advancement regarding traffic data collection is highlighted in the following comment made in the 2010 publication, *TCRP Synthesis 83: Bus and Rail Transit Preferential Treatments in Mixed Traffic*:

“The most accurate yet perhaps most time-consuming and expensive means to identify the impact of TSP is to conduct a ‘before’ and ‘after’ evaluation of changes in transit travel time and schedule adherence through field data collection. An on-board transit travel time and delay survey is the most appropriate tool to be applied. Measuring changes in general traffic delay associated with TSP is much more cumbersome because extensive staff is required to manually record vehicle delays in the field, videotape general traffic conditions, and then decipher changes in delay through video observations” (Danaher 2010).

With the advent of high-resolution traffic data, much of what was historically collected manually over the course of many hours can be collected and stored automatically as Automated Traffic Signal Performance Measures (ATSPM). Even with the development of ATSPM software and its widespread availability via the USDOT open source application development portal, very few studies currently analyze the general traffic for TSP operations outside of simulations.

2.6 Optimizing Transit Signal Priority Operations

TSP inherently involves a trade-off between positively impacting transit vehicles while negatively impacting general traffic. Thus, TSP optimization is performed to evaluate different scenarios in order to maximize the positive impacts of the operation while minimizing the negative ones. TSP optimization is performed by adjusting the parameters relating to various aspects of the TSP system and is done almost exclusively in a model under a simulated environment.

Simulations are preferred because they enable the system to be optimized prior to implementation and permit variables such as traffic volumes, cycle length, maximum allowable green time, or the requesting threshold to be easily changed and evaluated. Altering these parameters on a live system could be ineffective if not impossible, such as attempting to evaluate TSP for various traffic volumes or during different times of the year. Furthermore, simulations also facilitate performing a sensitivity analysis on a single variable while every other variable is held constant. In reality, the numerous variables affecting a TSP operation are rarely constant from day to day and can be vastly different from one hour to the next. The statistician George Box famously wrote, "...all models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind..." (Box and Draper 1987). Notwithstanding the differences between models and reality, analysis and optimization through simulations continue to be standard practice.

Table 2-8 summarizes several of the parameters commonly adjusted to optimize TSP. The most obvious parameter to adjust is the actual amount of extra green time that can be allocated to the bus when TSP is granted, which may vary by intersection or by how late the transit vehicle is running. The frequency of priority interruptions is important because an intersection may need some time to recover; that is, to clear queues built up during a priority

Table 2-8: TSP Optimization Parameters

System Component	Parameter
TSP Treatments	- Maximum and minimum allocable green time - Specify the conflicting phases from which green time is taken - Amount of green time taken per conflicting phase and allocated to transit vehicle
TSP Conditions	- Frequency of TSP granted (e.g., once every three cycles) - Requesting threshold (how far behind schedule before requesting) - Occupancy
Signal Timing	- Retiming - Adjusting cycle lengths - Improving coordination between signals
Physical Components	- Bus stop locations and frequency - Detector locations - Dedicated lane versus operating in mixed traffic

interruption or to return to a background cycle that enables progression. If interruptions occur too frequently, an intersection may not be able to recover, resulting in cycle failures (inability to clear queues) (Furth and Muller 2000).

2.7 Findings from Previous Transit Signal Priority Evaluations

The impact of TSP on bus performance has typically shown a reduction in travel times of 8 percent to 12 percent, while reduction in bus delay at signals has ranged from 6 percent to 80 percent. Meanwhile, the impact of TSP on general traffic has shown to be minimal and typically results in negligible increases in general traffic delay (Danaher et al. 2007; Ryus et al. 2013). Table 2-9 summarizes several reported TSP impacts for numerous North American TSP applications and shows that bus performance is rarely evaluated through schedule adherence with a focus on travel time, instead.

A study performed by the California Partners for Advanced Transportation Technology (PATH) program performed a field test to evaluate the impact of an adaptive TSP algorithm. A variety of MOEs were used to evaluate the 15 buses equipped with the needed technology and evaluated for 6 weeks with TSP turned off and 6 weeks with TSP turned on. This study found that bus delay at intersections was reduced by 19 percent for NB trips and 32 percent for SB trips with insignificant impacts on general traffic intersection delay. Notably, it was also discovered that TSP had relatively no impact on corridor-level travel time but did increase dwell time, as shown in Table 2-10. The increase in dwell time, the study reports, is likely attributed to a change in operator behavior in order to keep the bus on schedule and avoid early arrivals (Li et al. 2010).

Table 2-9: Summary of TSP Impacts (Ryus et al. 2013)

Location	Transit Mode	Number of Intersections	TSP Strategies	Benefit/Impact
Portland (Tualatin Valley Hwy)	Bus	10	EG, GE	- Bus travel time reduced 1.4-6.4% - Bus traffic signal delay reduced 20%
Portland (Powell Blvd)	Bus	4	EG, GE, queue jump	- Bus travel time reduced 5-8% - Bus person delay generally decreased - TSP impacts on traffic inconclusive
Seattle (Rainier Ave. at Genesee)	Bus	1	EG, GE	- Bus signal-related stops reduced 50% - Bus signal delay reduced 57% - Bus travel-time variability reduced 35% - Average person delay reduced 13.5% - Average vehicle delay did not change - Side-street impacts insignificant
Toronto	Streetcar	36	EG, GE	- Transit signal delay reduced 15-49% - One streetcar removed from service
Chicago (Cermak Rd)	Bus	15	EG, GE	- Bus travel time reduced 7-20% - Improved schedule reliability - Average vehicle delay reduced 1.5 s/veh - Side-street vehicle delay increased 8.2 s/veh - Fewer buses required to operate service - Improved passenger satisfaction
San Francisco	Light rail	16	EG, GE	- Transit signal delay reduced 6-25%
Minneapolis (Louisiana Ave.)	Bus	3	EG, GE, actuated transit phase	- Bus travel time reduced 0-38% - Average vehicle delay increased 4.4 s/veh - Skipping signal phases caused some motorist frustration
Los Angeles (Wilshire and Ventura Blvds)	Bus	211	EG, GE, actuated transit phase	- Bus travel time reduced 35% - Decrease in bus delay at traffic signals

Table 2-10: Field Test Results of Bus Travel Times Along El Camino Real in San Mateo, California (Li et al. 2010)

Direction	Without TSP (minutes)	With TSP (minutes)	Change		p-value of t-test
			Value	Percent	
NB	33.3	33.5	0.2	0.7%	0.5424
SB	31.2	31.6	0.4	1.2%	0.2733
NB (excluding dwell time)	27.2	25.2	-2.0	-7.3%	1.16E-11
SB (excluding dwell time)	26.3	23.6	-2.7	-10.4%	2.44E-19

Another study with striking resemblance to the analysis conducted by this research simulated International Drive in Orlando, Florida with a conventional bus route and a BRT bus route. The requesting thresholds evaluated were OFF (no TSP), 5 and 3 minutes (each conditioning the TSP request on the bus being more than 5 minutes and 3 minutes behind schedule, respectively), and ON (unconditional TSP where buses are always requesting). The results are quite linear and show that the corridor-level travel time decreases as the requesting threshold changes from OFF, to 5 minutes, to 3 minutes, and to ON. Averaging the EB and WB data and comparing each requesting threshold to the OFF threshold results in travel-time reductions for the conventional bus route of 10.5 percent (5-minute threshold), 13.3 percent (3-minute threshold), and 18.3 percent (ON). Similarly, the BRT bus route had travel-time reductions of 3.8 percent (5 minutes), 5.7 percent (3 minutes), and 13.6 percent (ON).

Traffic microsimulation software commonly reports on intersection queue length and vehicular delay, which is likely why most TSP evaluations that measure the impact of TSP on general traffic use these metrics. However, the literature review resulted in only four studies that evaluated TSP through split failure, which occurs when the duration of green for a movement, or split, at a signalized intersection is insufficient to serve the amount of demand present (Li et al. 2016). Of these four studies, two indicated that split failure was an MOE used in the evaluation but neither made any further mention of it in the report (Archibald 2017; Liu et al. 2006); one study used split fail to determine whether a general purpose lane could be converted to a

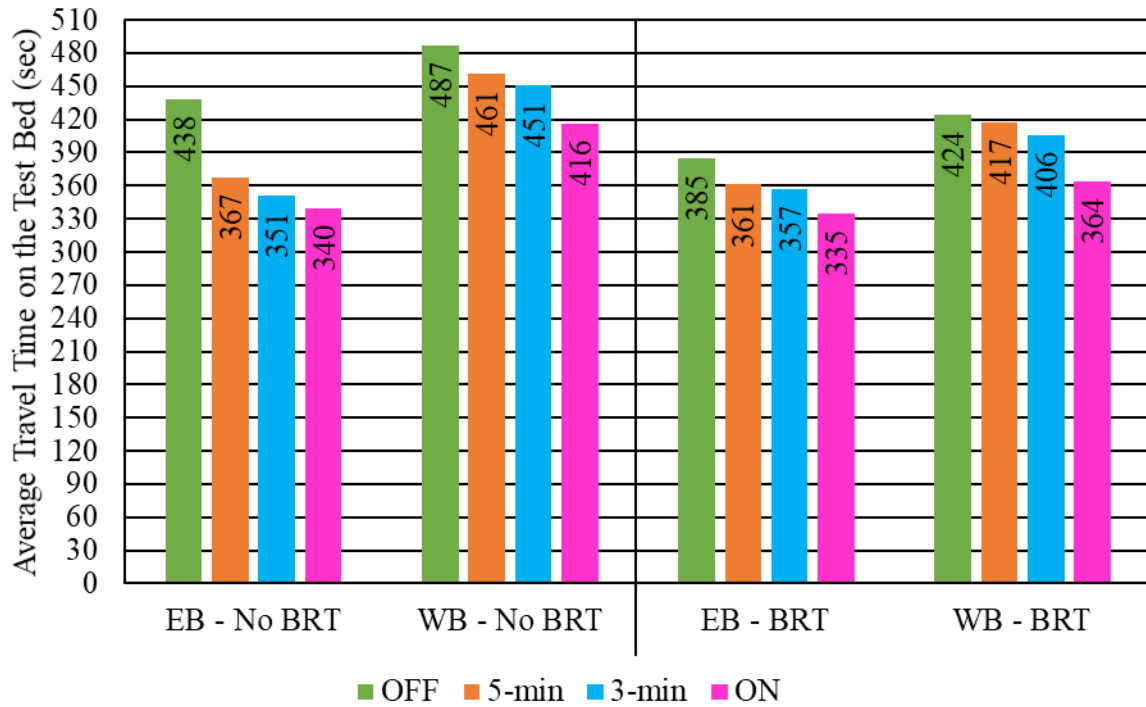


Figure 2-3: Simulation results of bus travel times at various requesting thresholds along the International Drive test bed in Orlando, FL (Alomari et al. 2016).

dedicated, bus-only lane (Muzyka 1974); and a study evaluating the South Snohomish Regional Transit System Priority system in the Seattle area concluded that after TSP was enabled, “the frequency of [split] failure slightly increased or decreased, depending on flow and signal control conditions” and did not result in a statistically significant change in the frequency of split failure (Zheng et al. 2009).

2.8 Chapter Summary

This chapter discussed the state of practice for TSP operations and highlights the differences between passive, active, and adaptive TSP. Much of the DSRC lexicon is covered, including V2X messages (BSM, SRM, SSM, SPaT, and MAP), the history of DSRC, and recent developments surrounding DSRC and the CV industry. Also addressed are failures and knowledge gaps for TSP evaluations, particularly regarding the abundance of simulation-based evaluations. When TSP is evaluated using field data, emphasis is placed almost exclusively on bus performance with considerably fewer studies addressing the impacts on general traffic.

3.0 EXPERIMENT METHODOLOGY

3.1 Overview

The DSRC-based TSP system in Utah is complex and allows for the communication and recording of data-rich information from multiple sources. Two transit routes, Route 217 and UVX, have this TSP system as part of its normal daily operations. Each route is unique in how the TSP system is set up with differences in the hardware and treatment parameters. This chapter covers the elements of the TSP system that are constant regardless of the route, including the controller software, TSP software, transit vehicle detection, the communication system, and data collection. Each route (Route 217 and UVX) is then discussed in detail highlighting differences surrounding the route itself, the controller and DSRC hardware, and how the research was conducted for each route.

3.2 Controller Software

The signalized intersections along Route 217 where RSUs are installed have a mixture of Intelight MaxTime controllers running MaxTime software and Econolite Cobalt controllers running ASC/3 software. A list of signalized intersections and the type of signal controller at each intersection is found in Table 3-5 in Section 3.7.3 for Route 217 and Table 3-10 in Section 3.8.3 for UVX.

Despite having TSP deployments all over the country for decades, different controllers handle requests for TSP via the SRM differently, which in some cases affects how TSP functions. One difference between the two controllers deals with the event code recorded by the high-resolution traffic signal controller, which is based on the enumerations established by the Indiana Department of Transportation and Purdue University (Sturdevant et al. 2012). As shown in Table 3-1, both controllers use the event code 112 and 115 for TSP check-in and checkout, respectively. However, when TSP is actually served, different event codes are recorded. For Intelight controllers, event code 517 is recorded when EG is served and 518 when GE is served. Econolite controllers record event codes 113 and 114 for those respective TSP treatments.

Table 3-1: Traffic Signal Event Codes for TSP Events

TSP Event	Intelight	Econolite
Check-In	112	112
EG	517	113
GE	518	114
Checkout	115	115

Another difference between the two controllers is the ability to appropriately handle the TSP checkout event, the purpose of which is to prevent excess allocation of green time to the phase serving the bus when the bus has already made it through the intersection. If, for example, 20 seconds of additional green time could be provided to the bus, it is important that the provision of this extra green time be terminated when the bus passes through the intersection so that the signal can return to normal operation as quickly as possible.

In this study, for example, the Econolite controllers, which operate using ASC/3 software, could not appropriately handle the TSP checkout event and always served the full amount possible. This was brought to the attention of Econolite and they have fixed this issue, but the solution was provided after the study concluded. Additional work is needed to implement and validate the solution.

3.3 Transit Signal Priority Software

Route 217 and UVX use MMITSS-UT, a modified version of the MMITSS application developed for the CV Pooled Fund Study by the University of Arizona and the University of California PATH Program (University of Arizona et al. 2016). Built into the software is a specific modification to enable conditional priority requests based on bus lateness, referred to as the requesting threshold. It is worth noting that the original TSP system was also conditioned upon satisfying a 20 percent occupancy criterion, the equivalent of 9 passengers or more (Leonard et al. 2019). The impact of changing the requesting threshold is the purpose of this study so the occupancy requirement was removed in order to isolate the effects of performing a sensitivity analysis on the requesting threshold only.

MMITSS-UT uses a binary “late” or “not late” status to decide whether to request TSP. When the requesting threshold changed, updates were sent to the mobile data computer (MDC) on the bus so that the late or not-late status output would be based on the new requesting threshold. This was problematic because UTA was unable to view the bus MDC settings to verify the lateness threshold assigned to each bus. Thus, data collection was suspended for an entire week to ensure that the updated requesting threshold was received by the buses, although there was still no way of confirming this without manually monitoring the bus and pulling data to see if requests were made according to the new requesting threshold only.

On June 10, 2019, approximately halfway through the data collection period, UTA completed the development of a methodology to verify the MDC settings, which resulted in the observation that some buses received the update immediately while others took up to 2 days for the update to occur. The differences on why this was the case were never determined with certainty. A surprising discovery in this process was that the entire UVX fleet was programmed with the wrong threshold. Instead of a 2-minute requesting threshold, a 5-minute threshold had been in effect for 2 months, a threshold that was not intended to be evaluated. Nevertheless, the 5-minute UVX data were not discarded and became one of the thresholds evaluated in this study. Although the requesting threshold affected bus status, the lateness threshold used for evaluating OTP remained unchanged throughout the study.

3.4 Transit Vehicle Detection

The TSP system for Route 217 and UVX utilizes GPS-based detection that originates from the DSRC OBU. This allows the bus to be detected without the need for any input or action by the bus operator. SAE J2735 specifies that the GPS coordinates are used with the MAP message to determine the lane of travel in which the bus is traveling so TSP is granted to the appropriate movement. However, this system does not have GPS correction and equipped buses are unable to get lane-level GPS accuracy. Instead, MMITSS-UT uses the heading data element to determine which phase will receive TSP. This works well for Route 217 because it runs almost entirely north and south. UVX, on the other hand, required the manual input of acceptable heading ranges for each intersection.

Figure 3-1 shows a screenshot of the DSRC OBE user interface (UI), which was used to track equipped buses and intersections. The data shown in Figure 3-1 reveals an instance of significant GPS drift. Each blue dot represents the GPS location of a single BSM. GPS drift of this magnitude was rare and was only observed when a bus was stationary at a timepoint or at a red light. Although no GPS correction was used and instances of 10-foot GPS drifting occurred, it was never observed that GPS drift prevented TSP from being called when it should have.



Figure 3-1: GPS drift.

SRMs are continuously generated when the schedule deviation of the bus exceeds the requesting threshold and are often received by multiple RSUs. MMITSS-UT only grants TSP at equipped intersections when the GPS coordinates of a requesting bus are detected within the

geofence of that intersection, which is defined by the MAP message. The size of the geofence varies widely by intersection and no standard guidance for MAP creation has been developed in the 13 years since SAE J2735 first published the DSRC standard for data elements contained in MAP messages.

The size of the geofence has a very strong influence on TSP operations and is something that should be heavily considered. If a bus is requesting TSP, the signal begins taking the green time from the conflicting movements to serve EG or extending the green time to serve GE (up to the defined maximums) as soon as the bus enters the geofence. If the geofence is too large or too small, the extra green time TSP provides the bus is inconsequential.

For example, Redwood Road and 1500 South is a simple T-intersection with no protected turning movements, so NB and SB movements occur simultaneously while EB traffic has a red light, and vice versa. The TSP logic at this intersection permits a maximum of 30 seconds to be served as GE. A SB bus approaching 1500 South enters the geofence 300 feet before the stop bar, as illustrated by the graphical display of MAP messages in Figure 3-2. In order to take full advantage of the 30 seconds the signal is able to extend green, the bus must enter the geofence immediately before the signal would turn yellow (if the bus arrives any later then it will have missed the chance to get GE but will get EG instead). Thus, instead of turning yellow, the bus arrives at just the right time and the GE begins. If the bus uses the entire 30 seconds of GE, this means that it would have traveled the 300 feet in 30 seconds for an average speed of 6.8 mph. For the 22,154 BSMs that were recorded by SB buses within this 300-foot approach during February of 2019, the average speed was 36.0 mph. This means that on average, only 5.7 seconds of the maximum 30 were utilized if the bus arrived at the perfect time. Any earlier and it would be fewer seconds of GE time provided to the bus. At 36.0 mph, the limits of the geofence for the SB approach need to be 1,560 feet. Conversely, if the geofence is too big, the bus would not make it to the light before the GE time is exhausted.



Figure 3-2: Route 217 MAP messages for 1500 South and 1700 South.

3.5 Communication System

DSRC is the means by which buses on Route 217 and UVX communicate with the signal controller and request TSP. DSRC OBUs are needed on each bus and DSRC RSUs are needed at each intersection, thereby making them “equipped” buses and intersections. In addition to the OBUs and RSUs, small, single-board Linux computers were needed on the bus and in the signal controller cabinet to run MMITSS-UT. BeagleBone Black industrial-grade Linux boards with a 1 GHz CPU and 4 GB of flash memory were selected because of their processing capability and performance in harsh working environments (Leonard et al. 2019).

Figure 3-3 shows an overview of the communication system for Route 217 and UVX. The MDC on the bus connects to the OBE processor to transmit the bus status of late or not late, which is only updated when the bus leaves a timepoint. If the status is “late,” the OBE starts generating and transmitting SRMs to be received by the RSE. Upon receiving the SRM, the RSE processor passes the message to the signal controller through a physical CAT5 connection which initiates the process of shortening the green time for the conflicting movements and allocating it to the bus movement. All DSRC data are recorded by the RSU, which does not store it, but sends it through UDOT’s fiber optic network and stores it on UDOT servers. Figure 3-4 charts the data elements that are part of each message and the data elements used to link one message with another.

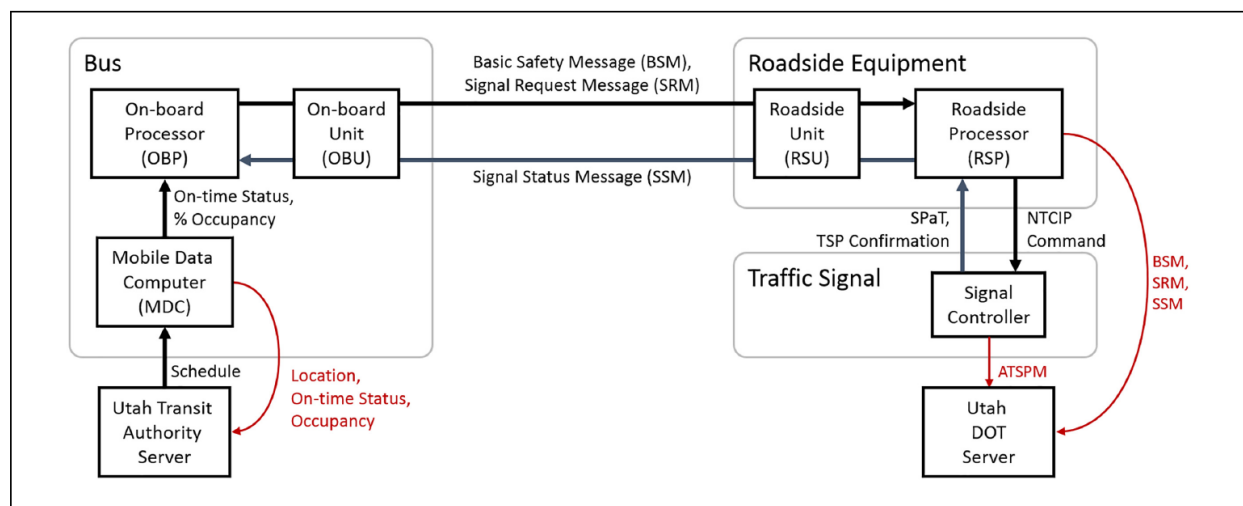


Figure 3-3: DSRC communication system flowchart (Leonard et al. 2019).

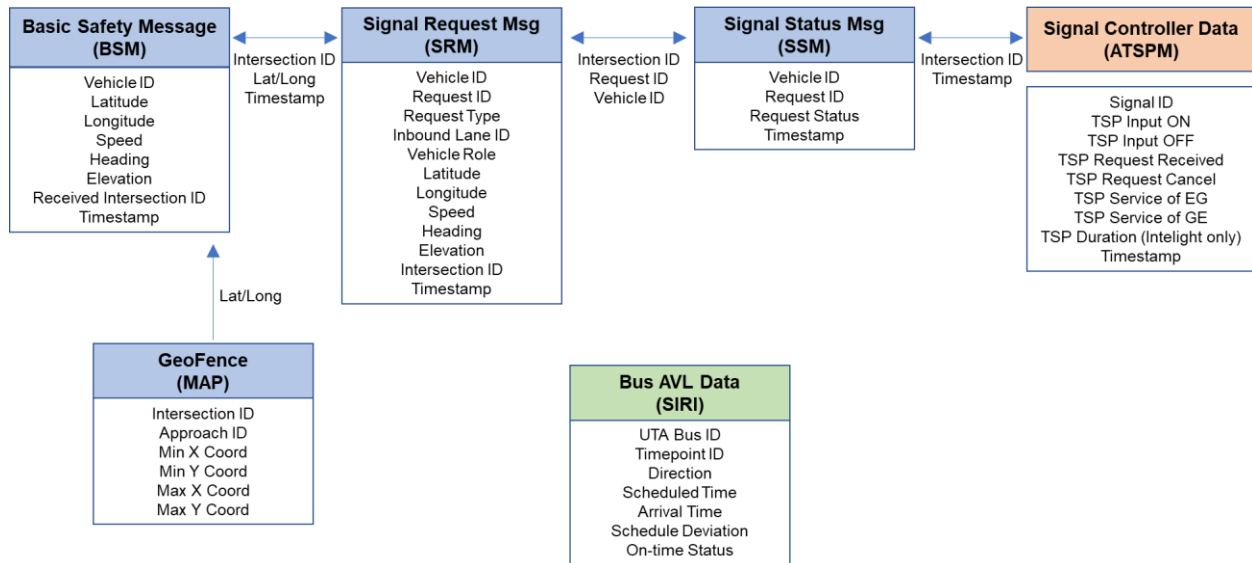


Figure 3-4: TSP messages and data elements.

3.6 Data Collection

Data collection was a primary focus of this research to ensure that enough data were collected at each requesting threshold analyzed. The data come from several sources, which are discussed in this section in greater detail, including UTA bus data, traffic data, and DSRC data.

3.6.1 Bus Data

Two separate and distinct datasets constitute the bus data that were used in this study: automatic vehicle location (AVL) data and bus stop data. The AVL and bus stop data are generated every 2 seconds by the MDC but are actually recorded less frequently; the AVL data are only recorded when a bus leaves the geofence of each timepoint and the bus stop data are recorded when a bus leaves the geofence of each bus stop, even if the bus did not actually stop. Both datasets are initially recorded on the MDC of each bus and then uploaded to UTA servers when the bus returns to the operations and maintenance facility (Avenue Consultants 2018). UTA measures OTP at several timepoints along a route and does so through its AVL data. Figure 3-6 shows a sample of the bus AVL data obtained from UTA and Table 3-2 describes the data elements contained therein. Figure 3-5 shows a sample of the bus stop data, from which the number of times a bus stopped to load or unload passengers was obtained. The bus stop data were used to create the statistical model that is discussed further in Section 4.3.2.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Date	Block	Trip	Vehicle	Route	Direction	Time Point	Schedule	Time	Status	Reliability	Dwell	Travel
2	02-06-2019	1053	09:23	12029	217	TO 7800 S TRAX	13-NRDWD	09:29	09:29:10	ON TIME	00:10	00:06	00:01:38
3	02-06-2020	1040	08:42	9010	217	TO ROSE PARK	BLNDCNTR	09:29	09:29:43	ON TIME	00:43	00:08	00:02:28
4	02-06-2021	1024	08:53	12028	217	TO 7800 S TRAX	RDWDJCTN	09:30	09:29:46	Early	-00:13	00:06	00:04:42
5	02-06-2022	1081	08:57	17043	217	TO ROSE PARK	RDWDJCTN	09:23	09:29:59	Late	06:59	00:40	00:03:30
6	02-06-2023	1066	08:38	17025	217	TO 7800 S TRAX	SLCCBRUN	09:26	09:30:16	ON TIME	04:16	01:12	00:02:38
7	02-06-2024	1012	09:12	17034	217	TO ROSE PARK	41-SRDWD	09:32	09:32:48	ON TIME	00:48	00:20	00:03:56
8	02-06-2025	1052	09:27	17027	217	TO ROSE PARK	70-SRDWD	09:32	09:32:51	ON TIME	00:51	00:14	00:05:34

Figure 3-6: Bus AVL data sample.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	DAY_OF_WK	BUS	BLOCK	ROUTE	TRIP	DIRECTION	STOP_SEQ_ID	STOP_NAME	TRIP_DATE	ACT_STOP_TIME	ACT_DEP_TIME	DWELL_TOT_MINS	PSGR_ON	PSGR_OFF	PSGR_LOAD	LATITUDE	LONGITUDE
2	1	17057	1000	217	408	0	1	117020 1300 N 1710 W	2/1/2019	4:08:26	4:08:33	0.12	1	0	0	1	40.79779 -111.93967
3	1	17057	1000	217	408	0	2	116046 1300 N 1788 W	2/1/2019	4:09:10	4:09:10	0	0	0	0	1	40.79776 -111.94185
4	1	17057	1000	217	408	0	3	116047 MORTON DR 1854 W	2/1/2019	4:09:46	4:09:46	0	0	0	0	1	40.79889 -111.94474
5	1	17057	1000	217	408	0	4	116048 MANDALAY RD 1396 N	2/1/2019	4:10:23	4:10:23	0	0	0	0	1	40.80094 -111.94554
6	1	17057	1000	217	408	0	5	116049 MANDALAY RD 1456 N	2/1/2019	4:10:59	4:10:59	0	0	0	0	1	40.80322 -111.94582
7	1	17057	1000	217	408	0	6	117061 MANDALAY RD 1560 N	2/1/2019	4:11:36	4:11:36	0	0	0	0	1	40.80536 -111.94419
8	1	17057	1000	217	408	0	7	117089 MORTON DR 1690 N	2/1/2019	4:12:12	4:12:12	0	0	0	0	1	40.80566 -111.94073

Figure 3-5: Bus stop data sample.

Upon receiving AVL data from UTA, a certain amount of “cleaning” needed to take place on the data. The AVL data did not always record properly, which resulted in either missing or partial records. For partial records, the record exists for a given bus at a specific timepoint, but the fields for departure time, status, reliability, dwell, and travel contain either “00:00:00,” “NO DATA,” or are empty. All partial records, approximately 1 percent of the data, were discarded and not included in the analysis.

Table 3-2: Data Elements for Bus AVL Data

Data Element	Format	Description
Date	mm-dd-yyyy	Day of the year on which the bus begins service
Block	Numerical	Number that references the daily operating schedule of the transit vehicle
Trip	hh:ss	Time of day the transit vehicle is scheduled to begin its trip
Vehicle	Numerical	Transit vehicle ID number
Route	String	Route name, usually a number
Direction	String	Trip direction, usually referencing the location or stop at the end of the route
Timepoint	String	Point on a route at which the departure of the transit vehicle is scheduled, the current timepoint
Schedule	hh:ss	Scheduled departure time
Departure Time	hh:mm:ss	Actual timepoint departure time
Status	String	Transit vehicle status (critical early, early, on time, late, or critical late)
Reliability	mm:ss	Schedule deviation, actual departure minus scheduled departure (positive if behind schedule)
Dwell	mm:ss	Length of time the transit vehicle spends at the timepoint
Travel	hh:mm:ss	Length of time spent traveling to the current timepoint once departing the previous timepoint

Furthermore, the data were not always recorded accurately, which sounds worse than it is. Normally, the AVL data are recorded accurately, but occasionally and for unknown reasons there are glitches or flaws in the recording algorithm. For instance, of the Route 217 records that

were not partial records, 79 suggested that the bus was more than 5 minutes early and 106 suggested that the bus was more than 20 minutes late, both of which are highly unlikely scenarios. The travel-time data field, which attempts to represent the time that had elapsed since the bus left the previous timepoint, was even worse. There were 485 records that suggested a travel time less than 30 seconds and 127 records suggested a travel time greater than 20 minutes. Perhaps defined a little more clearly, travel time as recorded represents the elapsed time since the bus left the previous timepoint that was recorded. If the record from the previous timepoint was missing, the recorded travel time would be the elapsed time since the bus left two timepoints prior. Nevertheless, it was not always clear why the data were recorded as they were, so outliers were removed from the data. The determination of outliers is discussed in detail for each route in Section 4.2.

3.6.2 Traffic Data

The traffic data were obtained through the UDOT ATSPM database, which records high-resolution traffic data from the signal controller every one-tenth of a second. ATSPM data are sent over the UDOT fiber optic network, to which each signal is connected, and stored on UDOT servers at the Traffic Operations Center. The data are recorded according to the *Indiana Traffic Signal Hi Resolution Data Logger Enumerations* and were used to evaluate general traffic. Only records containing event codes 1-11, 81, 82, 112-115, 171, 172, 176, 177, and 517 and 518 for Intelight controllers only, were used in this analysis, which replicate the Split Monitor and Purdue Split Failure reports developed by UDOT (Avenue Consultants 2018).

Table 3-3 contains a list of each event code used and its corresponding event descriptor, parameter, and description as found in the *Indiana Traffic Signal Hi Resolution Data Logger Enumerations*. The only exception is codes 517 and 518, which are not listed in the enumerations, but are used by Intelight to denote EG and GE TSP events, respectively. Figure 3-7 shows a sample of the controller event log data after it is downloaded from the ATSPM database.

Table 3-3: Event Codes Used to Analyze General Traffic (Sturdevant et al. 2012)

Event Code	Event Descriptor	Parameter	Description
1	Phase Begin Green	Phase # (1-16)	Set when either solid or flashing green indication has begun. Do not set repeatedly during flashing operation.
2	Phase Check	Phase # (1-16)	Set when a conflicting call is registered against the active phase. (Marks beginning of MAX timing)
3	Phase Min Complete	Phase # (1-16)	Set when phase min timer expires.
4	Phase Gap Out	Phase # (1-16)	Set when phase gaps out but may not necessarily occur upon phase termination. Event may be set multiple times within a single green under simultaneous gap out.
5	Phase Max Out	Phase # (1-16)	Set when phase MAX timer expires but may not necessarily occur upon phase termination due to last car passage or other features.
6	Phase Force Off	Phase # (1-16)	Set when phase force off is applied to the active green phase.
7	Phase Green Termination	Phase # (1-16)	Set when phase green indications are terminated into either yellow clearance or permissive (FYA) movement.
8	Phase Begin Yellow Clearance		Set when phase yellow indication becomes active and clearance timer begins.
9	Phase End Yellow Clearance		Set when phase yellow indication becomes inactive.
10	Phase Begin Red Clearance	Phase # (1-16)	Set only if phase red clearance is served. Set when red clearance timing begins.
11	Phase End Red Clearance	Phase # (1-16)	Set only if phase red clearance is served. Set when red clearance timing concludes. This may not necessarily coincide with completion of the phase, especially during clearance of trailing overlaps, red revert timing, red rest, or delay for other ring terminations.
81	Detector Off	DET Channel # (1-64)	Detector on and off events shall be triggered post any detector delay/extension processing.
82	Detector On	DET Channel # (1-64)	
112	TSP Check In	TSP # (1-10)	Set when request for priority is received.
113	TSP Adjustment to Early Green	TSP # (1-10)	Set when controller is adjusting active cycle to accommodate early service to TSP phases.

Table 3-3 (continued)

114	TSP Adjustment to Extend Green	TSP # (1-10)	Set when controller is adjusting active cycle to accommodate extended service to TSP phases.
115	TSP Checkout	TSP # (1-10)	Set when request for priority is retracted.
171	Test Input on		Cabinet test or special function input as defined by the local controller.
172	Test Input off		
176	Special Function Output on		Special function output as defined by the local controller.
177	Special Function Output off		Special function output as defined by the local controller.
517	TSP Adjustment to Early Green		
518	TSP Adjustment to Extend Green		

SignalID	Timestamp	EventCode	EventParam
7091	2/8/19 14:19:28.0	81	11
7091	2/8/19 14:19:28.6	82	11
7091	2/8/19 14:19:29.2	82	5
7091	2/8/19 14:19:29.5	81	5
7091	2/8/19 14:19:29.5	112	2
7091	2/8/19 14:19:29.6	114	2
7091	2/8/19 14:19:29.9	82	5

Figure 3-7: Controller event log data sample.

3.6.3 Dedicated Short-Range Communication Data

DSRC data includes BSMs, SRMs, and SSMs, which are transmitted by RSUs over the UDOT fiber optic network and stored on UDOT servers at the Traffic Operations Center. These data are used to evaluate the health of the TSP system by ensuring that each OBU is sending BSMs, each RSU in range is receiving BSMs, and that TSP requests are being made via SRMs.

Figure 3-8, Figure 3-9, and Figure 3-10 are screenshots of downloaded samples of BSM, SRM, and SSM records, respectively.

pkey	ReceivedAtIntersectionId	Timestamp	VehicleId	Latitude	Longitude	Elevation	Heading	Speed	DateCreated
245687450	7099	2/8/19 14:29:54	12030	40.720126	-111.938865	1275.6	0.6	29	2/8/19 14:29:58
245687443	7099	2/8/19 14:29:53	12030	40.7200022	-111.9388651	1275.6	359.675	32	2/8/19 14:29:53
245687397	7099	2/8/19 14:29:52	12030	40.7198996	-111.9388633	1275.6	359.563	36	2/8/19 14:29:52
245687388	7099	2/8/19 14:29:51	12030	40.7198235	-111.9388629	1275.5	0.6875	39	2/8/19 14:29:52
245687238	7099	2/8/19 14:29:50	12030	40.7197403	-111.9388636	1275.3	0.1875	43	2/8/19 14:29:52
245687214	7099	2/8/19 14:29:49	12030	40.7196069	-111.9388645	1275.2	0.1875	45	2/8/19 14:29:48
245687204	7099	2/8/19 14:29:48	12030	40.7195156	-111.9388647	1275.2	0.2625	45	2/8/19 14:29:48
245687105	7099	2/8/19 14:29:47	12030	40.7193764	-111.9388654	1275.3	0.55	46	2/8/19 14:29:47

Figure 3-8: BSM sample data.

pkey	Timestamp	IntersectionId	RequestId	RequestType	InboundLaneId	VehicleId	VehicleRole	Latitude	Longitude	Elevation	Heading	Speed
4554424	2/8/19 14:30:26	7099	4	cancel	5	12030	transit	40.7207166	-111.9388751	1279.3	1.25	31
4554423	2/8/19 14:30:25	7099	4	request-update	5	12030	transit	40.7206856	-111.9388755	1279.3	0.425	30
4554422	2/8/19 14:30:24	7099	4	request-update	5	12030	transit	40.7206125	-111.9388765	1279.3	359.425	27
4554420	2/8/19 14:30:23	7099	4	request-update	5	12030	transit	40.7205386	-111.9388782	1279.4	0.2375	21
4554415	2/8/19 14:30:22	7099	4	request-update	5	12030	transit	40.7204906	-111.9388787	1279.4	0.2625	16
4554414	2/8/19 14:30:21	7099	4	request-update	5	12030	transit	40.7204559	-111.9388775	1279.4	357.5625	11
4554413	2/8/19 14:30:20	7099	4	request-update	5	12030	transit	40.7204333	-111.9388764	1279.4	355.9375	7
4554412	2/8/19 14:30:19	7099	4	request-update	4	12030	transit	40.7204208	-111.9388755	1279.4	0.875	3
4554410	2/8/19 14:30:18	7099	4	request-update	4	12030	transit	40.7204165	-111.9388756	1279.4	0.875	0
4554405	2/8/19 14:30:17	7099	4	request-update	4	12030	transit	40.7204168	-111.9388753	1279.2	0.875	0
4554404	2/8/19 14:30:16	7099	4	request-update	4	12030	transit	40.7204172	-111.9388748	1279.1	0.875	0
4554403	2/8/19 14:30:15	7099	4	request-update	4	12030	transit	40.720418	-111.9388736	1278.9	0.875	0
4554402	2/8/19 14:30:14	7099	4	request-update	4	12030	transit	40.7204191	-111.9388723	1278.6	0.875	0
4554400	2/8/19 14:30:13	7099	4	request-update	4	12030	transit	40.7204195	-111.938871	1278.3	0.875	0
4554399	2/8/19 14:30:12	7099	4	request-update	4	12030	transit	40.72042	-111.9388695	1278	0.875	0
4554398	2/8/19 14:30:11	7099	4	request-update	4	12030	transit	40.7204205	-111.9388684	1277.7	0.875	0
4554397	2/8/19 14:30:10	7099	4	request-update	4	12030	transit	40.7204209	-111.9388671	1277.4	0.875	0
4554396	2/8/19 14:30:09	7099	4	request-update	4	12030	transit	40.7204213	-111.9388661	1277.1	0.875	0
4554432	2/8/19 14:30:08	7099	4	request-update	4	12030	transit	40.720421	-111.9388654	1276.9	0.875	0
4554434	2/8/19 14:30:07	7099	4	request-update	4	12030	transit	40.7204207	-111.9388645	1276.7	0.875	0
4554435	2/8/19 14:30:06	7099	4	request-update	4	12030	transit	40.7204204	-111.9388635	1276.6	0.875	0
4554436	2/8/19 14:30:05	7099	4	request-update	4	12030	transit	40.7204205	-111.9388624	1276.3	0.875	0
4554437	2/8/19 14:30:04	7099	4	request-update	4	12030	transit	40.7204204	-111.9388616	1276.1	0.875	0
4554442	2/8/19 14:30:03	7099	4	request-update	4	12030	transit	40.7204204	-111.9388613	1276	0.875	0
4554444	2/8/19 14:30:02	7099	4	request-update	4	12030	transit	40.7204184	-111.9388611	1275.9	0.875	2
4554445	2/8/19 14:30:01	7099	4	request-update	4	12030	transit	40.7204068	-111.9388609	1275.7	356.475	6
4554446	2/8/19 14:30:00	7099	4	request-update	4	12030	transit	40.7203849	-111.9388596	1275.6	358.5125	10
4554447	2/8/19 14:29:59	7099	4	request-update	4	12030	transit	40.7203592	-111.938859	1275.7	358.475	10
4554452	2/8/19 14:29:58	7099	4	request-update	4	12030	transit	40.7203313	-111.9388594	1275.6	0.8875	12
4554454	2/8/19 14:29:57	7099	4	request-update	4	12030	transit	40.7202935	-111.9388609	1275.6	1.4125	18
4554455	2/8/19 14:29:56	7099	4	request-update	4	12030	transit	40.7202296	-111.9388623	1275.7	1.45	23
4554456	2/8/19 14:29:55	7099	4	request-update	4	12030	transit	40.7201805	-111.9388639	1275.7	1.5	25
4554457	2/8/19 14:29:54	7099	4	request-update	4	12030	transit	40.7200965	-111.9388653	1275.6	0.4	30
4554462	2/8/19 14:29:53	7099	4	request-update	4	12030	transit	40.7200346	-111.9388655	1275.6	359.2875	31
4554464	2/8/19 14:29:52	7099	4	request-update	4	12030	transit	40.7199521	-111.9388642	1275.6	359.0875	34
4554465	2/8/19 14:29:51	7099	4	request-update	4	12030	transit	40.7198625	-111.9388629	1275.6	359.7375	38
4554466	2/8/19 14:29:50	7099	4	request-update	4	12030	transit	40.7197618	-111.9388636	1275.4	0.425	42
4554467	2/8/19 14:29:49	7099	4	request-update	4	12030	transit	40.719652	-111.9388642	1275.3	0.5	44
4554472	2/8/19 14:29:48	7099	4	request-update	4	12030	transit	40.7195386	-111.9388645	1275.2	0.225	46
4554482	2/8/19 14:29:47	7099	4	request	4	12030	transit	40.7194232	-111.9388649	1275.2	0.475	46

Figure 3-9: SRM sample data.

pkey	Timestamp	IntersectionId	SequenceNumber	RequestId	VehicleId	InboundLaneId	Status
4097635	2/8/19 14:30:25	7099	1	4	12030	5	processing
4097639	2/8/19 14:30:24	7099	1	4	12030	5	processing
4097621	2/8/19 14:30:23	7099	1	4	12030	5	processing
4097626	2/8/19 14:30:22	7099	1	4	12030	5	processing
4097599	2/8/19 14:30:21	7099	1	4	12030	5	processing
4097595	2/8/19 14:30:20	7099	1	4	12030	4	processing
4097606	2/8/19 14:30:19	7099	1	4	12030	4	processing
4097587	2/8/19 14:30:18	7099	1	4	12030	4	processing
4097578	2/8/19 14:30:17	7099	1	4	12030	4	processing
4097559	2/8/19 14:30:16	7099	1	4	12030	4	processing
4097570	2/8/19 14:30:15	7099	1	4	12030	4	processing
4097551	2/8/19 14:30:14	7099	1	4	12030	4	processing
4097547	2/8/19 14:30:13	7099	1	4	12030	4	processing
4097523	2/8/19 14:30:12	7099	1	4	12030	4	processing
4097534	2/8/19 14:30:11	7099	1	4	12030	4	processing
4097515	2/8/19 14:30:10	7099	1	4	12030	4	processing
4097527	2/8/19 14:30:09	7099	1	4	12030	4	processing
4097507	2/8/19 14:30:08	7099	1	4	12030	4	processing
4097498	2/8/19 14:30:07	7099	1	4	12030	4	processing
4097479	2/8/19 14:30:06	7099	1	4	12030	4	processing
4097490	2/8/19 14:30:05	7099	1	4	12030	4	processing
4097471	2/8/19 14:30:04	7099	1	4	12030	4	processing
4097467	2/8/19 14:30:03	7099	1	4	12030	4	processing
4097458	2/8/19 14:30:02	7099	1	4	12030	4	processing
4097439	2/8/19 14:30:01	7099	1	4	12030	4	processing
4097435	2/8/19 14:30:00	7099	1	4	12030	4	processing
4097447	2/8/19 14:29:59	7099	1	4	12030	4	processing
4097427	2/8/19 14:29:58	7099	1	4	12030	4	processing
4097418	2/8/19 14:29:57	7099	1	4	12030	4	processing
4097399	2/8/19 14:29:56	7099	1	4	12030	4	processing
4097410	2/8/19 14:29:55	7099	1	4	12030	4	processing
4097391	2/8/19 14:29:54	7099	1	4	12030	4	processing
4097387	2/8/19 14:29:53	7099	1	4	12030	4	processing
4097363	2/8/19 14:29:52	7099	1	4	12030	4	processing
4097360	2/8/19 14:29:51	7099	1	4	12030	4	processing
4097356	2/8/19 14:29:50	7099	1	4	12030	4	processing
4097367	2/8/19 14:29:49	7099	1	4	12030	4	processing
4097348	2/8/19 14:29:48	7099	1	4	12030	4	processing
4097347	2/8/19 14:29:47	7099	1	4	12030	4	processing

Figure 3-10: SSM sample data.

The SRM and SSM samples were chosen specifically to show the occurrence of a TSP event from start to finish. The SRM record at the bottom of Figure 3-9 shows that the initial request (RequestType = request) took place at 14:29:47 for a NB (Heading = 0.475 degrees) bus

(VehicleRole = transit) approaching the intersection of Redwood Road and 2320 South (IntersectionId = 7099) at 46 mph. Following the SRMs, it is observed that at 14:30:03 the bus has stopped at the light (speed = 0 mph) and does so for 16 seconds before it begins moving again at 14:30:19. The SRM record at the top of Figure 3-9 shows that RequestType = cancel, which indicates that the bus just crossed the stop bar and no longer needs TSP.

The SSM data in Figure 3-10, when compared with SRM data in Figure 3-9, show that the RSU at the same intersection of Redwood Road and 2320 South (IntersectionId = 7099) appropriately conveys that bus number 12030 (VehicleId = 12030) requested TSP (Status = processing) for the NB movement (InboundLaneId = 4). The RequestId and Timestamp fields can also be used to link the SRMs and SSMs to one another.

BSM and SPaT messages are sent every one-tenth of a second while SRM, SSM, and MAP messages are sent every one second. However, all messages are recorded as whole seconds, which means that there will be multiple BSM records with duplicate timestamps yet different GPS coordinates, speed, etc. as shown in Figure 3-11, a screenshot of downloaded BSM data.

pkey	ReceivedAtIntersectionId	Timestamp	VehicleId	Latitude	Longitude	Elevation	Heading	Speed
214374238	7091	2/4/19 23:34:37.0	12028	40.7586786	-111.9388861	1276.4	2.25	43
214374237	7091	2/4/19 23:34:37.0	12028	40.7586865	-111.9388858	1276.4	1.925	42
214374236	7091	2/4/19 23:34:37.0	12028	40.7586998	-111.9388852	1276.4	1.925	42
214374235	7091	2/4/19 23:34:37.0	12028	40.7587076	-111.9388848	1276.3	2.3	41
214374234	7091	2/4/19 23:34:37.0	12028	40.7587207	-111.9388841	1276.3	2.3	41
214374233	7091	2/4/19 23:34:37.0	12028	40.7587284	-111.9388838	1276.3	1.975	40
214374232	7091	2/4/19 23:34:37.0	12028	40.7587412	-111.9388832	1276.3	1.975	40
214374231	7091	2/4/19 23:34:37.0	12028	40.7587515	-111.9388827	1276.3	1.975	40
214374230	7091	2/4/19 23:34:37.0	12028	40.7587641	-111.9388822	1276.3	1.975	40
214374229	7091	2/4/19 23:34:37.0	12028	40.7587686	-111.9388821	1276.4	2	39

Figure 3-11: BSM records during a 1-second time interval.

3.7 Route 217: Redwood Road

The corridor utilized for data collection and analysis of a conventional bus route was Route 217 on Redwood Road in Salt Lake County. This section contains, for Route 217,

subsections discussing the route description, requesting thresholds, the TSP system, TSP strategies and treatments, bus operations, and PDU deployment.

3.7.1 Route 217 – Route Description

The 11-mile section of Redwood Road on which Route 217 runs carries annual average daily traffic (AADT) of 18,000 to 40,000 vehicles per day. It is a UDOT-owned corridor and crosses 30 signalized intersections and two light-rail crossings. The corridor is lined with a variety of land uses, including commercial and retail establishments, residential areas, and educational institutions.

Of the 30 signalized intersections along the equipped portion of the route, 24 have DSRC RSUs but only 22 are capable of serving TSP. The eight intersections that do not serve TSP are at freeway interchanges, continuous-flow intersections, and a light rail transit-grade crossing. A map of Route 217 is shown in Figure 3-12, which shows the signalized intersections along the route and whether they are equipped. Figure 3-12 also shows that the equipped portion of the corridor that has RSUs runs from 400 South to 8020 South.

3.7.2 Route 217 – Requesting Thresholds

The TSP system on Redwood Road was initially deployed in November 2017 with a 5-minute requesting threshold, which is also the threshold at which UTA considers Route 217 buses late. This consequently meant that only buses that were late were able to request TSP and benefit from it. One of the purposes of this research was to determine the impact on bus performance and general traffic of moving the requesting threshold closer to zero and allowing the bus to request TSP before it becomes late. The requesting thresholds analyzed in this study for Route 217 are 5, 3, 2, and 0 minutes behind schedule. Table 3-4 lists the requesting thresholds evaluated and the dates during which they were active.

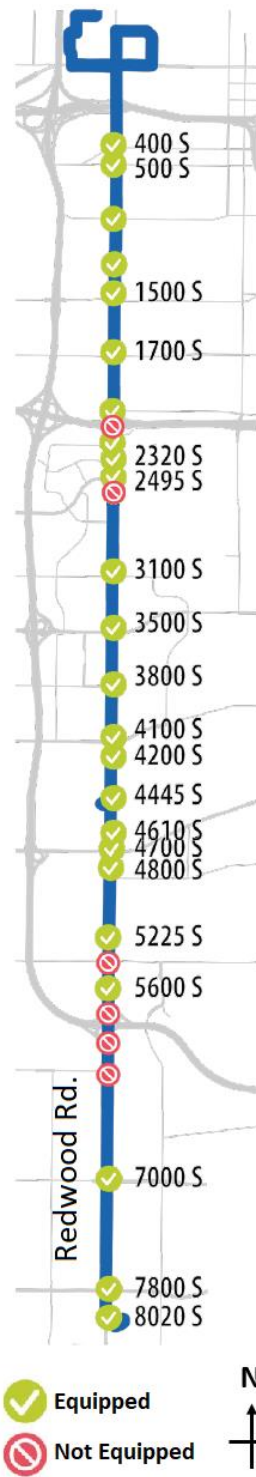


Figure 3-12: Route 217 map.

Table 3-4: Route 217 Requesting Thresholds

Requesting Threshold (minutes behind schedule)	Begin Date	End Date
5	2/4/19	3/22/19
3 ¹	4/1/19	5/10/19
2	5/20/19	6/28/19
0	7/1/19	8/2/19
3	8/8/19	8/31/19

¹ Excluded from analysis

Due to anomalies in the data from the first 3-minute requesting threshold, it was determined that the data should be excluded and collected again. One possible explanation for the anomalies was that a change day occurred on April 8, which had little effect on the schedule but put new operators on the route that were unfamiliar with it. UTA acknowledged that OTP is much lower in the first few weeks after a change day, which may explain the inconsistencies that were observed.

UTA developers were not certain whether the algorithm used on the bus MDC could appropriately handle a 0-minute requesting threshold. Therefore, it was decided to use a requesting threshold of 1 second, which was considered close enough to accurately reflect a 0-minute or 0-second requesting threshold. This meant that if a bus departed a timepoint exactly on schedule, 0 seconds behind schedule, it would not request TSP. This actually occurred 66 times out of the 10,620 records for equipped buses during the 0-minute threshold, or 0.006 percent of the time. The rarity of this event was thought to be negligible and did not prompt the exclusion of any data nor did it insist that a 0-second requesting threshold was needed.

3.7.3 Route 217 – Transit Signal Priority System

All equipped buses and each of the four PDUs were outfitted with Cohda OBUs, but there was a mixture of Lear and Cohda RSUs throughout the corridor. Table 3-5 lists all signalized intersections in the equipped portion of the corridor and which controller and RSU type is installed.

3.7.4 Route 217 – Strategies and Treatments

Route 217 had 22 equipped intersections capable of granting TSP but four of them had RSU hardware, software, or maintenance issues. These issues caused TSP to function intermittently throughout the study, so they were excluded from the analysis as consistent functionality was not maintained across the requesting thresholds being analyzed. The four intersections excluded were California Ave., 2320 South, 3100 South, and 5225 South, or Signal IDs 7093, 7099, 7101, and 7109, respectively. Table 3-6 shows the 18 intersections that were analyzed and the extra green time available due to EG and GE priority treatments.

3.7.5 Route 217 – Bus Operations

Route 217 operates on a timetable-based schedule, meaning that the scheduled departure time for each bus at each timepoint is published and adhered to. The holding policy for UTA is that early buses must wait at timepoints and then depart on time, a common practice for routes with a timetable-based schedule (Ryus et al. 2013). This holding strategy allows for slack to be added to the schedule to minimize the effect of unusual delay on OTP. Route 217 is in service on weekdays from 4:00 AM to 12:00 AM and generally operates at 15-minute headways between 6:00 AM and 7:00 PM. Otherwise, Route 217 buses are generally scheduled at 30-minute headways.

Figure 3-13 shows the published schedule for weekday service on Route 217 from April 8, 2019 to August 11, 2019, which resulted from the April 2019 change day. UTA refers to the date on which schedule changes may occur as a “change day,” with any changes made being effective from that day on until changed on a subsequent change day. The published schedule or the internal block schedule, which outlines the schedule for each bus throughout the day, can change on any of the three change days that UTA has each year in April, August, and December to refine published schedules and improve connections. Table 3-7 shows the effective date range for each change day that occurred in the time during which data were being collected for this research.

Table 3-5: Route 217 Controller and RSU by Intersection

Signal ID	Cross Street	Controller	RSU
7090	400 South	Intelight	Lear
7091	500 South	Intelight	Cohda
7092	Indiana Ave.	Econolite	Lear
7093	California Ave.	Econolite	Lear
7094	1500 South	Econolite	Cohda
7095	1700 South	Econolite	Lear
7096 ¹	2100 South	Intelight	Lear
7097	SR-201	Intelight	Not Equipped
7098 ¹	2200 South	Intelight	Lear
7099	2320 South	Intelight	Lear
7100	2495 South	Intelight	Cohda
7080	Research Way	Intelight	Not Equipped
7101	3100 South	Intelight	Cohda
7102	3500 South	Intelight	Lear
7103	3800 South	Intelight	Lear
7104	4100 South	Intelight	Lear
7105	4200 South	Intelight	Lear
7106	4445 South	Intelight	Lear
7605	4610 South	Intelight	Lear
7107	4700 South	Intelight	Lear
7108	4800 South	Intelight	Lear
7109	5225 South	Intelight	Lear
7110/7910	5400 South	Intelight	Not Equipped
7111	5600 South	Econolite	Lear
7112	I-215 S WB	Econolite	Not Equipped
7113	I-215 S EB	Econolite	Not Equipped
7114	6200 South	Intelight	Not Equipped
7115	7000 South	Econolite	Lear
7116	7800 South	Econolite	Lear
7229	8020 South	Econolite	Lear

¹ Equipped but TSP is not enabled

Table 3-6: Route 217 EG and GE Treatment Parameters

Signal ID	Cross Street	Controller	RSU	Maximum Extra Green Time From:	
				EG	GE
7090	400 South	Intelight	Lear	22	30
7091	500 South	Intelight	Cohda	10	30
7092	Indiana Ave.	Econolite	Lear	26	30
7094	1500 South	Econolite	Cohda	19	30
7095	1700 South	Econolite	Lear	18	30
7100	2495 South	Intelight	Cohda	23	23
7102	3500 South	Intelight	Lear	11	5
7103	3800 South	Intelight	Lear	20	15
7104	4100 South	Intelight	Lear	9	9
7105	4200 South	Intelight	Lear	15	15
7106	4445 South	Intelight	Lear	20	15
7605	4610 South	Intelight	Lear	26	11
7107	4700 South	Intelight	Lear	6	6
7108	4800 South	Intelight	Lear	27	17
7111	5600 South	Econolite	Lear	15	15
7115	7000 South	Econolite	Lear	16	10
7116	7800 South	Econolite	Lear	16	10
7229	8020 South	Econolite	Lear	20	30

UTA creates block schedules that normally consist of multiple routes, for efficiency of operations and to provide operators with variability throughout the day. This means that when a bus is assigned to a block consisting of trips on Route 217, it will also normally spend part of the day on other routes. For example, Table 3-8 contains the block schedule for block 1053 during the December 2018 change day. This shows that buses assigned to block 1053 ran three trips on Route 201, two trips on Route 218, and six trips on Route 217. When looking at the amount of time it took to run each trip, buses on block 1053 spent 18 percent of the time on Route 201, 12 percent on Route 218, and 70 percent on Route 217.

WEEKDAYS

To West Jordan City Center Station

To Rose Park

1300 N & 1754 W	1700 N & Morten Dr	1300 N & Redwood Rd	1950 W (Blind Center)	Power Station	1700 S & Redwood Rd	Redwood Junction Station	3500 S & Redwood Rd	4100 S & Redwood Rd	SLCC & Bruin Blvd	5400 S & Redwood Rd	6200 S & Redwood Rd	7000 S & Redwood Rd	West Jordan City Center Station
405a	408a	411a	419a	425a	436a	440a	444a	447a	450a	456a	459a	502a	511a
435	438	441	449	455	506	510	514	517	520	526	529	532	541
505	508	511	519	525	536	540	544	547	550	556	559	602	611
535	538	541	549	555	606	610	614	617	620	626	629	632	641
550	553	556	604	610	621	625	629	632	635	641	644	647	656
605	608	611	619	625	636	640	644	647	650	656	659	702	711
620	623	626	634	640	651	655	659	702	705	711	714	717	726
635	638	641	649	655	706	710	714	717	720	726	729	732	741
650	653	656	704	710	721	725	729	732	735	741	744	747	756
705	708	711	719	725	736	740	744	747	750	756	759	802	811
720	723	726	734	740	751	755	759	802	805	811	814	817	826
735	738	741	749	755	807	812	816	820	823	830	833	836	845
750	753	756	804	810	822	827	831	835	838	845	848	851	900
805	808	811	819	825	837	842	846	850	853	900	903	906	915
820	823	826	834	840	852	857	861	905	908	915	918	921	930
835	838	841	849	855	907	912	916	920	923	930	933	936	945
850	853	856	904	910	922	927	931	935	938	945	948	951	1000
905	908	911	919	925	937	942	946	950	953	1000	1003	1006	1015
920	923	926	934	940	952	957	1001	1005	1008	1015	1018	1021	1030
935	938	941	949	955	1007	1012	1016	1020	1023	1030	1033	1036	1045
950	953	956	1004	1010	1022	1027	1031	1035	1038	1045	1048	1051	1100
1005	1008	1011	1019	1026	1039	1046	1051	1055	1057	1103	1108	1112	1121
1020	1023	1026	1034	1041	1054	1101	1106	1110	1112	1118	1123	1127	1136
1035	1038	1041	1049	1056	1109	1116	1121	1125	1127	1133	1138	1142	1151
1050	1053	1056	1104	1111	1124	1131	1136	1140	1142	1148	1153	1157	1206p
1105	1108	1111	1119	1126	1139	1146	1151	1155	1157	1203p	1208p	1212p	1221
1120	1123	1126	1134	1141	1154	1201p	1206p	1210p	1212p	1218	1223	1227	1236
1135	1138	1141	1149	1156	1209p	1216	1221	1225	1227	1233	1238	1242	1251
1150	1153	1156	1204p	1211p	1224	1231	1236	1240	1242	1248	1253	1257	106
1205p	1208p	1211p	1219	1226	1239	1246	1251	1255	1257	103	108	112	121
1220	1223	1226	1234	1241	1254	101	106	110	112	118	123	127	136
1235	1238	1241	1249	1256	109	116	121	125	127	133	138	142	151
1250	1253	1256	104	111	124	131	136	140	142	148	153	157	206
105	108	111	119	126	139	146	151	155	157	203	208	212	221
120	123	126	134	142	156	202	207	211	214	222	227	231	240
135	138	141	149	157	211	217	222	226	229	237	242	246	255
150	153	156	204	212	226	232	237	241	244	252	257	301	310
205	208	211	219	227	241	247	252	256	259	307	312	316	325
220	223	226	234	242	256	302	307	311	314	322	327	331	340
235	238	241	249	257	311	317	322	326	329	337	342	346	355
250	253	256	304	312	326	332	337	341	344	352	357	401	410
305	308	311	319	327	341	347	352	356	359	407	412	416	425
320	323	326	334	342	356	402	407	411	414	422	427	431	440
335	338	341	349	357	411	417	422	426	429	437	442	446	455
350	353	356	404	412	426	432	437	441	444	452	457	501	510
405	408	411	419	425	439	447	455	500	503	515	527	534	543
420	423	426	434	440	454	502	510	515	518	530	542	549	558
435	438	441	449	455	509	517	525	530	533	543	553	556	605
450	453	456	504	510	524	532	540	545	548	558	608	611	620
505	508	511	519	526	538	545	551	556	558	605	610	613	622
520	523	526	534	541	553	600	606	611	613	620	625	628	637
535	538	541	549	556	608	615	621	626	628	635	640	643	652
550	553	556	604	611	623	630	636	641	643	650	655	658	707
605	608	611	619	626	638	645	651	656	658	705	710	713	722
635	638	641	649	656	708	715	721	726	728	735	740	743	752
705	708	711	719	726	738	745	751	756	758	805	810	813	822
735	738	741	749	756	808	815	821	826	828	835	840	843	852
805	808	811	819	826	838	845	851	856	858	905	910	913	922
835	838	841	849	856	908	915	921	926	928	935	940	943	952
935	938	941	949	956	1008	1015	1021	1026	1028	1035	1040	1043	1052
1035	1038	1041	1049	1056	1108	1115	1121	1126	1128	1135	1140	1143	1152

West Jordan City Center Station	7000 S & Redwood Rd	6200 S & Redwood Rd	5400 S & Redwood Rd	SLCC & Bruin Blvd	4100 S & Redwood Rd	3500 S & Redwood Rd	Redwood Junction Station	1700 S & Redwood Rd	Power Station	1950 W (Blind Center)	1300 N & 1754 W
444a	449a	451a	455a	459a	502a	506a	509a	514a	526a	529a	537a
514	519	521	525	529	532	536	539	544	556	559	607
544	549	551	555	559	602	606	609	614	626	629	637
614	619	621	625	629	632	636	639	644	656	659	707
627	632	635	639	643	647	650	653	659	711	714	722
642	647	650	654	658	702	705	708	714	726	729	737
657	702	705	709	713	717	720	723	729	741	744	752
710	715	718	722	726	730	733	736	742	754	757	805
727	732	735	739	743	747	750	753	759	811	814	822
742	747	750	754	758	802	805	808	814	826	829	837
757	802	805	809	813	817	820	823	829	841	844	852
812	817	820	824	828	832	835	838	844	856	859	907
827	832	835	839	843	847	850	853	859	911	914	922
842	847	850	854	858	902	905	908	914	926	929	937
857	902	905	909	913	917	920	923	929	941	944	952
912	917	920	924	928	932	935	938	944	956	959	1007
927	932	935	939	943	947	950	953	959	1011	1014	1022
937	942	945	950	955	959	1003	1007	1014	1026	1029	1037
952	957	1000	1005	1010	1014	1018	1022	1029	1041	1044	1052
1007	1012	1015	1020	1025	1029	1033	1037	1044	1056	1059	1107
1022	1027	1030	1035	1040	1044	1048	1052	1059	1111	1114	1122
1037	1042	1045	1050	1055	1059	1103	1107	1114	1126	1129	1137
1052	1057	1100	1105	1110	1114	1118	1122	1129	1141	1144	1152
1107	1112	1115	1120	1125	1129	1133	1137	1144	1156	1159	1207p
1121	1127	1129	1134	1140	1146	1149	1153	1159	1211p	1215p	1223
1136	1142	1144	1149	1155	1201p	1204p	1208p	1214p	1226	1230	1238
1151	1157	1159	1204p	1210p	1216	1219	1223	1229	1241	1245	1253
1206p	1212p	1214p	1219	1225	1231	1234	1238	1244	1256	100	108
1221	1227	1229	1234	1240	1246	1249	1253	1259	111	115	123
1236	1242	1244	1249	1255	101	104	108	114	126	130	138
1251	1257	1259	104	110	116	119	123	129	141	145	153
106	112	114	119	125	131	134	138	144	156	200	208
121	127	129	134	140	146	149	153	159	211	215	223
136	142	144	149	155	201	204	208	214	226	230	238
147	153	155	200	207	212	217	220	228	241	246	255
202	208	210	215	222	227	232	235	243	256	301	310
217	223	225	230	237	242	247	250	258	311	316	325
232	238	240	245	252	257	302	305	313	326	331	340
247	253	255	300	307	312	317	320	328	341	346	355
302	308	310	315	322	327	332	335	343	356	401	410
317	323	325	330	337	342	347	350	358	411	416	425
332	338	340	345	352	357	402	405	413	426	431	440
347	353	355	400	407	412	417	420	428	44		

Table 3-8: Block 1053 For December 2018 Change Day

Route	Direction	Start Time
201	NB	6:11
201	SB	6:47
218	NB	7:41
217	NB	8:12
217	SB	9:23
217	NB	10:52
217	SB	12:08
217	NB	13:36
217	SB	14:53
218	SB	16:18
201	NB	17:11

For the December 2018 change day, there were 19 blocks that contained Route 217 trips. Consequently, it was impossible to schedule one of the 10 equipped buses on every Route 217 trip. Scheduling the 10 equipped buses on blocks with the most Route 217 trips resulted in equipped buses running 62 percent of all Route 217 trips in a day. The addition of four PDUs essentially made it so that 14 buses were equipped, which meant that 82 percent of all Route 217 trips in a day could be serviced by equipped buses, a 32 percent increase in the amount of data that could be collected.

The requesting threshold changed throughout the study period, but the status threshold did not. Regardless of the requesting threshold being tested, “late” in terms of evaluating OTP was always considered 5 minutes or more behind schedule. The status thresholds for Route 217 are shown in Figure 3-14 with the open circle indicating up to but not including that value. For example, the status “on-time” includes 0 minutes behind schedule (closed circle) up to but not including 5 minutes behind schedule (open circle). UTA uses these status thresholds to assess routes or schedules that are experiencing extreme schedule deviations.

An interesting phenomenon was observed when buses departed timepoints; the bus would enter a sort of transition mode causing the MDC to output a schedule deviation of 0 seconds. This happened every time a bus departed a timepoint and updated to the actual schedule deviation within 2 seconds of leaving the geofence of the timepoint. This is not believed to have impacted TSP operations for equipped buses, but there was a scenario when PDU-equipped

buses under the automated TSP request mode were affected, which is discussed in subsection 3.7.6.3.

The majority of Route 217 bus stops and timepoints require the bus to stop in an active lane of traffic to load and unload passengers as shown by example in Figure 3-15, which is the SB 6200 South timepoint stop. This reduces variability by eliminating reentry delay but negatively impacts general traffic and bike lanes by impeding their movement while dwelling at the stop (Ryus et al. 2013). There are, however, several timepoints where the bus pulls outside the active lane of traffic in a dedicated shoulder area as shown in Figure 3-16, which is the NB 5400 South timepoint stop. While buses dwell at bus stops outside the active lane of traffic, traffic and cyclists may travel unimpeded, but bus performance variability increases as reentry delay is introduced.

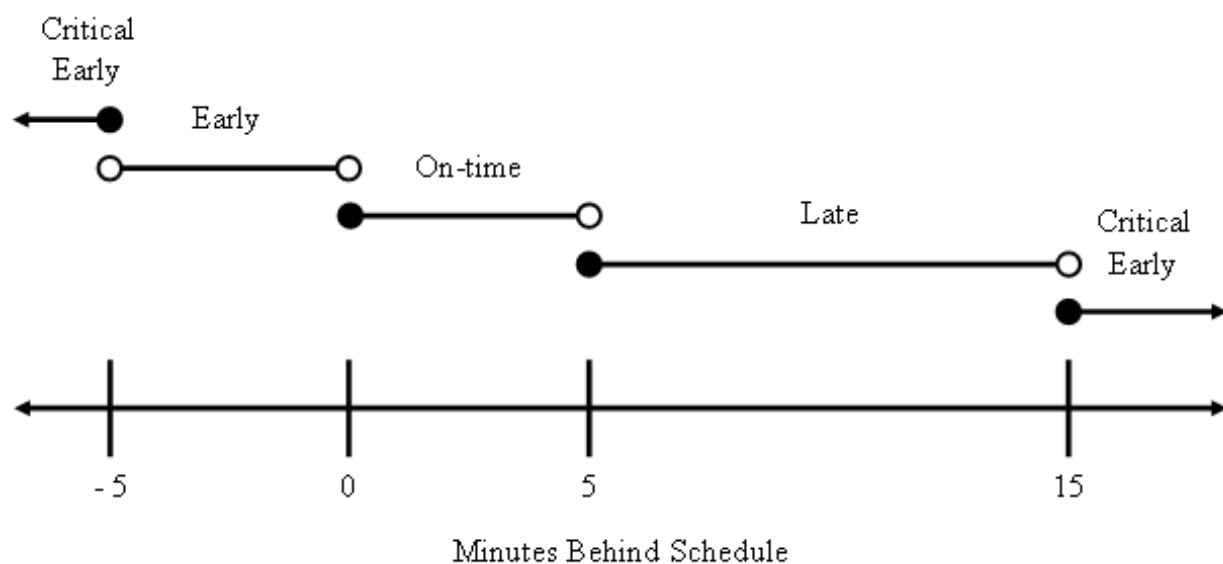


Figure 3-14: Route 217 status thresholds.



Figure 3-15: Route 217 bus stop within the active lane of traffic.

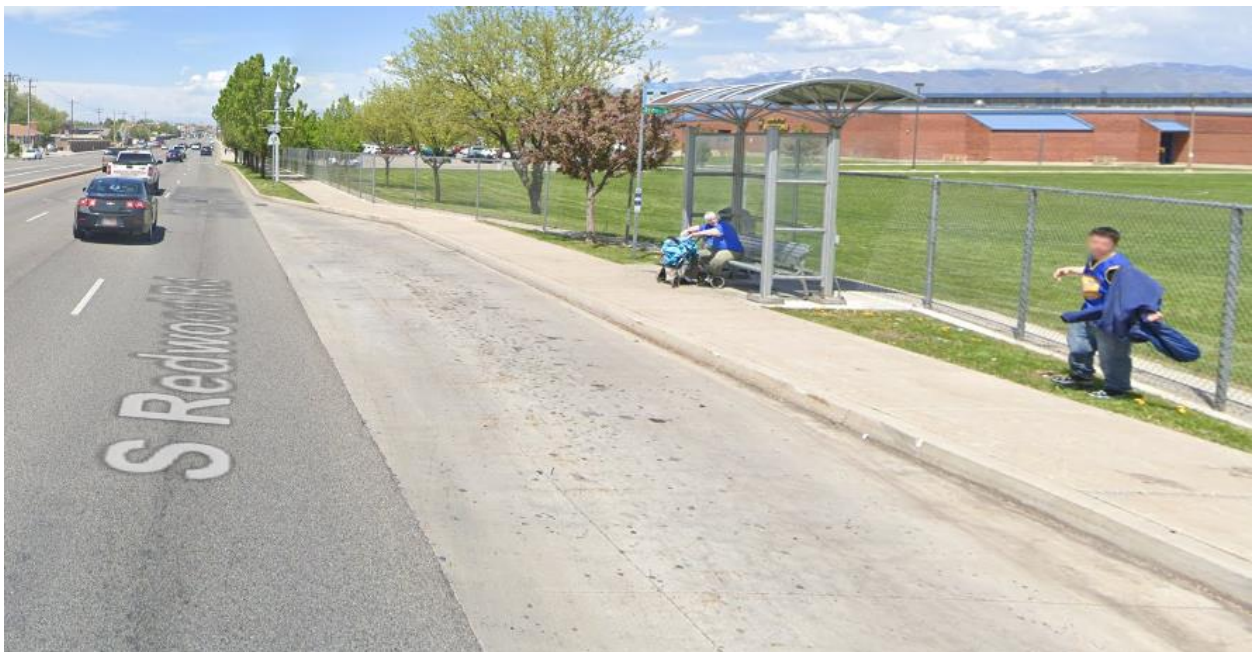


Figure 3-16: Route 217 bus stop outside the active lane of traffic.

3.7.6 Route 217 – Portable DSRC Unit Deployment

As noted in Section 3.7.5, four PDUs were created in addition to the 10 equipped buses to facilitate data collection. PDUs were placed on the dash of non-equipped buses, which enabled the bus to request TSP as if it were an equipped bus. Pictures of the internal components of the PDU and where it was placed on a bus are displayed in Figure 3-17. Figure 3-17(a) shows the internal components, including the green battery pack (top left), the processor (top right), and the cellular antenna (bottom left). Figure 3-17(b) shows the PDU placed on a bus with the DSRC antenna visible on top of the unit. The PDUs were developed by The Narwhal Group and were designed to mimic the performance of DSRC equipment on the equipped buses. The PDU deployment schedule, manual TSP request method, and automated TSP request method are discussed in the following subsections.

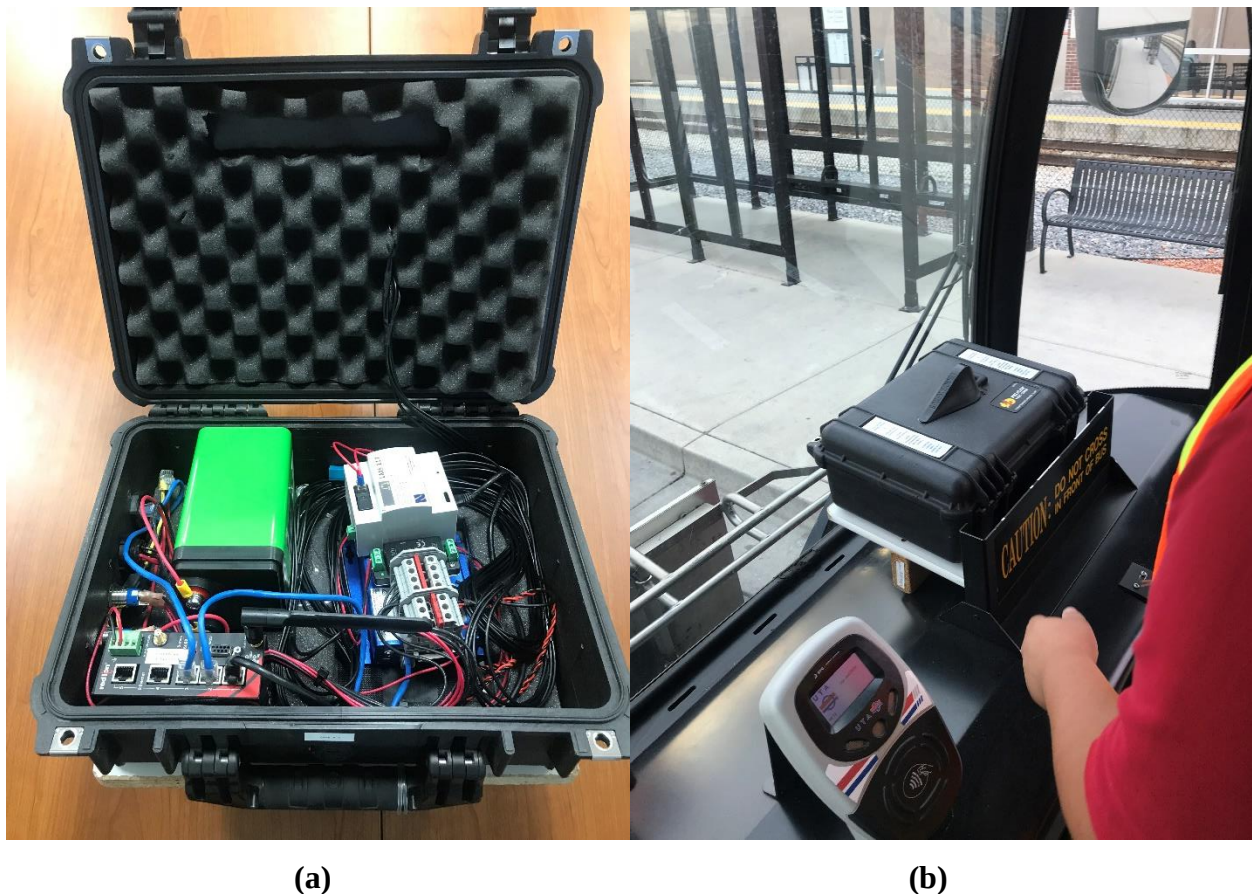


Figure 3-17: (a) PDU internal components and (b) PDU placed on bus.

3.7.6.1 Deployment Schedule

With each change day came a new block schedule and a new PDU deployment schedule. Considerable effort was needed to schedule which blocks would be serviced by equipped buses, non-equipped buses, and which blocks would have the PDUs. It was important to maximize the number of trips serviced by equipped buses. If all 14 equipped buses (10 equipped plus four PDUs) were placed on the blocks that serviced Route 217 the most, then 82 percent of all trips would be serviced by equipped buses. Conversely, if scheduled on the blocks that served Route 217 the least, then only 66 percent would be serviced by equipped buses.

Of equal importance when creating the deployment schedule was maximizing the number of early-morning or late-night trips serviced by non-equipped buses and maximizing the number of trips during peak hours serviced by equipped buses. This was done because the early-morning and late-night trips typically had high OTP, which would result in fewer requests for TSP and in many instances, the inability to measure the impact of changing the requesting threshold. For example, the 4:44 AM NB trip was on time 99.2 percent of the time throughout the entire study period. In other words, out of the 1,041 times a bus on this trip departed from a timepoint, there were only eight instances when it left more than 5 minutes behind schedule. Furthermore, UDOT and UTA were interested primarily in the peak periods when ridership and congestion were typically highest, so ensuring that trips during the AM and PM peaks were serviced by equipped buses was also a high priority when scheduling buses.

The PDUs were deployed Monday through Friday from March 15, 2019 through August 23, 2019 with few exceptions due to scheduling conflicts, school breaks, or changes to the requesting threshold. The PDUs were placed on the buses manually each morning and collected later in the day so that they could charge overnight. Figure 3-18 displays the block schedule established by the December 2018 change day and the deployment schedule that was utilized from February 4, 2019, when data collection began, through April 5, 2019, the last day data were collected prior to the April 2019 change day. As shown in the legend, red highlights indicate a trip serviced by an equipped bus, blue highlights indicate a PDU, and white means that a non-equipped bus serviced that trip. The green box, meanwhile, represents the deployment and collection windows for the PDUs.



Figure 3-18: Route 217 PDU deployment schedule from March 15, 2019 to April 7, 2019.

To deploy the PDUs, the research assistant deploying that day would first drive them to the West Jordan City Center Station, the southern end of Route 217, in preparation to place them on the NB buses scheduled to depart at 8:27, 9:12, 9:37, and 10:07. Then, after confirming that the non-equipped bus at the station was assigned to the desired block, the PDU was placed on the bus and the bus number, or vehicle ID, was recorded in the configuration tab of the DSRC OBE UI from any device capable of accessing the web, as shown in Figure 3-19. The vehicle ID, 17030 in this example, was then incorporated into the BSMs and SRMs that the PDU would transmit through the day. The “Late Threshold” field was the only other field that was changed during this study, which was where the requesting threshold in seconds was recorded. The research assistant would then wait at the station for the next three buses that were scheduled to the desired blocks and deploy the last three PDUs, which would conclude deployment.

Vehicle	Maps	Config
Vehicle Info		
Role:	transit	
Id:	17030	
Name:	Case #2	
Message Operations		
DSRC manufacturer:	Cohda	
Operations		
TSP algorithm:	uta-portable	
Late threshold:	300	
Age threshold:	180	
API URL:	http://api.rideuta.com/vehicleinfoapi/api/info/	
API port:	6150	
API interval:	10	
		Cancel Save

Figure 3-19: Configuration tab of the DSRC OBE UI.

Later in the day, a research assistant would return to West Jordan City Center Station and collect the units one by one as the SB trips beginning at 15:35, 16:20, 17:05, and 17:20 would come in. This process was continued until May 1, 2019 when arrangements were made with UTA to pick them up even later in the day all at once at the Meadowbrook maintenance garage

where the buses park at the end of the night. This not only saved time, but it also allowed for extended data collection.

3.7.6.2 *Manual Priority Request Method*

Initially, the PDU software was not fully developed so each of the four buses with a PDU on board was monitored remotely in order to manually activate TSP requests once the lateness of the bus exceeded the requesting threshold that was being tested at the time. Several years ago, UTA developed a web application programming interface (API) called SIRI (Service Interface for Real-Time Information) that provides the GPS location of each bus in the fleet with a 10-second refresh rate. This SIRI feed enables a UTA-hosted vehicle locator site to track the location of each bus, which was used in this research to specifically track the buses with a PDU on board and compare it to the published schedule. If the bus was running later than the requesting threshold being tested, then request mode for the corresponding PDU was turned on remotely via the DSRC OBE UI. By so doing, the PDU would begin sending out SRM messages once a second to request TSP. Just like normally equipped buses, the PDU would request TSP as long as its schedule deviation was greater than the requesting threshold being tested at that time.

While one research assistant was in the field deploying PDUs, a second research assistant was located in the Brigham Young University (BYU) Transportation Lab to monitor them. Figure 3-20 shows what the monitoring station looked like in the Transportation Lab when the PDUs were deployed under the manual method. Each of the two main screens was split in fourths to monitor the PDUs. The left screen contains the UTA vehicle locator websites and the middle screen contains the DSRC OBE UI websites for the four PDUs. The third screen on the right was used to display the time, which facilitated the live monitoring of schedule deviation. Figure 3-21 shows a screenshot of the UTA-hosted vehicle locator website. The interface automatically centers the map on buses that are selected and changes the icon to yellow if the bus is late (5 minutes or more behind schedule). If the bus is ever critical late, the icon turns red.

Figure 3-22 shows a portion of the PDU monitoring worksheet, which continues for several pages and contains 220 timepoint records. At the top of the page, the bus numbers on which each PDU is placed are recorded, as well as the name of the research assistant monitoring the data and the date. The “Sched” column indicates the time that the bus is scheduled to depart

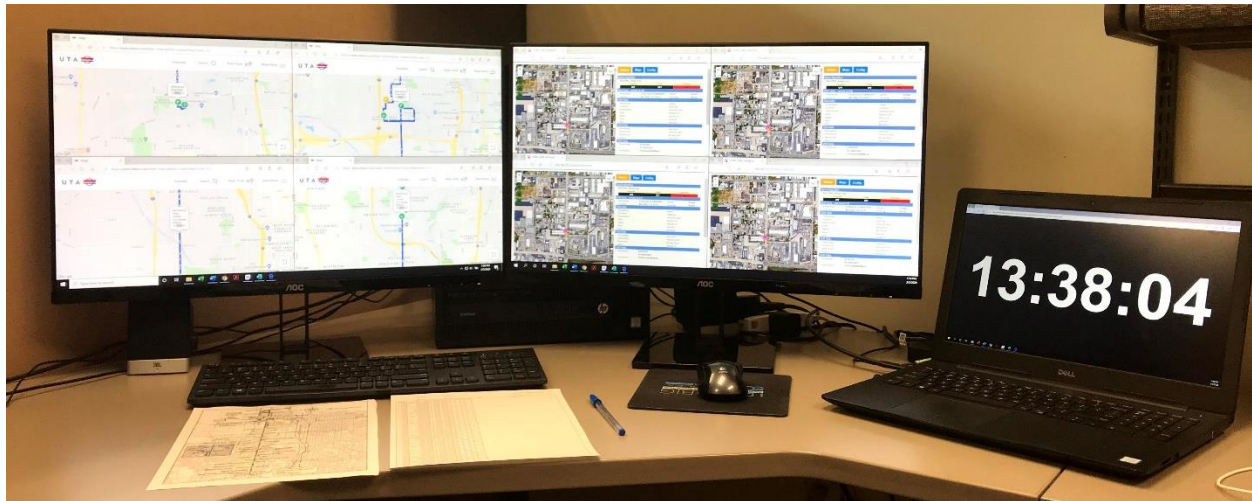


Figure 3-20: Setup for monitoring PDU deployment via the manual method.

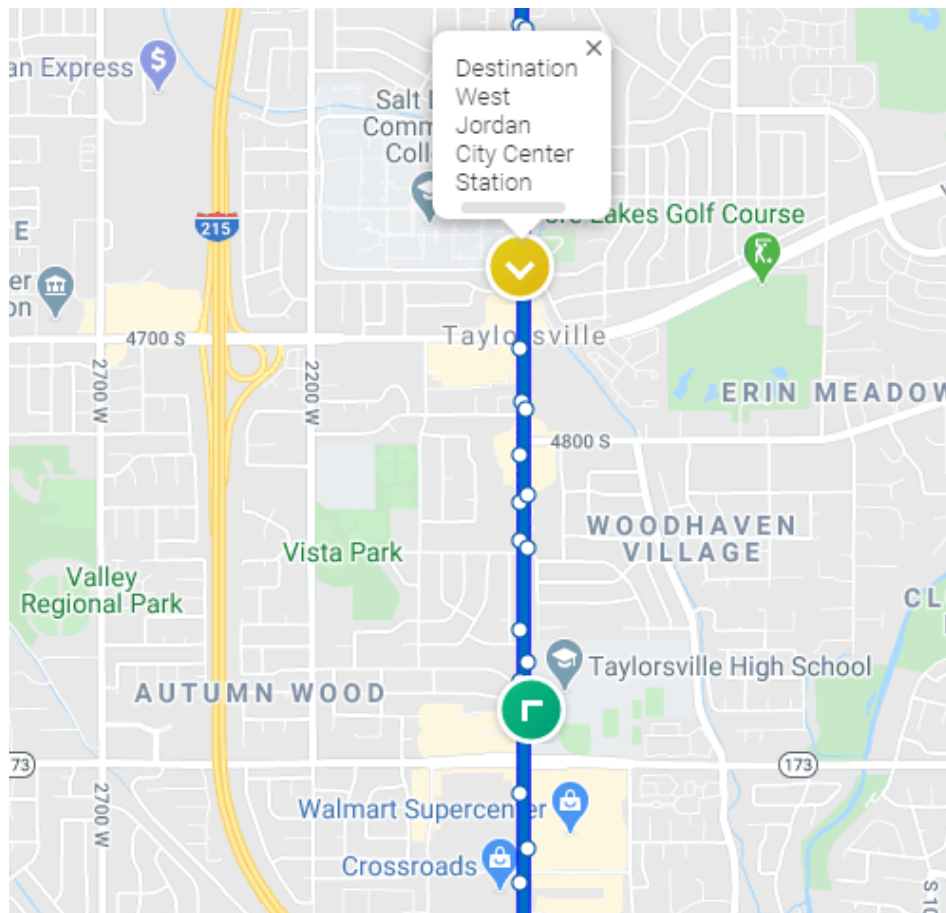


Figure 3-21: UTA-hosted vehicle locator website.

the stop, or timepoint, on that same row. The “Late” column indicates the time after which the bus is considered late. In this example, buses are being monitored at the 5-minute threshold, hence the “Late” column is 5 minutes greater than the “Sched” column. The “#” column represents the PDU number, which made it crucial that the PDUs were deployed in the right order to maintain the integrity of the monitoring sheet.

#1 BUS _____ #2 BUS _____

#3 BUS _____ #4 BUS _____

Name _____ Date _____

Block	Stop	Dir	Late	Sched	#	E	OT	La	ΔTSP	Notes
1104	Beg - WJCCS	NB	8:32	8:27	1					
1104	7000 S	NB	8:37	8:32	1					
1104	6200 S	NB	8:40	8:35	1					
1104	5400 S	NB	8:44	8:39	1					
1104	SLCC	NB	8:48	8:43	1					
1104	4100 S	NB	8:52	8:47	1					
1104	3500 S	NB	8:55	8:50	1					
1104	RDWDJS	NB	8:58	8:53	1					
1104	1700 S	NB	9:04	8:59	1					
1104	POWER	NB	9:16	9:11	1					
1012	Beg - WJCCS	NB	9:17	9:12	2					
1012	7000 S	NB	9:22	9:17	2					
1012	6200 S	NB	9:25	9:20	2					
1104	End - 1300 N	NB	9:27	9:22	1					
1012	5400 S	NB	9:29	9:24	2					
1012	SLCC	NB	9:33	9:28	2					
1012	4100 S	NB	9:37	9:32	2					
1012	3500 S	NB	9:40	9:35	2					
1033	Beg - WJCCS	NB	9:42	9:37	3					
1012	RDWDJS	NB	9:43	9:38	2					
1104	Beg - 1300 N	SB	9:43	9:38	1					
1033	7000 S	NB	9:47	9:42	3					
1012	1700 S	NB	9:49	9:44	2					
1033	6200 S	NB	9:50	9:45	3					
1033	5400 S	NB	9:55	9:50	3					
1033	SLCC	NB	10:00	9:55	3					
1012	POWER	NB	10:01	9:56	2					
1104	POWER	SB	10:03	9:58	1					
1033	4100 S	NB	10:04	9:59	3					
1033	3500 S	NB	10:08	10:03	3					
1004	Beg - WJCCS	NB	10:12	10:07	4					
1012	End - 1300 N	NB	10:12	10:07	2					
1033	RDWDJS	NB	10:12	10:07	3					
1104	1700 S	SB	10:15	10:10	1					
1004	7000 S	NB	10:17	10:12	4					

Figure 3-22: PDU manual monitoring worksheet.

The “E,” “OT,” and “La” columns in the monitoring worksheet stand for early, on time, and late, respectively, with late meaning that the schedule deviation exceeded the requesting

threshold. An “X” was placed in the correct column to reflect the status of the bus upon timepoint departure. Whenever the status changed to or from “late,” the research assistant monitoring the buses would toggle TSP request mode accordingly and place an “X” in the “ Δ TSP” column. Toggling request mode for a PDU simply entailed clicking an icon displayed within the DSRC OBE UI.

There were times when the bus arrived at and departed from a timepoint very close to the requesting threshold, which made manually triggering the request mode challenging. What made this such a challenge is that the SIRI feed only updates every 10 seconds, thus making it difficult to ascertain the moment at which the bus departed the timepoint and whether its schedule deviation exceeded the requesting threshold. To overcome this, the BSM data displayed in the DSRC OBE UI with a 0.1 second refresh rate was consulted to determine the location and speed of the bus. Although there was potential for discrepancy between what was observed through a combination of the vehicle locator website and BSMs and what the bus MDC was reporting, the research team felt comfortable that this was not an issue and that the TSP request mode could be satisfactorily toggled. This was not a concern for equipped buses because the MDC updates every 2 seconds, which ensures that the bus status likewise refreshes within 2 seconds of departure.

3.7.6.3 Automated Priority Request Method

Nearly 10 hours each day of monitoring the buses with PDUs and manually toggling request mode was avoided through an automated process developed by The Narwhal Group. The PDUs still required daily deployment and collection once this process was developed, but the data collection process was automated. UTA developed a vehicle info API on March 14, 2019 specifically for this research, which provided the bus number, the route it was on, the block it was assigned to, its GPS coordinates, speed, heading, timestamp, and its schedule deviation. The vehicle info API was updated every 10 seconds, just like SIRI.

Returning to Figure 3-19, the “API URL” field and the “Id” field were used collectively to capture the information from this feed through the cellular antenna on the PDU. As soon as the vehicle ID was recorded, the PDU would begin receiving the data elements contained in the vehicle info API and could automatically toggle request mode through an algorithm developed

by The Narwhal Group. Also worth noting is the “Age threshold,” which represents how long the information received through the vehicle info API was valid. If the bus were to lose its connection and cease providing up-to-date information, the system would turn request mode off rather than having the status of request mode based on information more than 180 seconds old.

There was one issue that was observed with PDU-equipped buses under automated TSP request mode that was a non-issue when request mode was toggled manually. In manual mode, a combination of the SIRI feed and BSMs were used to accurately toggle request mode. In automated mode, however, the algorithm did not use information contained in BSMs but relied solely on the vehicle info API, which had a 10-second refresh rate. Beholden to the API refresh rate, the toggling of request mode could likewise only occur every 10 seconds.

A 10-second lag in toggling request mode was normally not a concern because most timepoint bus stops were on the far side of the intersection, which meant that the next downstream signalized intersection was far enough away and there was no impact. However, there was one location, 5400 South in the NB direction, where buses would enter the geofence of the next downstream signalized intersection during this 10-second lag. Figure 3-23 is a screenshot of the DSRC OBE UI that illustrates this event at a time when the 0-minute requesting threshold was being tested. The 5400 South timepoint bus stop can be seen just north of the intersection, the blue dots represent BSMs, the green dot represents the SRM, and the pink vehicle icon represents the bus. Figure 3-24 is a screenshot of the data shown on the DSRC OBE UI when the screenshot of Figure 3-23 was taken.

Upon departing the timepoint, the bus momentarily enters its transition mode and the MDC outputs a 0-second schedule deviation. Either the bus was not late before arriving at the 5400 South timepoint, so no TSP requests were being made, or the vehicle info API just happened to refresh during the 2 seconds that the bus was in transition mode, because request mode was not active for the 10 seconds leading up to when these screenshots were taken. This is shown in Figure 3-24 by the absence of additional green dots representing the location of transmitted SRM messages, which should have been present the moment the bus entered the geofence. The green dot shown in Figure 3-24 represents the location of the bus when the PDU

ultimately received the updated information, that the bus was 81 seconds behind schedule, and an SRM was finally transmitted, 262 feet into the geofence and a mere 50 feet from the stop bar.

This is the only location where the 10-second refresh rate affected TSP operations for PDU-equipped buses under automated request mode. For regularly equipped buses, the OBE is



Figure 3-23: DSRC OBE UI map when 10-second refresh rate affects TSP operations.

connected to the MDC, which updates every 2 seconds, so this is not a concern for equipped buses. It can be seen that if the affected intersection were 262 feet further downstream and the geofence were the same size, this first SRM would have been transmitted the moment it entered the geofence. No other signalized intersection is close enough to the timepoint bus stop for this to be an issue.

UDOT/UTA Portable EPRG Algorithm			
algorithm can run, vehicle 12007 is 81 seconds behind schedule			
request	relay	monitor	
ON	OFF	ON	
Bus Data			
Timestamp:	07/08/19, 10:21:38:808	Speed:	24 mph
Location:	40.65497/-111.93873	Heading:	North
Vehicle:	12007	Block:	1004
Route:	217	Operator:	03805
FixTime:	07/08/19, 10:21:29:893	Reliability:	81
BSM Data - vehicle id 12007			
Timestamp:	07/08/19, 10:21:40:262	Speed:	9 mph
Location:	40.6557/-111.9387	Heading:	North
SRM Data - intersection # 7109			
Timestamp:	07/08/19, 10:21:39:865	Speed:	10 mph
Location:	40.6557/-111.9387	Heading:	North
Intersection:	5225SouthRedwoodRoad	Inbound Lane:	5
Type:	request-update	Request Id:	10
Name:	Case #4	Vehicle Id:	12007
ETA:	7/8/2019, 10:21:45	Elevation:	1302
SSM Data - intersection # 7109			
Timestamp:	07/08/19, 10:21:40:250	Seq Num:	1
Intersection:	5225SouthRedwoodRoad	Inbound Lane:	5
Request Id:	10	Rq Seq Num:	1
Status:	processing	Vehicle Id:	12007
SPaT Data			
Timestamp:	07/08/19, 10:20:12:237		
Intersection:	5600SouthRedwoodRoad		

Figure 3-24: DSRC OBE UI data when 10-second refresh rate affects TSP operations.

3.8 UVX – Provo-Orem Bus Rapid Transit

The corridor utilized for data collection and analysis of a BRT route was the UVX corridor in Utah County. This section contains, for UVX, subsections discussing the route description, requesting thresholds, the TSP system, TSP strategies and treatments, and bus operations.

3.8.1 UVX – Route Description

UVX is a 10.5-mile BRT route with 51 percent of the route operating on dedicated lanes. Its articulated buses only allow boarding and alighting from 18 station-like stops. A significant portion of this route runs on state highways with an AADT of 28,000 to 57,000 vehicles per day, with trucks making up 23 to 44 percent of that traffic (UDOT 2016). This route connects two universities that each have over 30,000 students (BYU 2019; UVU 2019), and passes by numerous shopping centers, high-density residential areas, and commercial and industrial land uses.

All 47 intersections along the route are equipped with DSRC RSUs, but only 44 are capable of serving TSP. Two of the three intersections excluded from serving TSP are at a freeway interchange with the third being the intersection of University Parkway and State Street, the highest-volume signalized intersection in the state. A map of UVX and the location of each signalized intersection along its route is shown in Figure 3-25, which shows the equipped intersections along the route and whether TSP is enabled.

3.8.2 UVX – Requesting Thresholds

The requesting thresholds analyzed in this study for UVX are 5 minutes and 2 minutes, as well as ON and OFF scenarios; ON meant the buses were always requesting regardless of how late they were, while OFF meant that no requests were made and operations would be as if there were no TSP at all. Table 3-9 lists the requesting thresholds evaluated and the dates during which they were active. To avoid the complication of actually disabling TSP for the OFF scenario, the requesting threshold was set to 1200 seconds, which meant that only buses more than 20 minutes behind schedule would request TSP, effectively turning it off. Likewise, the ON scenario had a requesting threshold set to -1200 seconds, which meant that all buses would request unless they were more than 20 minutes early.

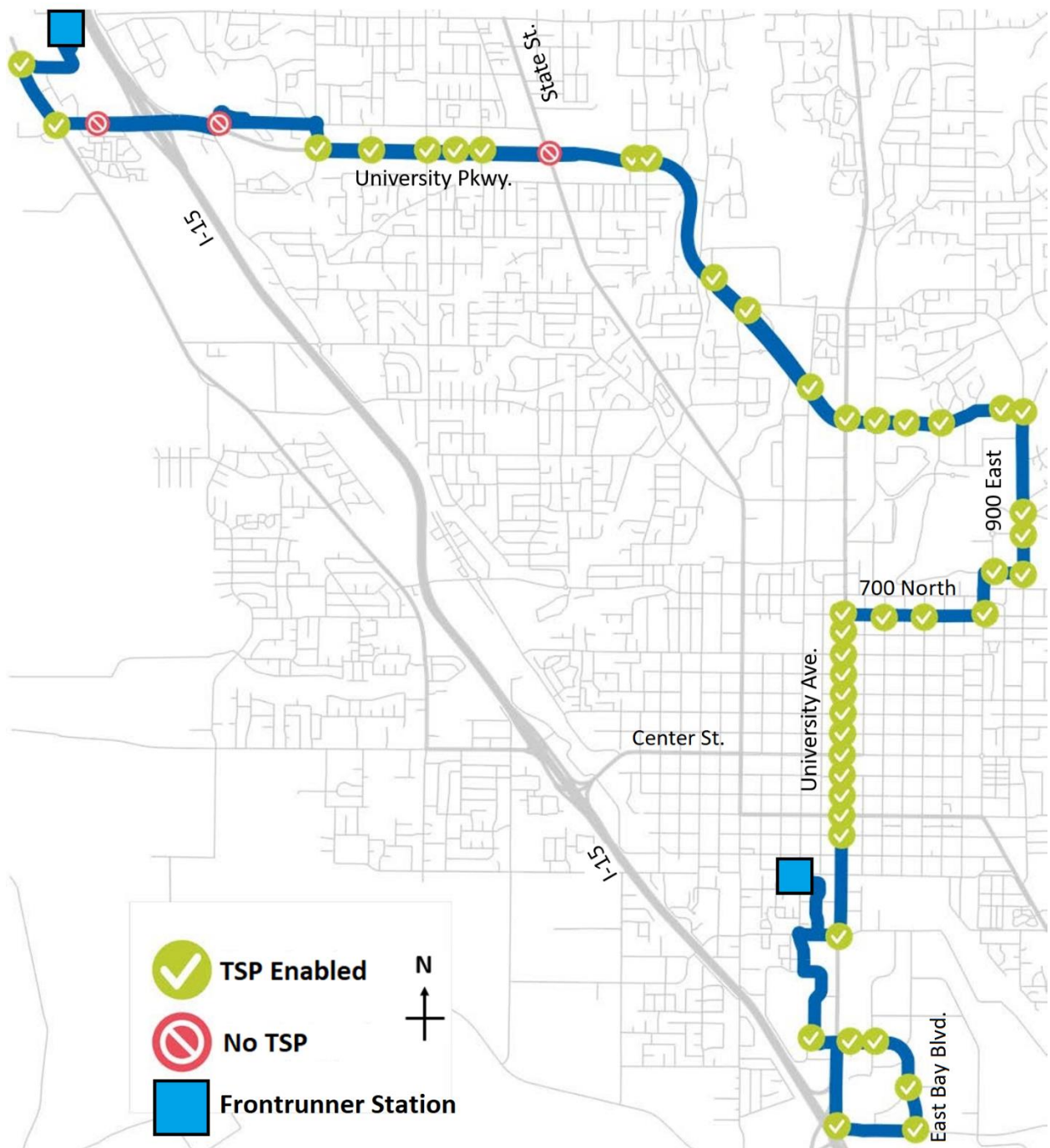


Figure 3-25: UVX map.

Table 3-9: UVX Requesting Thresholds

Requesting Threshold (minutes behind schedule)	Begin Date	End Date
5	4/8/19	6/7/19
2	6/10/19	7/12/19
OFF	7/15/19	7/26/19
ON	7/30/19	8/9/19

More data were collected for UVX than were ultimately used in the analysis because the schedule established by the December 2018 change day was adjusted so much on the April 2019 change day that substantial differences in OTP and schedule deviation were observed in the data before and after the change day occurred. The research team felt that the operating environments were so different that it would not be appropriate to compare data from one change day with the data from the other. Therefore, data from all four requesting thresholds were collected between April 8 and August 9, 2019 under the same schedule that was established on the April 2019 change day.

3.8.3 UVX – Transit Signal Priority System

Cohda OBUs were used to equip all UVX buses while a combination of Lear and Cohda RSUs were installed throughout the corridor. Table 3-10 contains a list of the signalized intersections, controllers, and RSUs along the UVX route.

Table 3-10: UVX Controller and DSRC RSU Type by Intersection

Signal ID	Intersection	Controller	RSU
6315	1000 S & Geneva Rd	Econolite	Cohda
6316	University Pkwy & Geneva Rd	Econolite	Cohda
6317 ¹	University Pkwy & I-15 SUI	Econolite	Cohda
6318 ¹	University Pkwy & Sandhill Rd	Econolite	Cohda
6319	University Pkwy & 400 W	Econolite	Cohda
6320	University Pkwy & 200 W	Econolite	Cohda
6321	University Pkwy & Main St	Intelight	Cohda
6330	University Pkwy & 100 E (Family Center)	Econolite	Cohda
6322	University Pkwy & 200 E	Econolite	Cohda
6324 ¹	University Pkwy & State St	Econolite	Cohda
6328	University Pkwy & 750 E	Econolite	Cohda
6325	University Pkwy & 800 E	Econolite	Cohda

¹ No TSP enabled

Table 3-10 (continued)

6461	University Pkwy & Plum Tree (2310 N)	Econolite	Cohda
6436	University Pkwy & 550 W (2230 N)	Econolite	Lear
6435	University Pkwy & Freedom Blvd	Econolite	Cohda
6417	University Pkwy & University Ave	Intelight	Cohda
6633	University Pkwy & Canyon Rd	Econolite	Cohda
6634	University Pkwy & 350 E	Econolite	Cohda
6635	University Pkwy & 450 E	Econolite	Cohda
6641	University Pkwy & 730 E	Econolite	Cohda
6628	University Pkwy & 900 E	Econolite	Cohda
6627	Birch Lane (Heritage Dr) 900 E	Econolite	Cohda
6619	1100 N (Campus Lane) 900 E	Econolite	Cohda
6625	900 N & 900 E	Econolite	Cohda
6626	900 N & East Campus Dr	Econolite	Cohda
6624	700 N & 700 E	Econolite	Lear
6642	700 N & 400 E	Econolite	Cohda
6643	700 N & 200 E	Econolite	Cohda
6411	700 N & University Ave	Intelight	Cohda
6462	600 N & University Ave	Econolite	Cohda
6410	500 N & University Ave	Econolite	Cohda
6463	400 N & University Ave	Econolite	Cohda
6464	300 N & University Ave	Econolite	Cohda
6409	200 N & University Ave	Econolite	Cohda
6408	100 N & University Ave	Econolite	Cohda
6407	Center St & University Ave	Econolite	Cohda
6406	100 S & University Ave	Econolite	Cohda
6427	200 S & University Ave	Econolite	Cohda
6405	300 S & University Ave	Econolite	Cohda
6465	400 S & University Ave	Econolite	Cohda
6404	900 S & University Ave	Econolite	Cohda
6655	Town Centre Dr & Town Centre Blvd	Econolite	Cohda
6402	Towne Centre Dr & University Ave	Econolite	Cohda
6654	East Bay Blvd & 180 E	Econolite	Cohda
6652	1860 S & East Bay Blvd	Econolite	Cohda
6651	1860 S & Novell Place	Econolite	Lear
6401	1860 S & University Ave	Econolite	Cohda

¹ No TSP enabled

3.8.4 UVX – Strategies and Treatments

There are several stark contrasts to the TSP strategies and treatments found in the TSP system for UVX that are not present on Route 217. The most notable is that UVX operates on dedicated lanes for 51 percent of the route. The majority are center-running lanes, as shown in

Figure 3-26, but some are curbside lanes, as shown in Figure 3-27. These dedicated lanes provide passive TSP to the buses because they do not have to wait in the general traffic queues that build up at stoplights but can come right up to the stop bar each time.



Figure 3-26: UVX dedicated center-running lanes.



Figure 3-27: UVX dedicated curbside lanes.

Another noticeable difference in TSP for UVX are the transit-only signals, referred to as light-rail transit signals in the *Manual on Uniform Traffic Control Devices* (FHWA 2009), as shown in Figure 3-28. Most of the time when this signal is vertical, indicating that the bus may proceed, the through movements in the same direction are also green. Only at a few select intersections is this transit-only signal the only signal indicating permissible movement.

Due to the short headways on UVX, there was concern that TSP might be called too often and cause too many disruptions. Indeed, at 6-minute headways a bus passes through each intersection every 3 minutes on average. Consequently, the TSP logic is such that two clean cycles with no TSP must take place before TSP can be granted at that intersection again. During the ON requesting threshold scenario, when buses were always in request mode, this posed a unique concern: A bus that was not late might request and get served with TSP while the subsequent bus to pass through the same intersection that actually was behind schedule and needed TSP would be unable to receive it. If this were to happen, TSP would have little effect on OTP but would still improve average schedule deviation.



Figure 3-28: UVX transit-only signal.

3.8.5 UVX – Bus Operations

The entire UVX fleet are 60-foot long articulated buses that operate on a timetable-based schedule. However, the schedule provided to the public is based on headways, as shown in Figure 3-29. A rider does not know the time at which the bus is scheduled to arrive at intermediate stops between 7:00 and 20:00, but simply knows to expect the arrival of a bus every 6 or 10 minutes, depending on the time of day. The existence of an internal, timetable-based schedule enables the calculation of schedule deviation at each timepoint, which is necessary to determine when TSP should be requested and to calculate OTP.

UTA does not have a holding strategy for UVX nor do its operators keep a set schedule. Indeed, a disclaimer on the published schedule, shown in Figure 3-30, states that operators will leave the first timepoint on time and travel as quickly as possible to the end of the route. Thus, for all intents and purposes, UVX should be considered a headway-based route. Maintaining a desired headway may change the nature of the route and how TSP is requested in the future, for if all buses are equally late, the desired headway is maintained and riders perceive perfect adherence to the schedule of which they have knowledge.

Unique to UVX with respect to all other bus routes are different status thresholds, which are shown in Figure 3-31. While a bus on Route 217 is considered late when it is 5 minutes or more behind schedule, UVX buses are late when they are 2 minutes or more behind schedule. The status thresholds for critical early and critical late remain the same for both routes.

3.9 Chapter Summary

This chapter contained information on how the experiment was set up and outlined differences between Route 217 and UVX. MMITSS-UT, a third-party TSP software package, was used to enable TSP at 22 signalized intersections on Route 217 and 44 signalized intersections on UVX. The buses are detected through GPS and use DSRC to communicate with the signal controller. TSP may be requested by equipped buses only if their schedule deviation exceeds the requesting threshold, which is conveyed from the bus to the signal controller using DSRC. The requesting thresholds evaluated for Route 217 are 5, 3, 2, and 0 minutes. For UVX, 5

North To Orem Central Station

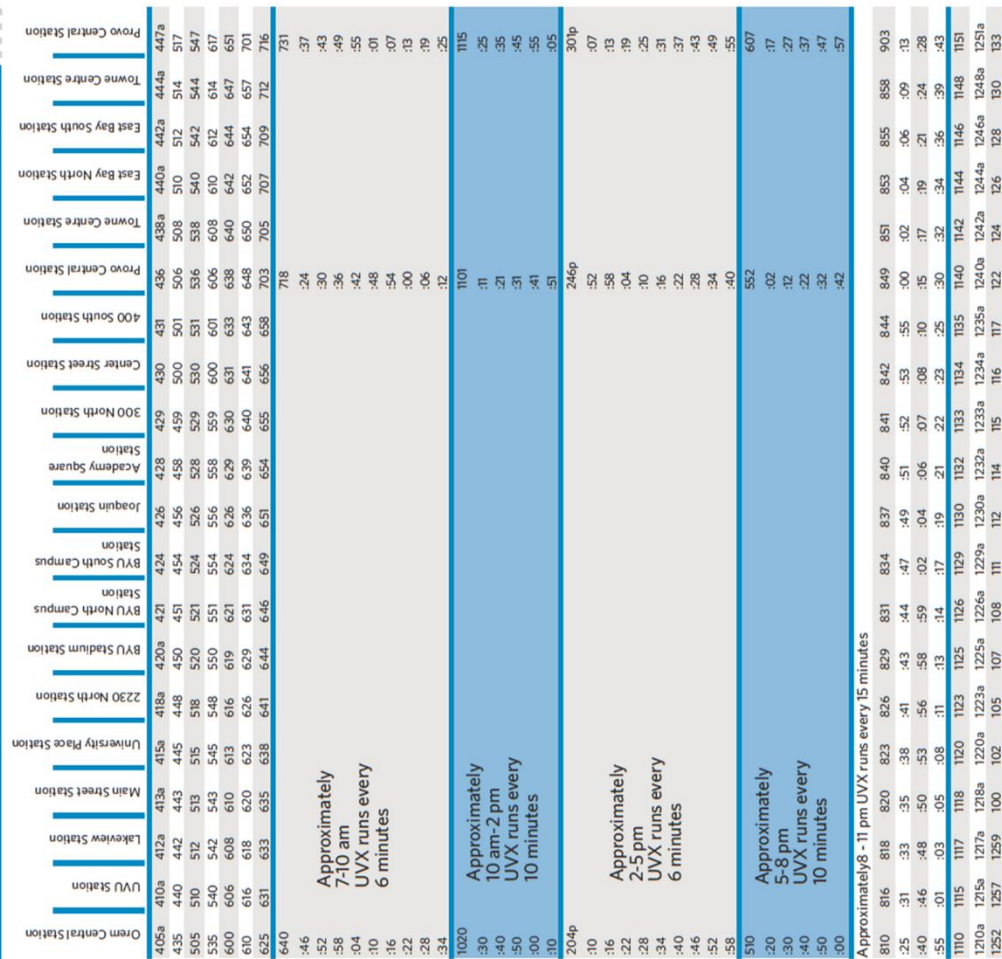


Figure 3-29: UVX weekday schedule from April 8, 2019 to August 11, 2019.

WILL OPERATORS WAIT AT TIMEPOINTS?

No. Operators will leave the first timepoint on time and then travel as quickly as possible to the end of the route. Operators stop to let customers on and off the bus, but the operator does not keep a set schedule.

Figure 3-30: UVX schedule disclaimer.

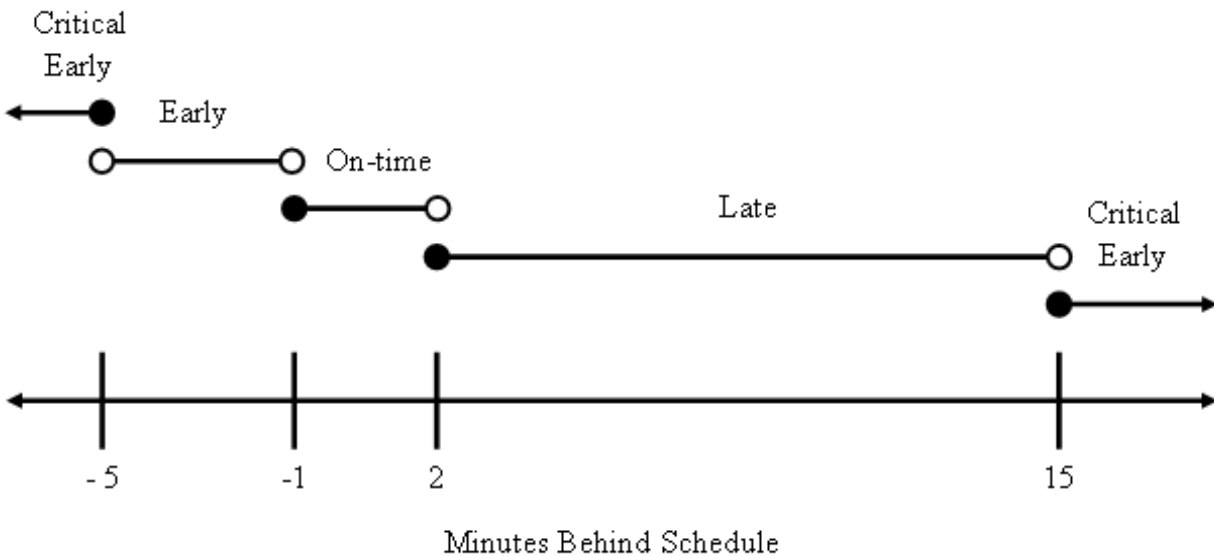


Figure 3-31: UVX status thresholds.

and 3 minutes, as well as OFF, meaning no requests are made, and ON, meaning buses are always requesting, were the four requesting thresholds evaluated.

Because all UVX buses were equipped with DSRC OBUs, the scheduled headways were short, and schedule changes on every change day had major schedule adherence impacts, data were collected very quickly and lasted from April 8, 2019 to August 9, 2019. On Route 217, headways were longer and not all buses were equipped, so portable units capable of requesting TSP were developed to facilitate data collection, which lasted from February 4, 2019 to August 31, 2019.

4.0 ANALYSIS METHODOLOGY

4.1 Overview

The data were primarily analyzed by direction (NB and SB) and by peak period (AM and PM). These four directional peak scenarios (AM NB, AM SB, PM NB, and PM SB) were used to analyze impacts at each timepoint individually and were aggregated at the corridor level. The AM peak was defined as 06:00 to 09:00 and included all records that fell within that timeframe. Likewise, the PM peak was defined as 15:00 to 18:00. Although data were obtained for off-peak times of day, UTA and UDOT were primarily interested in the peak periods when ridership and congestion are typically highest, so this analysis likewise focuses on the peak periods. Figure 4-1 is a basic flowchart that outlines the data sources, the analysis in which they are used, the results measured by the analysis, and the specific metrics evaluated.

This chapter covers the methodology of excluding data, analyzing bus performance, and briefly covers the methodology behind the general traffic analysis that was developed by Avenue Consultants.

4.2 Data Exclusion

Data were excluded from the analysis based on timepoint or the determination that the record was an outlier. The following subsections discuss exclusions for Route 217 due to the timepoint and outliers, and exclusions for UVX due to outliers.

4.2.1 Route 217 – Exclusion Based on Timepoint

Results were calculated from the timepoints that were part of the equipped portion of the route only. This meant that the northernmost four timepoints were excluded, namely 1300 North and 1754 West, 1700 North and Morton Drive, 1300 North and Redwood Road, and 1950 West (Blind Center). The research team considered whether to include the northernmost four

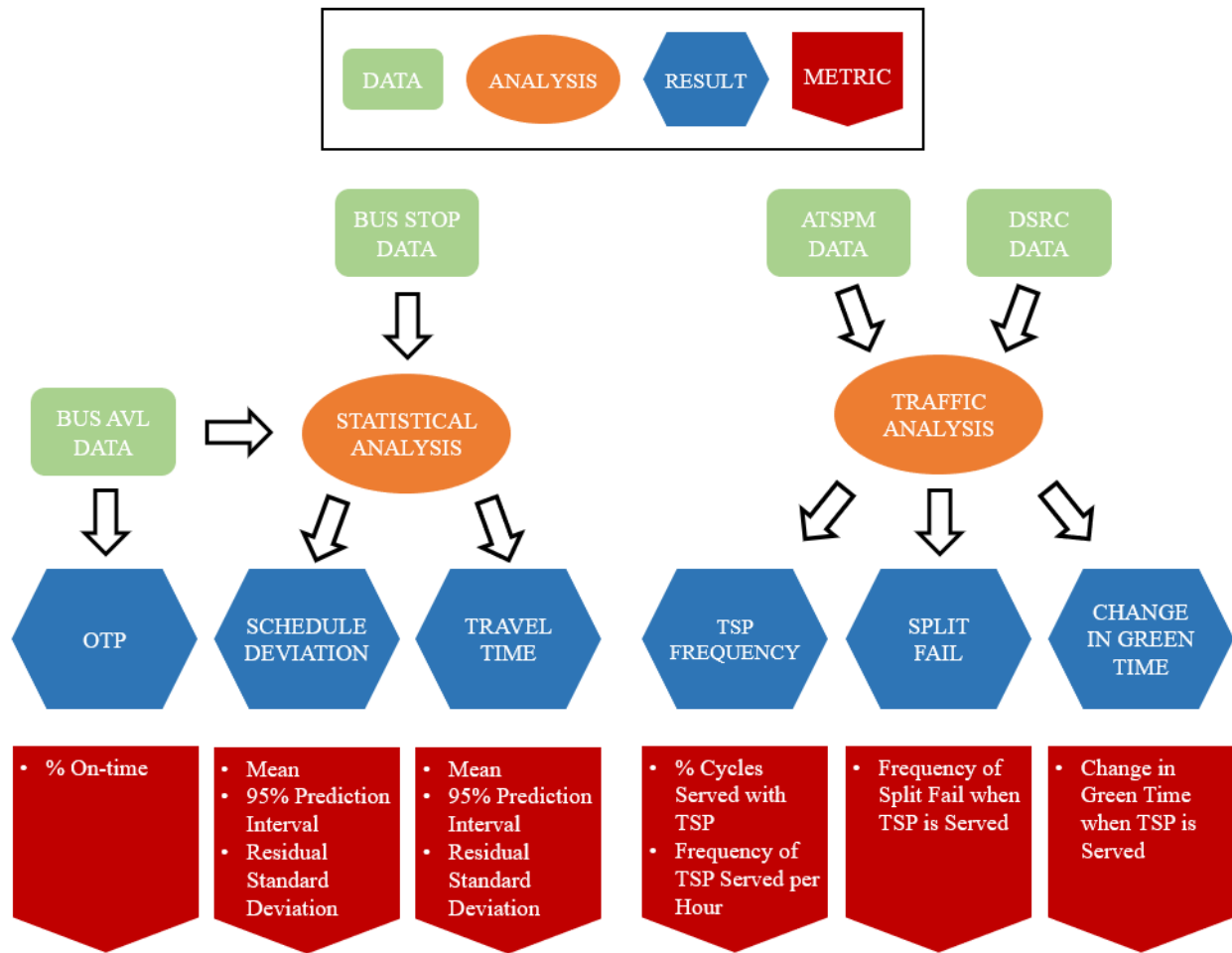


Figure 4-1: Analysis flowchart.

timepoints that were outside the equipped portion of the route because NB buses would take the benefit of TSP with them as they traveled to these northern timepoints. A similar benefit would not be present in the SB direction, however, so the decision was made to exclude them in order to maintain consistency in the analysis as much as possible between NB and SB scenarios.

Additionally, the southernmost timepoint, West Jordan City Center was excluded from the corridor-level analysis because the schedule was set to allow several minutes of schedule deviation to be recovered as a SB bus traveled from the second-to-last timepoint (7000 South) to the last one (West Jordan City Center). In fact, SB buses had an average schedule deviation of 72

seconds at 7000 South and -243 seconds, or 243 seconds ahead of schedule, at West Jordan City Center, a difference of 5 minutes and 15 seconds. There was concern that this drastic change in values would improperly influence the mean or median schedule deviation for the directional peak scenario being analyzed at the corridor level. Although this issue only exists for the West Jordan City Center timepoint in the SB direction, this timepoint was also excluded in the NB corridor-level analysis so that data from the same timepoints were used regardless of the direction being analyzed.

4.2.2 Route 217 – Exclusion of Outliers

In addition to excluding records based on timepoint, some records were also excluded because their values were not feasible. Sometimes, the values for reliability or travel time were so high that it was determined that they were erroneously recorded and were discarded. For schedule deviation, any record that had a value less than -240 seconds or greater than 900 seconds was discarded, which resulted in the exclusion of 0.3 and 0.4 percent of data, respectively. In other words, if the data showed that a bus was more than 4 minutes early or more than 15 minutes late then it was discarded. These upper and lower limits of acceptable data values were largely determined based on the distribution of schedule deviation, but a contributing factor was that Route 217 buses have a scheduled headway of 15 minutes throughout most of the day. Route 217 operators are instructed to wait at a timepoint if they are early so that they can depart on time. This holding strategy makes it very unlikely that a bus would be more than 4 minutes early under ordinary circumstances and when the data are recorded correctly.

Likewise, extremely high or low values for travel time were also discarded. The ranges of acceptable values were determined by timepoint and by direction of travel to reflect the distance the bus had to travel (to arrive at a given timepoint, NB and SB buses travel different distances from the preceding timepoint). Figure 4-2 is a histogram of the recorded travel-time distribution for the SB West Jordan City Center timepoint that also indicates the upper and lower limits that define the range of acceptable values used to determine outliers. Appendix A.1 contains the

histograms by direction for each Route 217 timepoint used in the analysis. Table 4-1 summarizes the travel-time filters by direction and timepoint, which usually excluded the top and bottom 0.5 percent of data. Overall, this filter resulted in approximately 5 percent of the data being discarded.

4.2.3 UVX – Exclusion of Outliers

Data used for UVX included all timepoints with exclusions based only on the value of a record. For schedule deviation, any record that had a value less than -600 seconds or greater than 1020 seconds was discarded, which resulted in the exclusion of 0.06 and 0.03 percent of data, respectively. In other words, if the data showed that a bus was more than 10 minutes early or more than 17 minutes late then it was discarded. Figure 4-3 shows the distribution of schedule deviation for UVX, the cumulative percent of recorded values, and the upper and lower limits used to define the range of acceptable values.

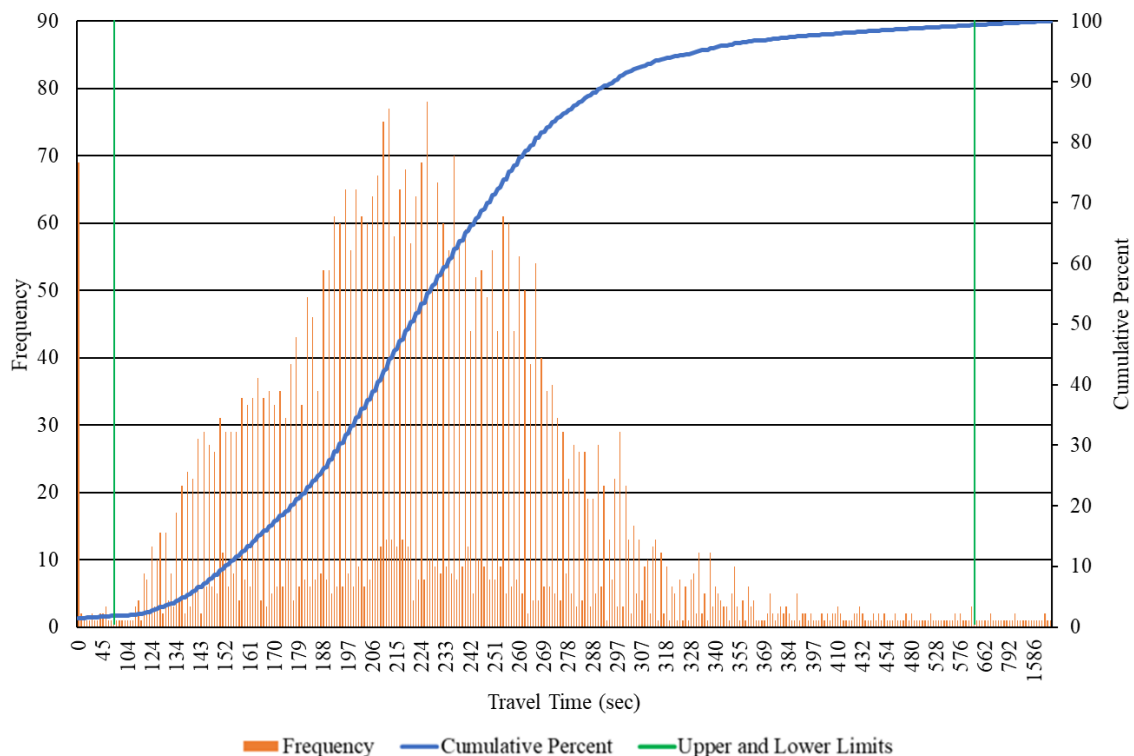


Figure 4-2: Route 217 travel-time distribution - SB West Jordan City Center.

Table 4-1: Route 217 Travel Time Range of Acceptable Values [lower, upper] (seconds)

Timepoint	SB	NB
Power Station	n/a ¹	[500,1200]
1700 South	[360,1080]	[180,660]
Redwood Junction	[120,720]	[60,480]
3500 South	[60,600]	[60,480]
4100 South	[60,540]	[60,480]
SLCC	[60,360]	[60,600]
5400 South	[180,1080]	[60,480]
6200 South	[60,1080]	[60,420]
7000 South	[60,600]	[60,600]
West Jordan City Center	[60,600]	n/a ¹

¹ range not needed because travel time is zero as it is the first timepoint of the trip

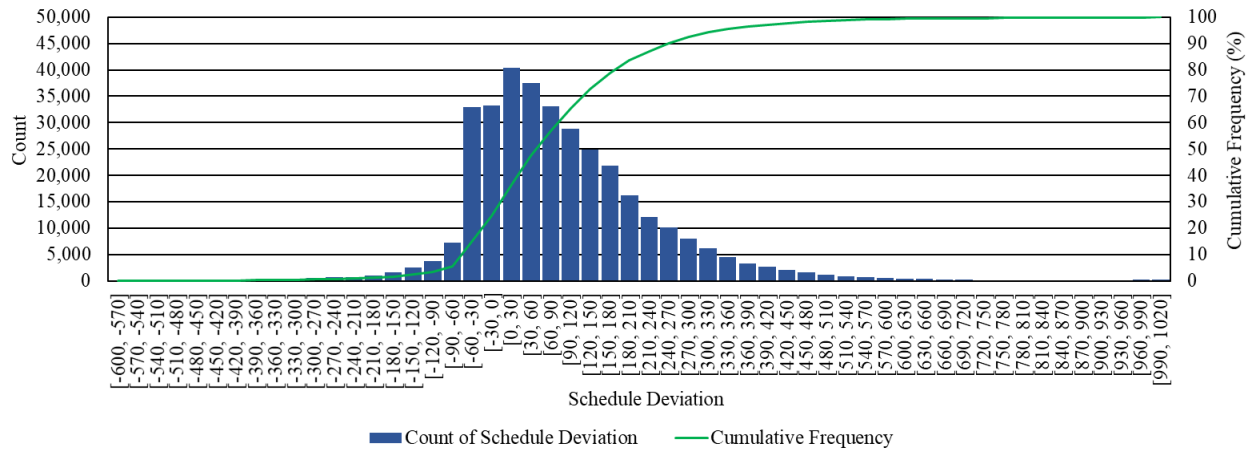


Figure 4-3: UVX schedule deviation distribution.

For travel time, the ranges selected usually omitted the records contained in the top and bottom 0.5 percent of travel-time values at a given timepoint, but exceptions sometimes occurred at timepoints near the beginning or end of the route due to malfunctions in how the data were recorded. For example, UVX NB buses at the 400 South timepoint have approximately the top 15 percent of data excluded as shown in Figure 4-4 which displays the distribution of recorded travel times, cumulative percent, and the upper and lower limits used to define the range of acceptable values. Table 4-2 summarizes the travel-time filters by direction and timepoint starting with the northernmost timepoint, Orem Central. Figures showing the travel-time

distribution of all timepoints for NB and SB are found in Appendix B.1. Including all timepoints in the analysis and selecting conservative ranges of acceptable values for schedule deviation and travel time were done because UVX is a new route that lacks the consistency and a well-established schedule that accurately reflects bus performance that exists for Route 217.

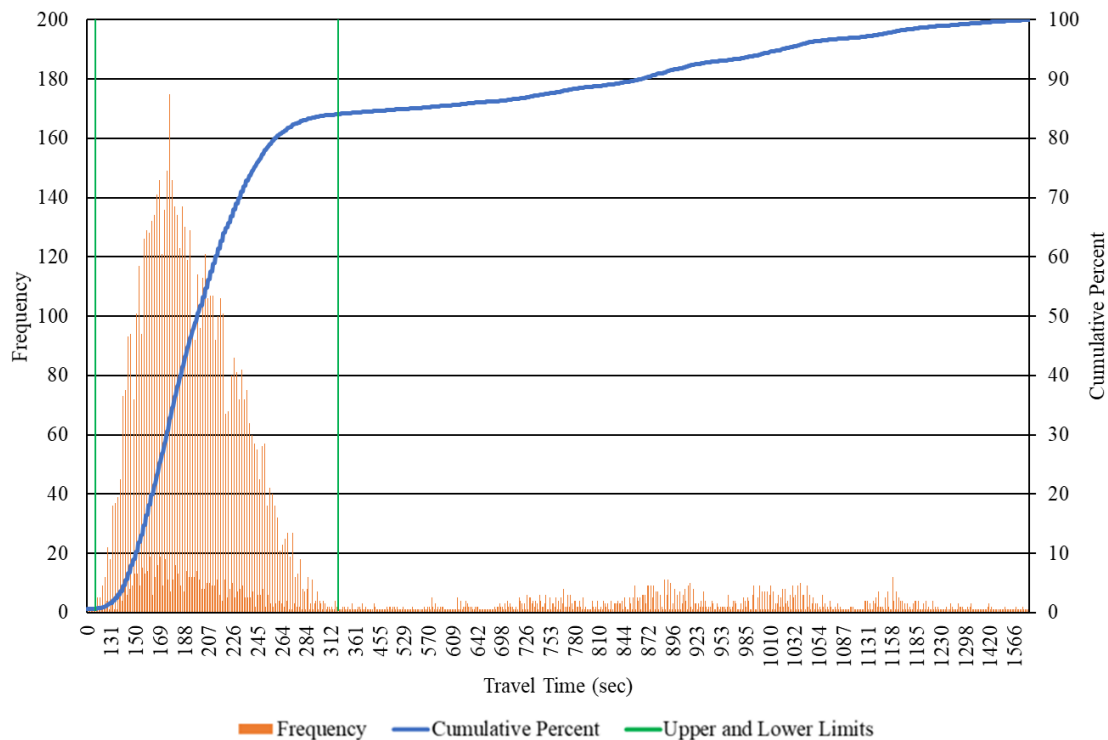


Figure 4-4: UVX travel-time distribution - NB 400 South

4.3 Bus Performance

Bus performance was evaluated primarily through three different metrics: OTP, schedule deviation, and travel time. OTP was evaluated through an observational analysis while impacts on schedule deviation and travel time were measured through a statistical analysis. The methodology behind the observational analysis of OTP and the statistical analysis of schedule deviation and travel time are discussed further in the following subsections.

Table 4-2: UVX Travel Time Range of Acceptable Values [lower, upper] (seconds)

Timepoint	SB	NB¹
Orem Central	n/a ²	[180,600]
UVU	[180, 720]	[90,300]
Lakeview	[60, 300]	[45,300]
Main St	[60, 180]	[60,420]
University Place	[60, 420]	[90,240]
2230 North	[90, 360]	[60,360]
BYU Stadium	[120, 420]	[45,180]
BYU North Campus	[30, 240]	[120,360]
BYU South Campus	[120, 360]	[60,240]
Joaquin	[60, 240]	[60,300]
Academy Square	[60, 360]	[30,180]
300 North	[45, 180]	[45,180]
Center St	[30, 180]	[45,240]
400 South	[45, 180]	[60,300]
Provo Central	[120, 480]	n/a ²
Towne Centre Blvd	[120, 300]	
East Bay North	[45, 300]	
East Bay South	[60, 240]	
Towne Centre Blvd	[60, 360]	
Provo Central	[90, 180]	

¹ NB trips begin at Provo Central and do not make the southern loop

² Range not needed because travel time is zero as it is the first timepoint of the trip

4.3.1 On-Time Performance

OTP, the proportion of the time that a transit system adheres to its published schedule within stated tolerances (Ryus et al. 2013), was the most important metric to UTA in determining whether TSP improved bus performance. Consequently, OTP was the primary metric used for evaluating bus performance and was accomplished through an observational analysis. The stated tolerances, or the defined range in which a bus is considered “on time,” is when schedule deviation is less than 300 seconds (5 minutes) late for Route 217 and less than 120 seconds (2 minutes) late for UVX. For OTP calculation purposes, the status of the bus defined by UTA as critical early, early, and on time were grouped together and classified as “on time” while late and critical late are collectively considered “late.” Table 4-3 shows the ranges of on time and late for OTP calculation purposes, with the bracket indicating that the endpoint is included in the interval. Although the requesting threshold changed throughout the study, the status thresholds

outlined in Table 4-3 remained constant. OTP is calculated by dividing the sum of all on-time departures by the sum of all departures during the study period, as shown in Equation 4-1. OTP was evaluated timepoint by timepoint and at the corridor level for the four directional peak scenarios.

Table 4-3: Status Threshold Ranges for OTP Calculation (minutes behind schedule)

OTP Status	On Time	Late
Route 217	$(-\infty, 5)$	$[5, \infty)$
UVX	$(-\infty, 2)$	$[2, \infty)$

$$\text{On-time percentage (OTP)} = \frac{\text{number of on-time departures}}{\text{number of all departures}} \quad (4-1)$$

UTA indicated that a 1 percent improvement in OTP would be meaningful. In order to perform an analysis capable of evaluating a statistically significant OTP change of 1 percent, 40,000 data points would be needed at each timepoint for each directional peak scenario. This would require a data collection period for each requesting threshold of approximately 130 weeks for Route 217 and 60 weeks for UVX. Consequently, only an observational analysis was performed on OTP.

4.3.2 Statistical Analysis

A statistical analysis was performed on the data to evaluate the impact of changing the requesting threshold (the treatment) on schedule deviation and travel time. Specifically, analyses were performed on the mean, the 95 percent prediction interval, and variability in the data. The statistical package SAS v9.4 was used to perform a mixed-model multiple regression analysis blocking on hour of day and timepoint. Blocking is performed to adjust for correlation in the data due to lack of independence. For example, schedule deviation (actual departure time minus scheduled departure time) is dependent on how the schedule is set. If the schedule inaccurately reflects actual bus performance for a specific timepoint, the schedule will cause better or worse schedule deviation than would a schedule that accurately reflects bus performance. Rather than having the statistical model estimate schedule deviation by grouping timepoints with a good

schedule together with timepoints that have a bad schedule, blocking is performed on timepoint because the value of schedule deviation is dependent on timepoint. Likewise, there is correlation among traffic patterns and volumes that fall within the same hour of the day, so blocking was also performed on hour of day during which the record was recorded. In addition to blocking on hour of day and timepoint as explanatory variables, the number of times a bus had to stop to load or unload passengers was included in the model as a covariate. The number of times a bus had to stop to load or unload passengers was included to control for the effect that frequent or infrequent stops would have on schedule deviation and travel time for a single bus trip. After controlling for the explanatory variables' hour of day, timepoint, and number of times a bus had to stop to load or unload passengers, schedule deviation and travel time were estimated. Estimates were created for each requesting threshold at the timepoint and corridor level for the four directional peak scenarios (AM NB, AM SB, PM NB, and PM SB).

Missing data and partial records, particularly at timepoints beginning and ending the route, made it challenging to accurately sum the travel times of a specific trip to obtain the cumulative travel time. So, travel time was only evaluated at the timepoint level. The bus AVL data has a field for travel time, but it actually includes any dwell time at the timepoint it just left as well. To compensate for this, dwell time at timepoints, a separate metric recorded in the bus AVL data, was subtracted from the recorded "travel time." The result is a value that represents the elapsed time from departure of the previous timepoint to arrival at the current timepoint. This was especially important for Route 217, which has a holding strategy requiring buses to dwell if they are early.

The statistical model for UVX blocked on time of day, timepoint and scheduled headway, but did not include number of stops to load or unload passengers as a covariate. Scheduled headway was included to control for variations that occur based on whether buses are scheduled to operate at 6-, 10-, or 15-minute headways. The number of stops to load or unload passengers was excluded because UVX has a pre-defined number of stops (each timepoint) and must stop at each one.

The estimated mean was analyzed between different requesting thresholds using a two-sided t-test on the difference in means. Because multiple comparisons were made across the various requesting thresholds, a pseudo-Bonferroni adjustment was used; the mean values compared between requesting thresholds were significantly different if the resulting p-value was less than or equal to 0.01. The pseudo-Bonferroni adjustment provides protection from the Type I error, which would indicate that there is a significant difference between requesting thresholds when there is none.

Through collaboration with UDOT and UTA, the baseline requesting threshold was determined to be 5 minutes for Route 217 and 2 minutes for UVX. Consequently, the analysis focused primarily on comparing the other thresholds to the baseline. For Route 217, the comparison pairs (the two thresholds being compared) were 5 minute vs 3 minute, 5 minute vs 2 minute, 5 minute vs 0 minute, and 2 minute vs 0 minute. For UVX, the comparison pairs were 2 minute vs OFF, 2 minute vs 5 minute, 2 minute vs 0 minute, and OFF vs ON.

Standard deviation (SD) is a measure of spread, or variability, in the data where the mean (μ) $\pm$ 2 SD creates a range wherein roughly 95 percent of measurements fall, as illustrated in Figure 4-5. However, when the data are not normally distributed, as is the case with the schedule deviation and travel-time data for these routes, this range inaccurately represents the actual spread of the data. Figure 4-6 is a histogram of schedule deviation for Route 217 that illustrates how the data are positively skewed. Instead of using SD to create the range that contains the estimated 95 percent of the data, the raw data values were grouped by timepoint and by directional peak scenario to find the 2.5th percentile and 97.5th percentile values to create the 95th percent prediction interval for each group. While not a statistical measure in and of itself, the 95th percent prediction interval was used to illustrate variability in the data and provide a range of expected values for schedule deviation and travel time.

The analysis of variability in the data was performed to determine if significant differences in variability exist between requesting thresholds. The metric for the analysis of

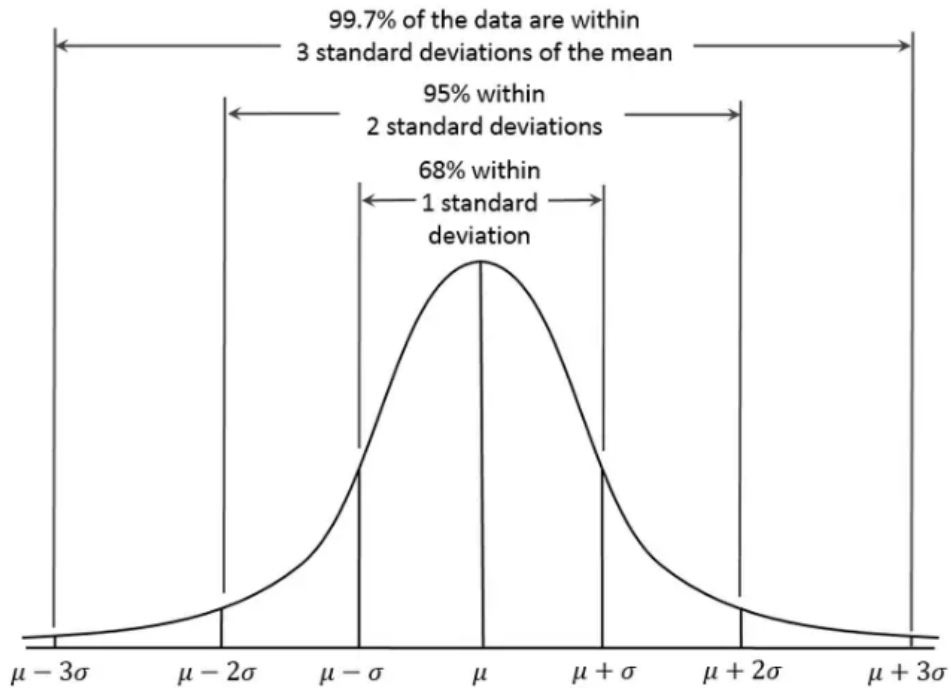


Figure 4-5: Standard deviations and normally distributed data (Kiersz 2014).

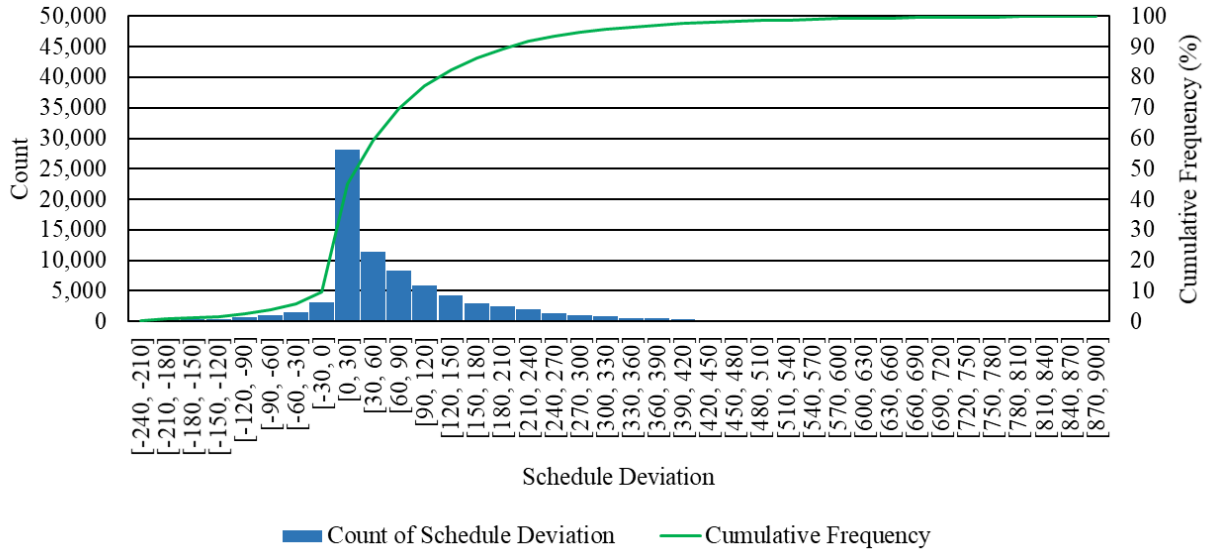


Figure 4-6: Route 217 schedule deviation histogram.

variability was mean residual SD, where the residual and residual SD are calculated according to Equation 4-2 and Equation 4-3, respectively. The residual is defined as the difference between the schedule deviation or travel-time value of an individual record ($actual_i$) and the estimated median of all records for the specific timepoint and directional peak scenario to which $actual_i$ belongs. The median value was estimated at each timepoint for each directional peak scenario because the median is a better indicator of central tendency than the mean for skewed data. The residual SD was calculated for each by timepoint and directional peak scenario. Finally, the mean residual SD of all days within each requesting threshold was calculated by timepoint and directional peak scenario with a two-sided t-test performed on the mean to evaluate the difference in variability.

$$R_i = actual_i - estimated\ median_{(direction, peak, timepoint)} \quad (4-2)$$

where:

R_i = residual

$actual_i$ = actual value of a single record

$estimated\ median_{(direction, peak, timepoint)}$ = estimated median value of all records
matching the direction, peak, and timepoint of $actual_i$.

$$residual\ standard\ deviation = \sqrt{\frac{\sum_{i=1}^n (R_i^2)}{n-1}} \quad (4-3)$$

where:

R_i = residual

n = number of records per timepoint and directional peak scenario

4.4 Traffic Analysis

The traffic analysis was performed through a process developed by Avenue Consultants and guided by UDOT traffic signal engineers. ATSPM and DSRC data stored on UDOT servers were used in this analysis to evaluate the impact of TSP on general traffic by measuring changes in split fail and green time when TSP was granted, and the number of times TSP was requested

and granted. Extensive data manipulation and processing was needed to perform this analysis, which was only performed for equipped intersections along Route 217. The *Draft Redwood Road TSP Implementation Study* (Avenue Consultants 2018) contains additional details about the traffic analysis, but this section summarizes how split fail, green time, and TSP frequency were used to evaluate the impact of TSP on general traffic.

4.4.1 Split Fail

Split fail, which was the primary metric used to measure the impact of TSP on general traffic, occurs when the duration of green for a movement, or split, at a signalized intersection is insufficient to serve the amount of demand present (Li et al. 2016). For this study, split failure occurred when vehicle occupancy exceeded 85 percent of both green time and the first 5 seconds of red time. For a given conflicting phase, the frequency of split failure during the 10 minutes before TSP was served was compared to the frequency of split failure during the 10 minutes after TSP was served. If any of the conflicting phases experienced an increase in split fail from pre-TSP to post-TSP, it was determined that there was a negative impact to general traffic.

4.4.2 Green Time

In addition to split fail, which measures the impact on general traffic, the change in green time was evaluated for the phases served with TSP (usually the NB and SB through movements, or phases 2 and 6), which measures the impact of serving TSP on the signal timing. For the phases served with TSP, the average green time in the 10 minutes prior to TSP being served is compared to the amount of green time allocated to these same phases during the cycle in which TSP was served.

One of the deficiencies with the traffic analysis is its inability to distinguish between the allocation of extra green time to the phases being served TSP due to the conflicting phases gapping out or TSP being served. Signal timings are set up so that all phases have a minimum number of seconds that they must be green (min green) and a maximum number of seconds they can be green (max green), as long as the presence of vehicles is detected. Whenever the duration of green time for a phase is less than max green, a “gap-out” occurs. When TSP is served, it prevents conflicting phases from achieving max green even if there are vehicles present, and

allocates the amount of green time taken from conflicting phases to the phases being served TSP. So, when TSP is served and extra green time is allocated to phases being served with TSP, this analysis compares the duration of green time for the served phases in the cycle TSP was served (X seconds) with the average duration of green time for the served phases during the 10 minutes prior to TSP being served (Y seconds). “X” minus “Y” then equals the extra green time in seconds when TSP was served.

The major issue with this methodology is that if gap-outs of conflicting phases occur in the 10 minutes prior to TSP being served, the average duration of green time for phases served TSP will include “g,” which equals the extra time allocated to phases served TSP due to gap-outs. If there are no gap-outs in the cycle when TSP is served, a reasonable scenario because TSP is shortening the conflicting phases, and the TSP treatment adds green time that equals “g” seconds, then the analysis will comparatively show that there was no change in green time due to TSP.

This phenomenon is easily apparent at the intersection of Redwood Road and 2100 South, which is an equipped intersection, but TSP is not enabled. The RSU receives SRM messages and forwards the TSP request to the controller just like any other equipped intersection, but the timing remains unchanged because TSP is not enabled. However, if a gap-out occurs during the cycle in which TSP is requested, the high-resolution data recorded by the controller make no differentiation between the two; the generated data are identical to a TSP-enabled intersection that actually granted TSP. Both Econolite and Intelight controllers record the data in such a way that there is no distinction in the data.

At intersections capable of granting TSP, the concern is the inability to determine how much extra green time allocated to phases served TSP resulted from gap-outs versus TSP. In some cases, the analysis showed that the change in green time when TSP was served was negative. This meant that in the 10 minutes before TSP was served, more extra green time was allocated to phases served TSP due to gap-outs than the extra green time allocated during the cycle when TSP was served. It is not possible to determine whether the allocated green time came from TSP alone or TSP plus gap-outs. Conversely, if no gap-outs occurred in the 10 minutes prior to TSP being served but they did occur during the cycle that serves TSP, the

analysis could report a change in green time greater than what TSP allows. Thus, the resulting interpretation is unable to state conclusively that the additional allocated green time was due to TSP, but that it was allocated when TSP was served.

4.4.3 Transit Signal Priority Frequency

The frequency at which TSP was served is used to evaluate the overall impact to the system. For example, if traffic is negatively affected 50 percent of the time TSP is served and TSP is served twice an hour, then traffic is negatively impacted once an hour on average. This information can be used to draw conclusions on the overall impact of TSP by peak period and by timepoint.

4.5 Chapter Summary

The data were evaluated by timepoint and at the corridor level for data pertaining to AM NB, AM SB, PM NB, and PM SB, the four directional peak scenarios. The data were filtered and excluded based on timepoint and the determination of outliers. For Route 217, data from the northernmost four timepoints were excluded because they were outside the equipped portion of the corridor. The West Jordan City Center timepoint data were also excluded because the schedule deviation values at this timepoint were so extreme that they would have unduly influenced the corridor-level analysis. No data were excluded for UVX based on timepoint. Additionally, outliers were determined based on the observed values for schedule deviation and travel time. Generally speaking, a record was determined to be an outlier if its value for schedule deviation or travel time was in the top or bottom 0.5 percent of the data.

An observational analysis was performed on OTP while a statistical analysis was used to evaluate schedule deviation and travel time. The statistical analysis performed a mixed-model multiple regression analysis on the data, which controlled for the correlative effects of the hour of the day, timepoint, scheduled headway, and the number of times a bus stopped to load or unload passengers. The statistical analysis focused on measuring the change in variability among the data as the requesting threshold changed through the residual standard deviation.

Finally, a traffic analysis was performed through a process developed by Avenue Consultants to evaluate the impact of changing the requesting threshold on split fail and change in green time when TSP was served. Additionally, the frequency of TSP requests and grants were used to further understand the impact on general traffic.

5.0 RESULTS

5.1 Overview

It is expected that as the requesting threshold approaches zero and TSP is requested and consequently served more often, there will be greater positive impacts on bus performance and greater negative impacts on general traffic. Thus, it is anticipated that a positive correlation will exist between the frequency of TSP being served and bus performance while impacts to general traffic will have a negative correlation. In other words, it is expected that as the number of times TSP is granted increases, bus performance will improve and impacts to general traffic will worsen. Therefore, the optimal requesting threshold is sought in order to balance the positive impacts of TSP on bus performance with the negative impacts on general traffic.

This chapter contains the results from analyses of Route 217 bus performance, Route 217 general traffic, and UVX bus performance to test these expectations.

5.2 Route 217 Bus Performance Results

The purpose of TSP is to facilitate the movement of transit vehicles through traffic-signal controlled intersections. To verify the extent that this goal is being met, bus performance must be evaluated. For the four directional peak scenarios, the results show fairly consistent trends in line with the expectations for the AM peak regardless of direction of travel. In the PM peak, however, these trends are not as noticeable. Numerous factors such as traffic volume, traffic patterns, bus ridership levels, and weather may influence bus performance. The objective of this research was not to determine the impact of these other factors, but to study the impact of the requesting threshold, on which a sensitivity analysis was performed. Nevertheless, it is understood that traffic patterns and volumes generally have greater variability during the PM peak hours. It is believed that the inconsistencies observed in the results for the PM peak may be attributed to the influence of external factors, such as traffic patterns and volumes, that collectively have a greater impact on bus performance than TSP. During the AM peak, these same external factors may not be as influential, which is one of the reasons why trends and

consistencies may be more apparent for the AM peak. Consequently, Route 217 bus performance analyses emphasize the AM NB and AM SB directional peak scenarios.

The impact of changing the requesting threshold on bus performances is evaluated through OTP, schedule deviation, travel time, and dwell time which are each discussed in the following subsections.

5.2.1 Route 217 – On-Time Performance

OTP measures the percentage of on-time departures from a timepoint and is evaluated at the corridor and timepoint levels for each of the directional peak scenarios. The results of the corridor-level OTP analysis are shown in Figure 5-1. The data show that as the requesting threshold approaches zero, OTP generally increases with the 0-minute threshold usually having the highest OTP. An anomaly is that the data indicate that OTP is often higher at the 5-minute threshold than at the 3-minute threshold. This is most likely due to the effect of the April 2019 change day, which changed the schedule for the time during which data were collected at the 3-, 2-, and 0-minute requesting thresholds; the 5-minute data were collected pre-change day and had a slightly different schedule. On average, when data from all directional peak scenarios are combined, OTP increased 2.0 percent when the requesting threshold changed from 3 minutes to 2 minutes, and 2.5 percent when the requesting threshold changed from 2 minutes to 0 minutes.

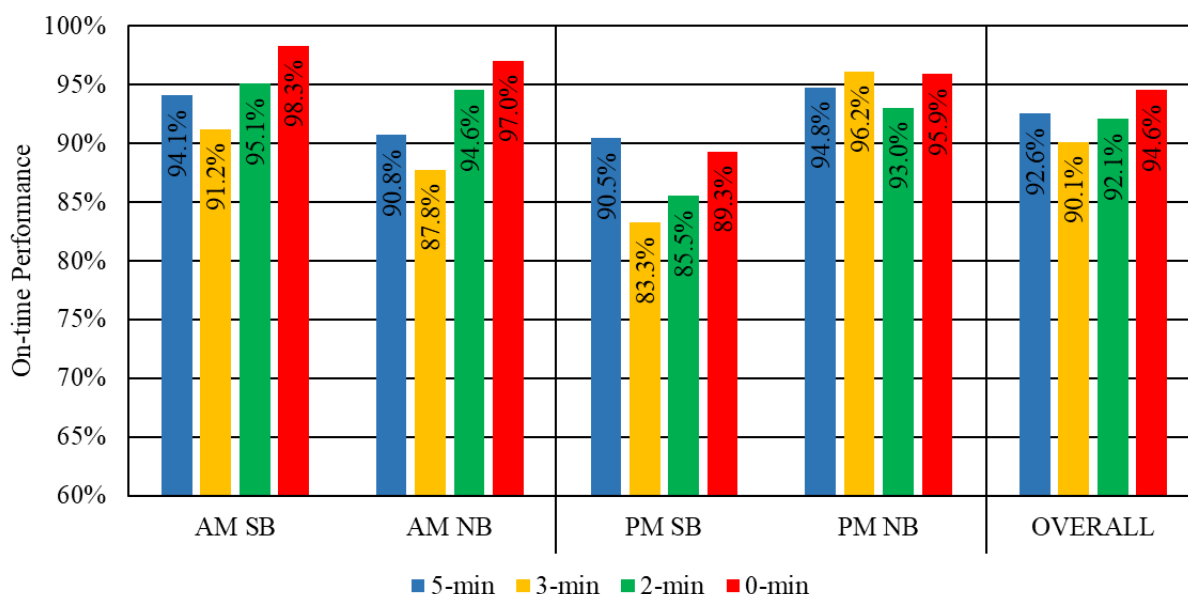


Figure 5-1: Route 217 corridor-level OTP.

Other than PM NB, an interesting trend is observed for the other three directional peak scenarios following the April 2019 change day when the requesting threshold changed from 5 minutes to 3 minutes. It was observed numerically that OTP dropped 2.9 percent for AM SB, 3.0 percent for AM NB, and 7.2 percent for PM SB. This implies that even though the requesting threshold was 3 minutes instead of 5 minutes, the new schedule affected OTP enough that it could not be overcome with a more favorable TSP environment alone (a 3-minute requesting threshold being more favorable than a 5-minute threshold because requests would be made more frequently). Once the new schedule was in place, OTP increased an average of 3.6 percent (AM SB), 4.6 percent (AM NB), and 3.0 percent (PM SB) each time the requesting threshold changed.

It also important to note the magnitude of the range between the highest and lowest OTP values for each directional peak scenario under the new schedule (3-, 2-, and 0-minute thresholds), which is 7.1 percent (AM SB), 9.2 percent (AM NB), 6.0 percent (PM SB), and 3.2 percent (PM NB). This is important because it shows the range of impact that the requesting threshold has. These ranges are lower in the PM scenarios, indicating that TSP may have less of an influence at this time of day.

Figure 5-2 and Figure 5-3 illustrate the OTP results at the timepoint level for the AM and PM peak, respectively, with the percent in parentheses representing the corridor-level OTP. The numerical results are shown in Table 5-1. It is important to note that SB bus performance at the Power Station timepoint (the first timepoint listed in the SB direction) is not affected by TSP settings because there are no equipped intersections north of Power Station. The opposite cannot be said of NB bus performance at the 7000 South timepoint (the first timepoint listed in the NB direction) because there are equipped intersections through which NB buses pass prior to arriving at the 7000 South timepoint.



Figure 5-2: Route 217 AM OTP.

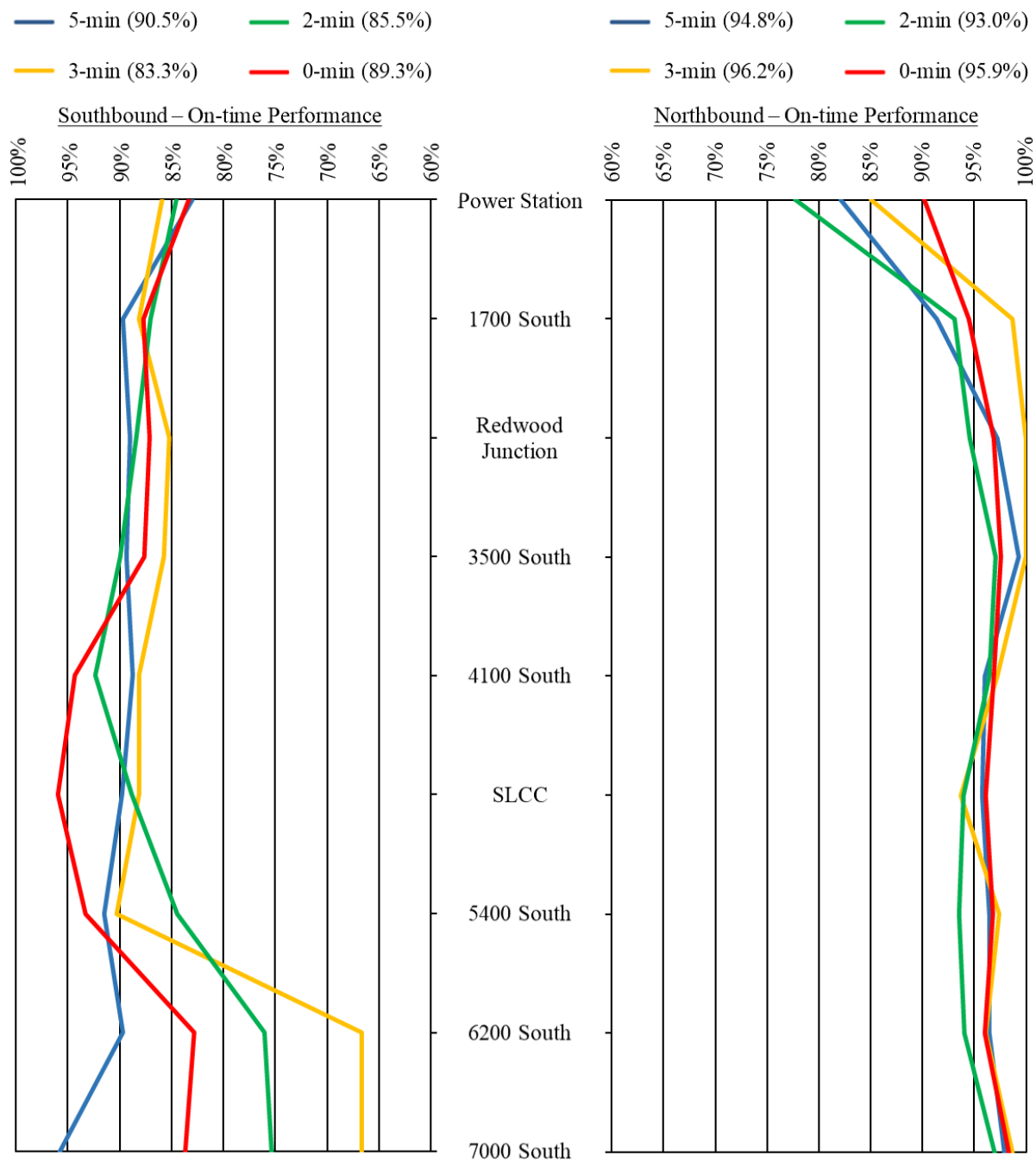


Figure 5-3: Route 217 PM OTP.

Table 5-1: Route 217 Timepoint-level OTP (percentage)

Timepoint (Listed North to South)	AM SB				AM NB				PM SB				PM NB			
	5 min	3 min	2 min	0 min	5 min	3 min	2 min	0 min	5 min	3 min	2 min	0 min	5 min	3 min	2 min	0 min
Power Station	91.3	86.4	93.4	93.0	91.4	84.6	91.8	97.6	82.9	85.9	84.5	83.3	82.1	85.1	77.7	90.2
1700 South	95.7	91.7	97.5	97.2	90.1	84.4	93.5	96.7	89.7	88.1	87.0	87.7	91.4	98.7	93.1	94.4
Redwood Junction	91.4	89.4	93.0	98.6	88.3	84.4	90.6	92.9	89.0	85.2	88.4	87.1	97.2	100	94.6	96.9
3500 South	93.9	93.5	94.0	96.8	87.8	82.4	92.5	94.9	89.3	85.7	89.9	87.6	99.3	100	97.0	97.6
4100 South	93.1	93.5	96.0	96.8	89.2	88.9	93.8	95.9	88.7	88.2	92.3	94.3	96.0	97.3	96.5	96.9
SLCC	97.2	93.5	98.0	100	90.3	77.8	95.5	97.8	89.7	88.2	88.8	95.9	95.8	93.8	94.0	96.1
5400 South	94.3	93.2	95.0	100	92.3	93.0	95.9	98.8	91.5	90.3	84.4	93.3	96.5	97.4	93.5	96.8
6200 South	94.2	87.5	93.6	100	92.1	90.9	97.9	100	89.7	66.7	76.1	82.8	96.5	96.2	94.1	96.0
7000 South	93.1	88.2	92.2	98.0	95.7	97.7	100	100	95.7	66.7	75.3	83.7	97.9	98.7	97.0	98.4
CORRIDOR	94.1	91.2	95.1	98.3	90.8	87.8	94.6	97.0	90.5	83.3	85.5	89.3	94.8	96.2	93.0	95.9

One way to analyze the data is to look at OTP when buses begin the route and how it changes as progression is made through the corridor. The AM NB data, which are shown in Figure 5-4 for illustrative purposes, show the average OTP as buses began the route (7000 South) at 97.7 percent (3-minute threshold) and 100 percent (2-minute threshold), a 2.3 percent difference numerically. Buses arrived at the end of the equipped corridor (Power Station) with an average OTP of 84.6 percent (3-minute threshold) and 91.8 percent (2-minute threshold), a 7.2 percent difference. Thus, the cumulative impact of the change in threshold can be calculated by subtracting the difference in OTP at the beginning of the route (2.3 percent) from the difference in OTP at the end of the route (7.2 percent), which in this example results in a cumulative impact of 4.9 percent in the AM NB as the threshold changed from 3 to 2 minutes.

Timepoint (Listed North to South)	AM NB			
	5 min	3 min	2 min	0 min
Power Station	91.4	84.6	91.8	97.6
1700 South	90.1	84.4	93.5	96.7
Redwood Junction	88.3	84.4	90.6	92.9
3500 South	87.8	82.4	92.5	94.9
4100 South	89.2	88.9	93.8	95.9
SLCC	90.3	77.8	95.5	97.8
5400 South	92.3	93.0	95.9	98.8
6200 South	92.1	90.9	97.9	100
7000 South	95.7	97.7	100	100

91.8 - 84.6 = 7.2

7.2 - 2.3 = 4.9

100 - 97.7 = 2.3

Figure 5-4: Route 217 timepoint-level OTP for AM NB (percentage).

The results of applying this methodology to the four directional peak scenarios after the new bus schedule was implemented (3-, 2-, and 0-minute thresholds only) are found in Table 5-2. This trend was not always present and in two instances, when the threshold changed from 3 to 2 minute for the AM SB and PM NB, negative values were obtained. OTP was impacted unexplainably at 6200 South in the PM SB scenario that resulted in obtaining large values in Table 5-2 for PM SB. No effort was made to normalize or equalize the OTP at the start of the route and the data were reported as observed.

Table 5-2: Route 217 OTP Cumulative Impact of Threshold Changes

Threshold Change	AM		PM	
	SB	NB	SB	NB
3-min to 2-min	-3.1%	4.9%	10.1%	-5.6%
2-min to 0-min	6.2%	5.8%	9.5%	11.1%

In summation, for AM NB, AM SB, and PM SB data collected after the schedule change (3-, 2-, and 0-minute requesting thresholds), the implementation of a 0-minute requesting threshold resulted in the highest OTP at the corridor level and at nearly every timepoint. The 2-minute threshold likewise resulted in the second highest OTP at the corridor level and at nearly every timepoint. For all directional peak scenarios, the average numerical difference in corridor-level OTP is 3.2 percent higher for the 0-minute threshold when compared to the 2-minute threshold, and 4.3 percent higher for the 2-minute threshold when compared to the 3-minute threshold.

5.2.2 Route 217 – Schedule Deviation

Schedule deviation measures the difference between the actual and scheduled departure time in seconds, a more granular way to measure schedule adherence than OTP which is binary (on time or late). Subsections include the results of evaluating schedule deviation through the difference in means analysis, the 95 percent prediction interval, and the analysis of variability.

5.2.2.1 Route 217 – Schedule Deviation: Difference in Means

The statistical model was used to estimate the mean schedule deviation and the standard error (SE) of the mean for each directional peak scenario and overall. Figure 5-5 contains estimates of the mean schedule deviation at the corridor level and overall, which combines data from all directional peak scenarios.

The comparison of means between two requesting thresholds was performed through a two-sided t-test, which measures whether there is a statistically significant difference in mean schedule deviation. The corridor-level p-values from the difference in means statistical analysis are displayed in Table 5-3 and are organized by directional peak scenario and comparison pair. The p-values in this table have been converted from the original, two-sided t-test p-values to one-

sided t-test p-values in order to reflect the anticipated decrease in mean schedule deviation as the requesting threshold approaches zero (the null hypothesis). Consequently, a low p-value for any comparison pair supports the concept that mean schedule deviation decreases as the requesting threshold approaches zero. When the difference in means supports the null hypothesis, as is the case in the AM NB 2-minute vs 0-minute comparison pair where mean schedule deviation decreases, the new p-value equals the original p-value divided by two, which is shown in Equation 5-1. When the difference in means goes against the null hypothesis, as is the case in the AM NB 5-minute vs 3-minute comparison pair where mean schedule deviation increases, the new p-value equals one minus the original p-value divided by two, which is shown in Equation 5-2.

In addition to the standard comparison pairs evaluated for Route 217, Table 5-3 also contains the results of the 3-minute vs 2-minute and 3-minute vs 0-minute comparison pairs. The shaded cells in Table 5-3 emphasize p-values less than 0.01 (the pseudo-Bonferroni adjustment) and indicate that a statistically significant improvement in mean schedule deviation exists for the given comparison pair and directional peak scenario according to the null hypothesis.

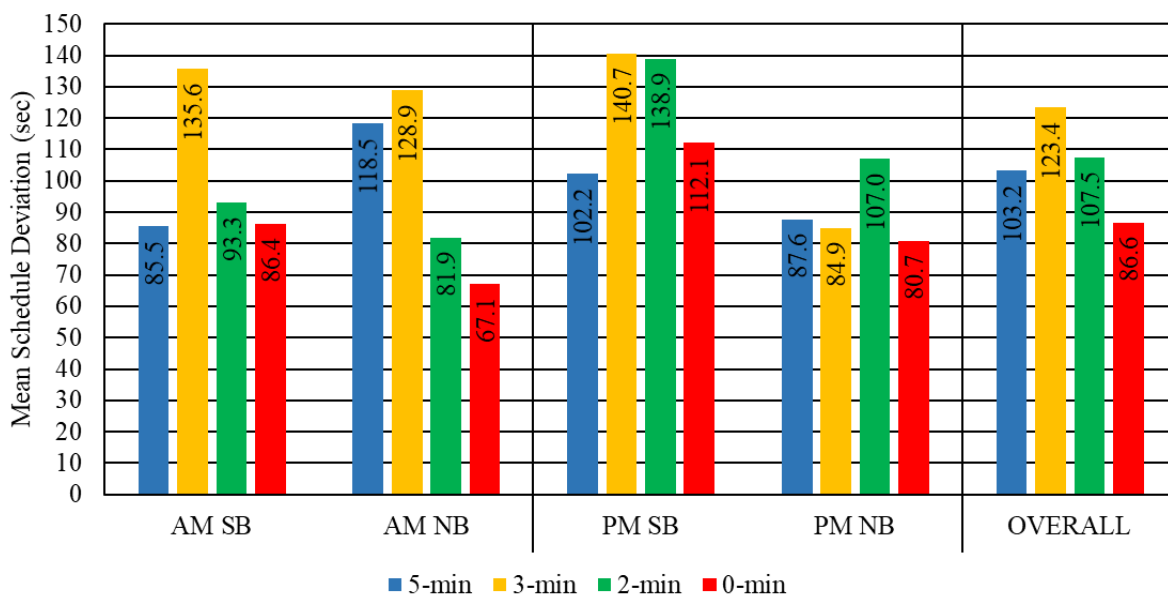


Figure 5-5: Route 217 mean corridor-level schedule deviation.

Table 5-3: Route 217 Corridor-Level Difference in Means P-Values

Comparison Pair	AM SB	AM NB	PM SB	PM NB	OVERALL
5-min vs 3-min	>0.9999	0.9164	0.9992	0.3005	>0.9999
5-min vs 2-min	0.8614	<0.0001	0.9994	>0.9999	0.84285
5-min vs 0-min	0.5491	<0.0001	0.8037	0.0663	0.0001
2-min vs 0-min	0.1959	0.0059	0.0105	<0.0001	<0.0001
3-min vs 2-min	<0.0001	<0.0001	0.44145	>0.9999	0.0005
3-min vs 0-min	<0.0001	<0.0001	0.0108	0.2114	<0.0001

$$\text{new } p\text{-value that supports null hypothesis} = \frac{\text{original } p\text{-value}}{2} \quad (5-1)$$

$$\text{new } p\text{-value that rejects the null hypothesis} = 1 - \frac{\text{original } p\text{-value}}{2} \quad (5-2)$$

Practically the same trends are present for mean schedule deviation as was observed for OTP. After the 5-minute data were collected, the April 2019 change day occurred, which modified the schedule for the remaining data collection periods. The schedule change that likely caused the decrease in OTP from the 5-minute to the 3-minute requesting threshold appropriately and inversely resulted in an increase in mean schedule deviation. Anomalies are once again seen in the PM NB, but for the remaining three directional peak scenarios, the corridor-level mean schedule deviation always improved as the requesting threshold changed from 3 minutes to 2 minutes, and from 2 minutes to 0 minutes.

Despite the PM NB anomalies, the overall mean schedule deviation drops from 123.4 seconds at the 3-minute threshold to 107.5 seconds at the 2-minute threshold ($p = 0.0005$), and from 107.5 seconds at the 2-minute threshold to 86.6 seconds at the 0-minute threshold ($p < 0.0001$). On average, mean schedule deviation improved 18.4 seconds each time the requesting threshold changed from 3 minutes to 2 minutes, and from 2 minutes to 0 minutes. Although there is convincing evidence that mean schedule deviation improves (decreases) as the requesting threshold approaches zero and mean schedule deviation for AM SB, AM NB, and PM SB always improved as the requesting threshold changed from 3 minutes to 2 minutes, and from 2 minutes to 0 minutes, the improvement was not always statistically significant. In fact, it was only the AM peak period where significant improvements occurred consistently.

At the timepoint level, the results of the difference in means are shown graphically by plotting the estimated mean and the SE range at each timepoint, with the range being calculated using Equation 5-3. The figures in this subsection are listed in Table 5-4 and are organized by directional peak scenario and by comparison pair. Four comparison pairs were evaluated; each requesting threshold was compared to the baseline 5-minute requesting threshold and then the 0-minute and 2-minute thresholds were compared against each other. Tabulated statistical results for each directional peak scenario and figures for the PM peak are found in Appendix A.2.

$$\text{standard error range} = \mu \pm (2 \times SE) \quad (5-3)$$

where:

μ = mean schedule deviation

SE = standard error

Table 5-4: Route 217 Schedule Deviation Difference in Means Figures List

Comparison Pair	AM SB	AM NB
5-min vs 3-min	Figure 5-6	Figure 5-11
5-min vs 2-min	Figure 5-7	Figure 5-12
5-min vs 0-min	Figure 5-8	Figure 5-13
2-min vs 0-min	Figure 5-9	Figure 5-14
All Means	Figure 5-10	Figure 5-15

Generally, if the mean of one requesting threshold falls within the SE range of the other threshold, there is not a statistically significant difference between the estimated means at that timepoint. In Figure 5-6, for example, the p-value of the two-sided t-test is 0.0014 at Power Station where the SE ranges barely overlap; 0.0239 at 3500 South where the means fall just outside the SE range of the other requesting threshold; 0.1711 at 4100 South where the 3-minute mean falls just outside the 5-minute SE range but the 5-minute mean is within the 3-minute SE range; and 0.2230 at SLCC where both means fall within the SE range of the other threshold. At the corridor level, the p-value for the two-sided t-test is contained within the caption of the figure. In some cases, the corridor-level p-value is significant while p-values at each timepoint are insignificant. This is because the small, insignificant difference in means at timepoints cumulate towards a significant difference in means at the corridor level.

The mean is compared between requesting thresholds for each of the four comparison pairs listed in Table 5-4 at nine timepoints (36 comparisons) for each of the four directional peak scenarios (overall total of 144 comparisons). Of these 144 comparisons, there is a difference in means with a p-value less than 0.01 at 14 of them (1 for AM SB, 6 for AM NB, 3 for PM SB, and 4 for PM NB). A statistically significant difference in means only 10 percent of the time (14 out of 144) does not provide strong statistical evidence supporting the claim that mean schedule deviation decreases as the requesting threshold approaches zero. Moreover, there was not consistency in which the comparison pair had instances of statistically significant differences in means. Of the 14 instances with a statistically significant difference in means, five were comparing 0- and 5-minute requesting thresholds and there were three instances each comparing 2- and 5-minute, 3- and 5-minute, and 0- and 2-minute. Furthermore, consistency was also lacking based on which timepoints had instances of statistically significant differences in means. Of the 14 instances, one occurred at Power Station, one at 1700 South, zero at Redwood Junction, two at 3500 South, two at 4100 South, zero at SLCC, one at 5400 South, three at 6200 South, and four at 7000 South.

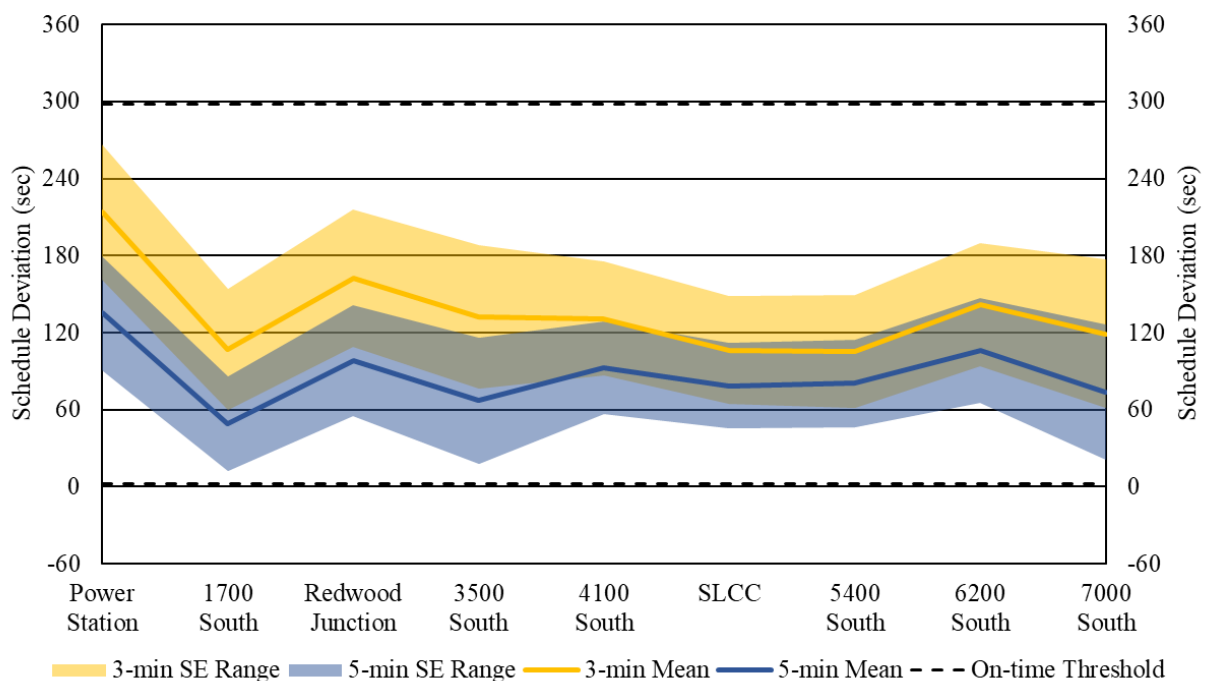


Figure 5-6: Route 217 AM SB schedule deviation SE range 5-min vs 3-min (p-value=<0.0001).

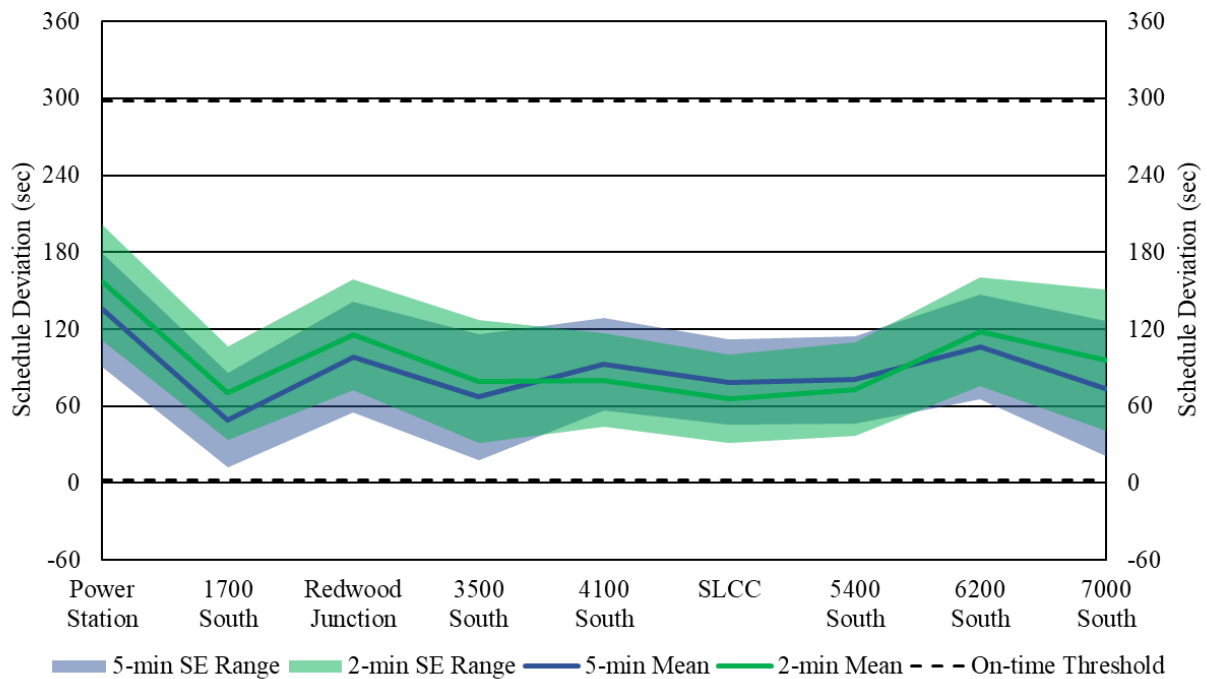


Figure 5-7: Route 217 AM SB schedule deviation SE range 5-min vs 2-min (p-value=0.2773).

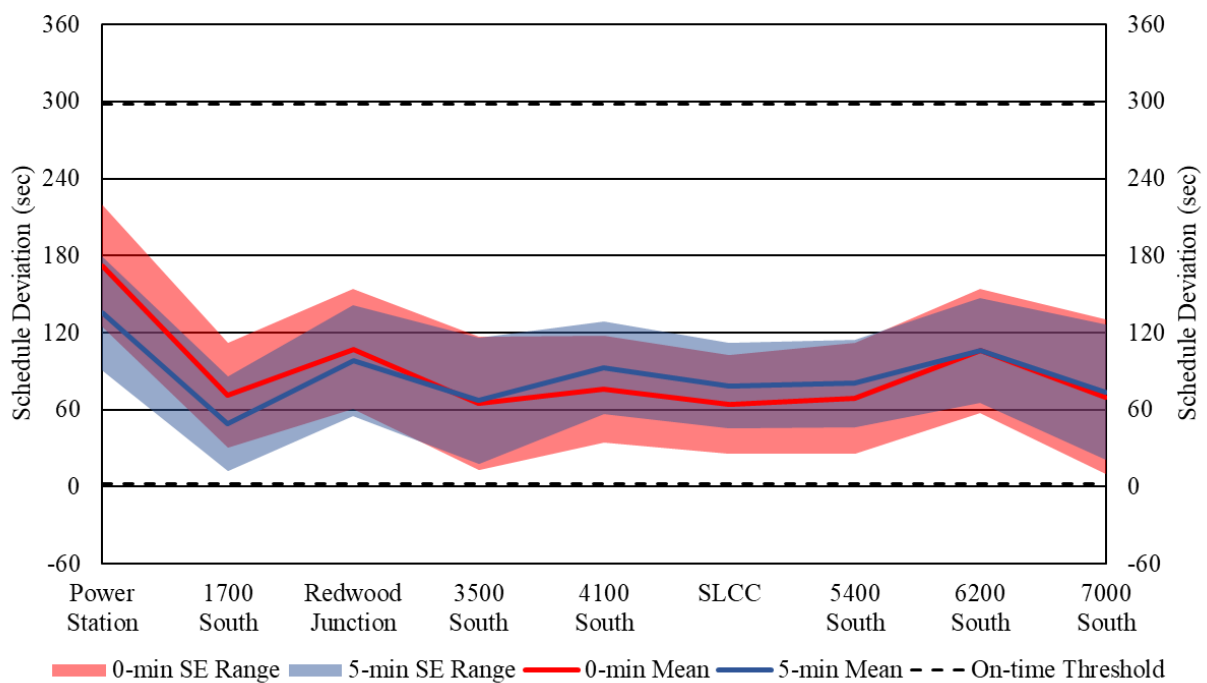


Figure 5-8: Route 217 AM SB schedule deviation SE range 5-min vs 0-min (p-value=0.9018).

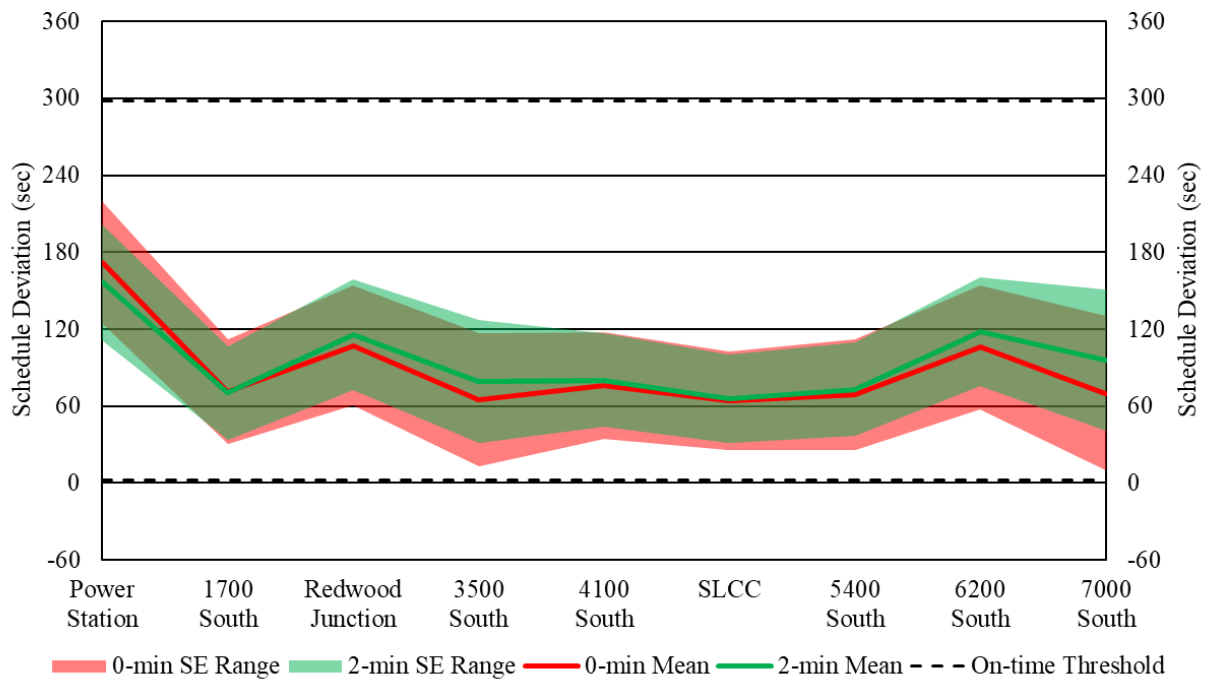


Figure 5-9: Route 217 AM SB schedule deviation SE range 2-min vs 0-min (p-value=0.3917).

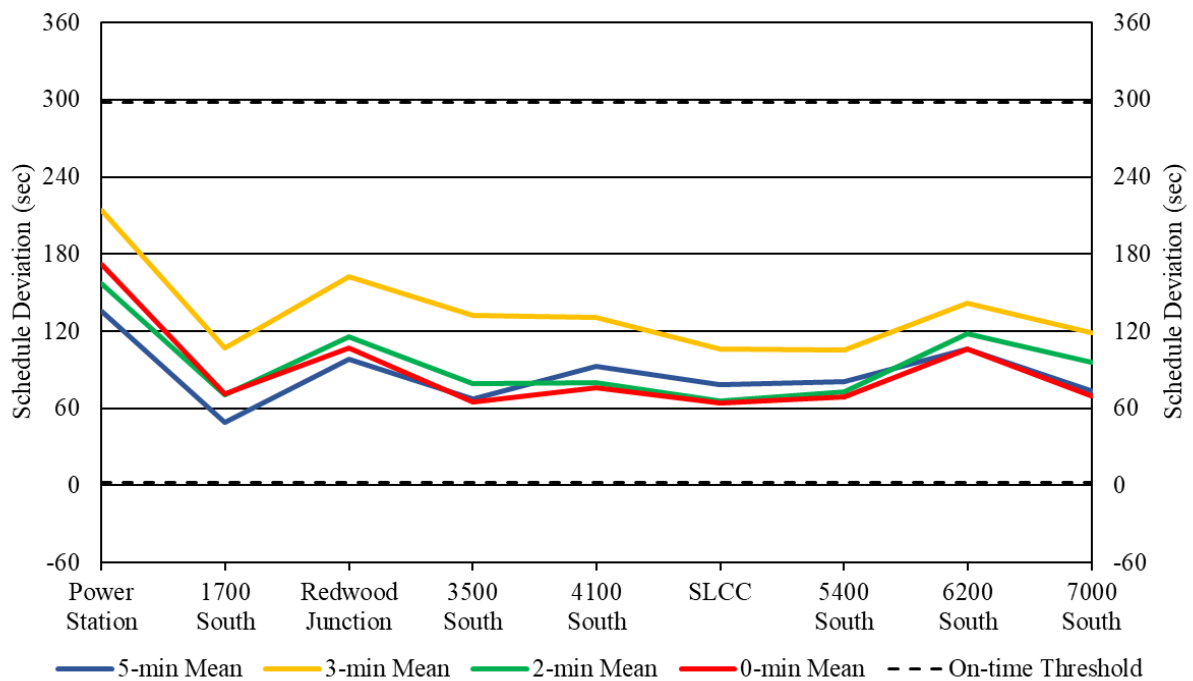


Figure 5-10: Route 217 AM SB mean schedule deviation.

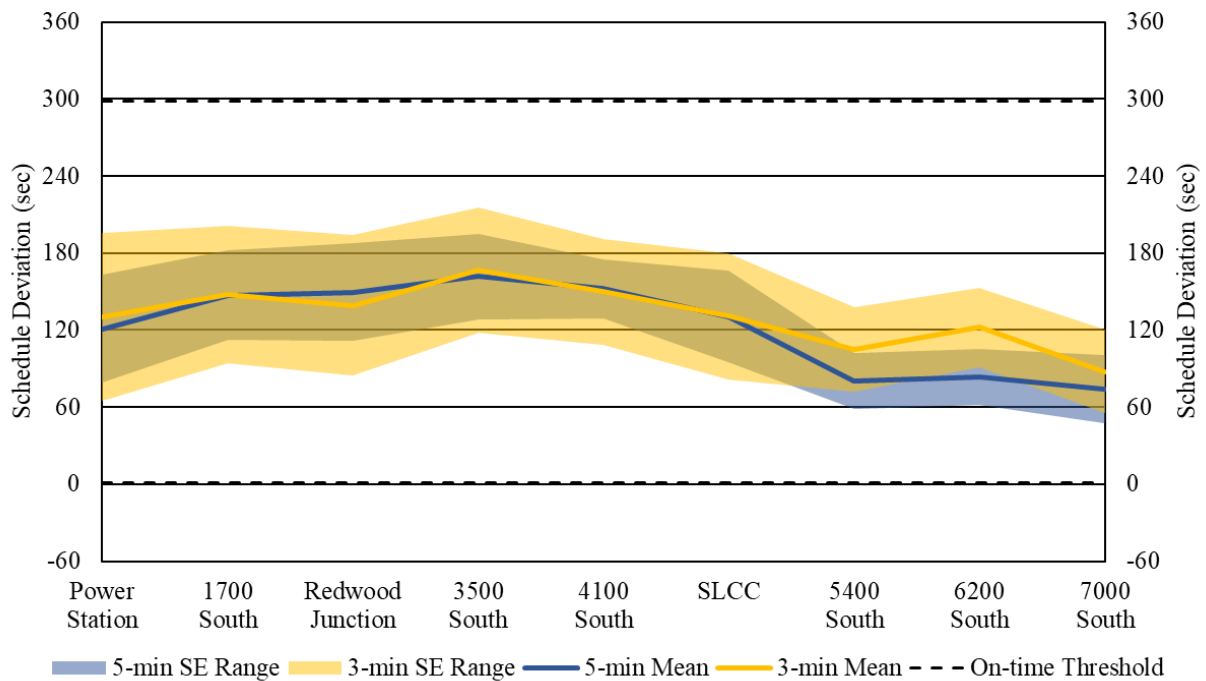


Figure 5-11: Route 217 AM NB schedule deviation SE range 5-min vs 3-min (p-value=0.1673).

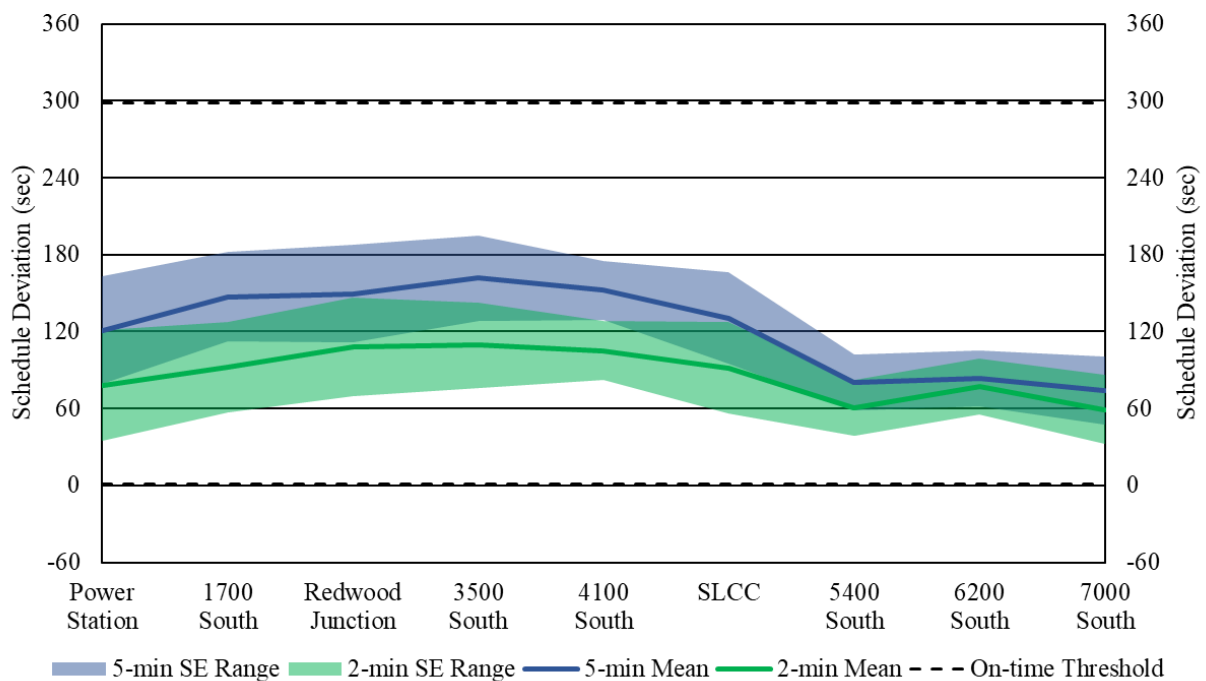


Figure 5-12: Route 217 AM NB schedule deviation SE range 5-min vs 2-min (p-value=<0.0001).

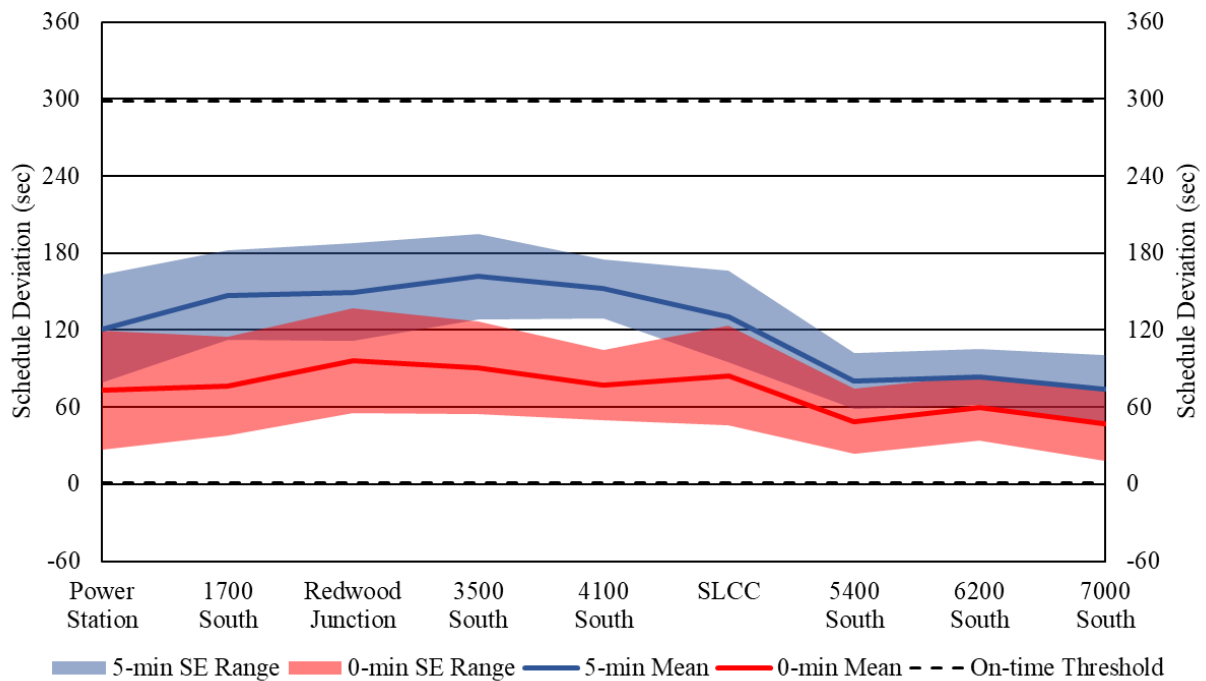


Figure 5-13: Route 217 AM NB schedule deviation SE range 5-min vs 0-min (p-value=<0.0001).

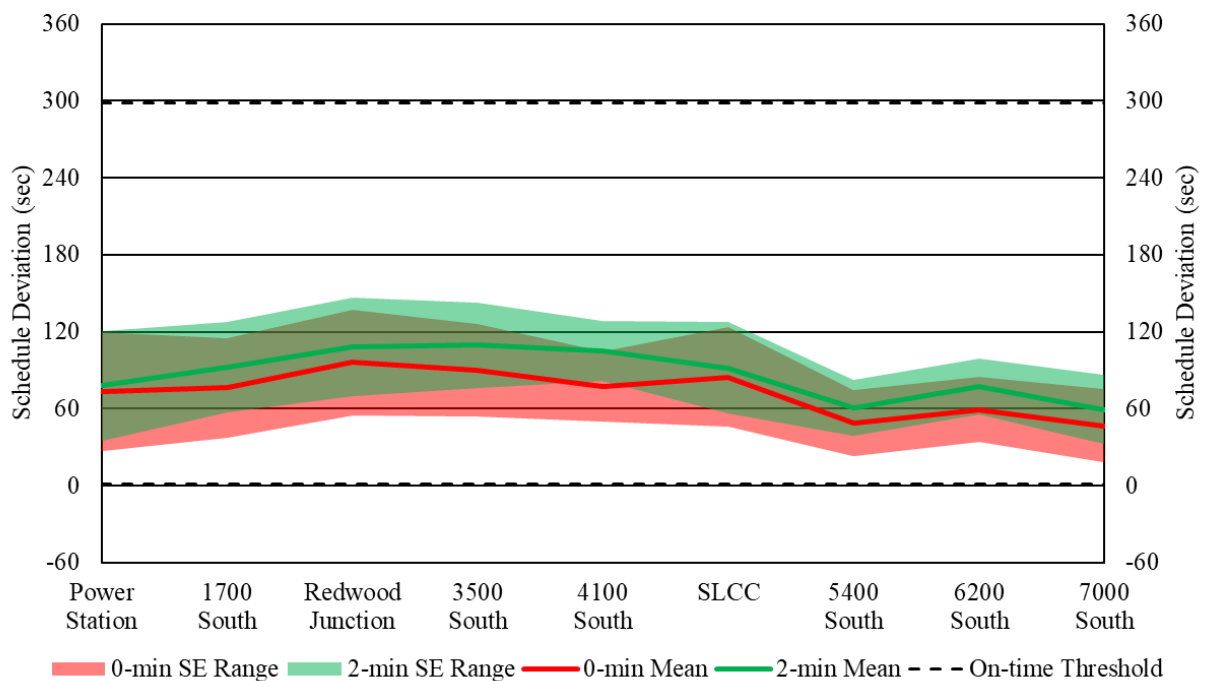


Figure 5-14: Route 217 AM NB schedule deviation SE range 2-min vs 0-min (p-value=0.0118).

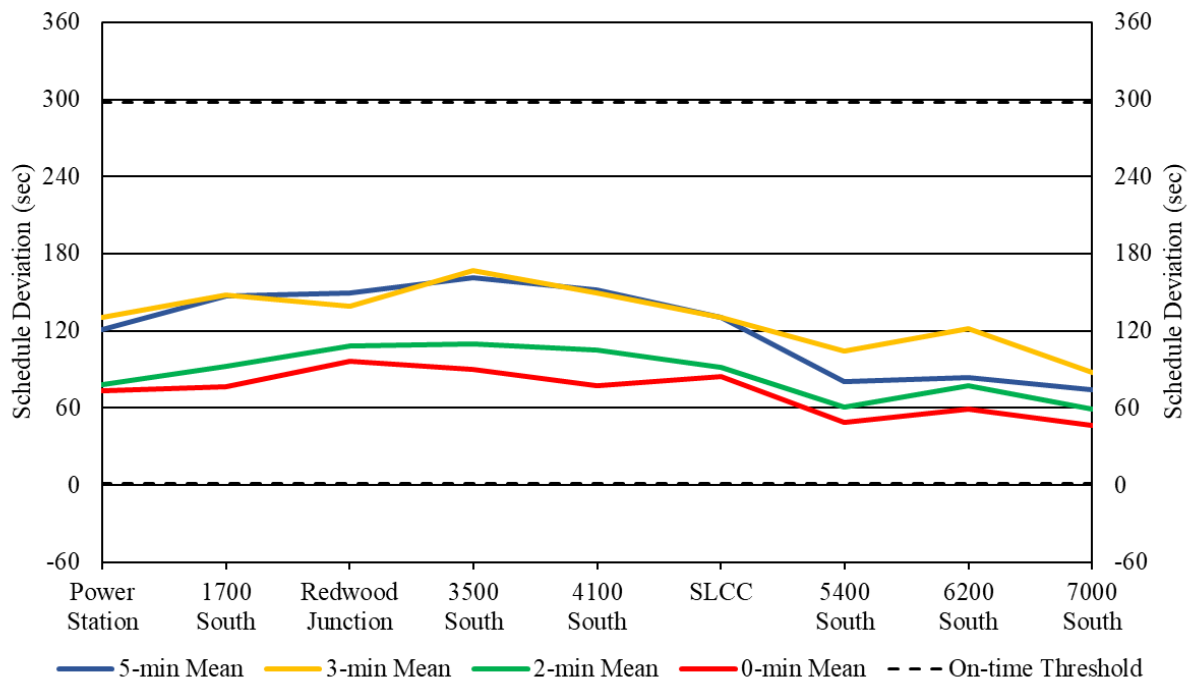


Figure 5-15: Route 217 AM NB mean schedule deviation.

However, when the graphs shown in this subsection are combined and displayed a slightly different way there is an obvious trend and evidence, albeit not statistical, that indicates that as the requesting threshold approaches zero, mean schedule deviation decreases. The combined AM SB graphs are displayed in Figure 5-16 and AM NB in Figure 5-17. The main addition to these graphs is a trendline drawn between the mean schedule deviation values at each timepoint for the 3-, 2-, and 0-minute requesting thresholds. The trendline slope is negative, indicating that schedule deviation improves as the requesting threshold approaches zero, at all 18 timepoints during the AM peak (nine per direction) and 13 of the 18 timepoints during the PM peak.

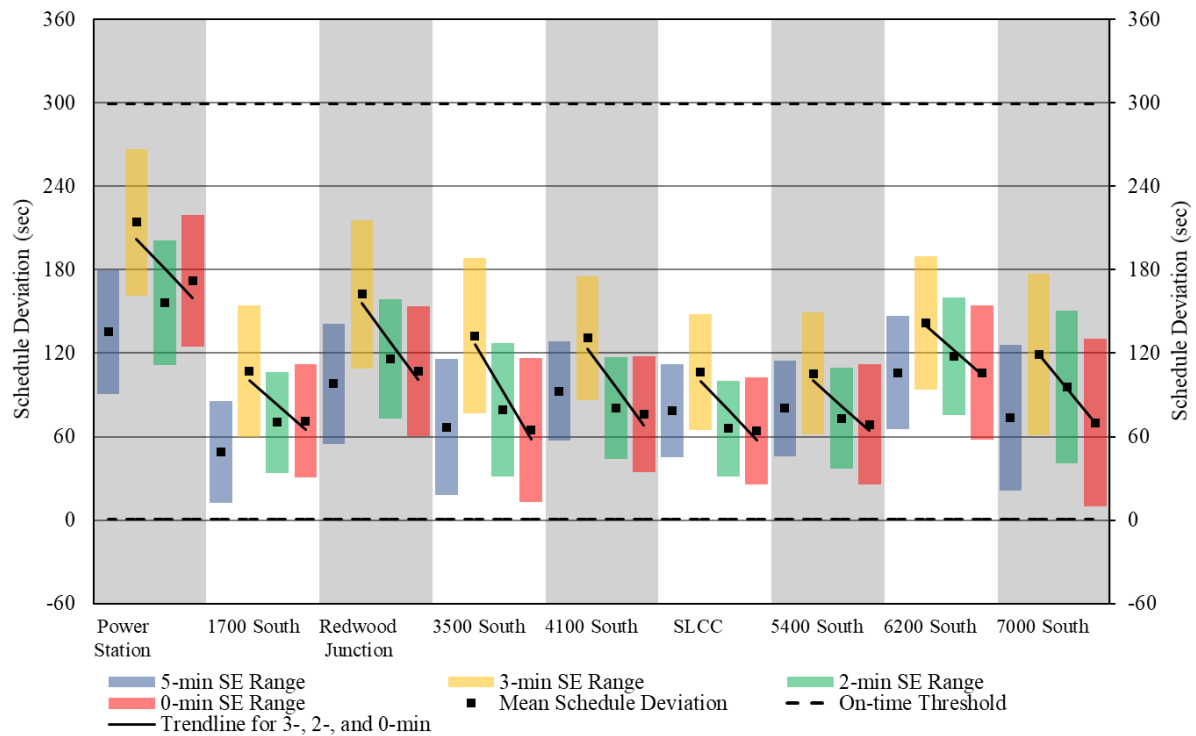


Figure 5-16: Route 217 AM SB schedule deviation SE range with all thresholds.

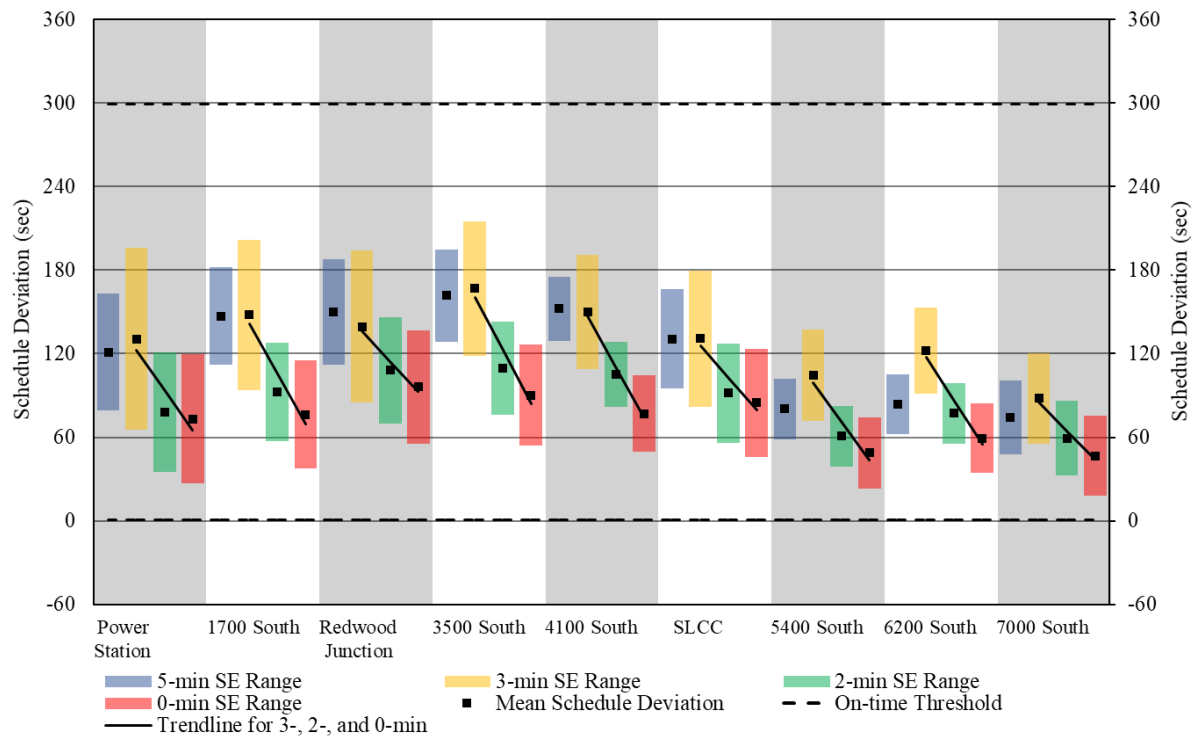


Figure 5-17: Route 217 AM NB schedule deviation SE range with all thresholds.

5.2.2.2 *Route 217 – Schedule Deviation: 95 Percent Prediction Interval*

The 95 percent prediction interval is the range of expected values based on the value of the 2.5th and 97.5th percentiles, thus representing the middle 95 percent of data. The magnitude of the 95 percent prediction interval is determined by calculating the difference in seconds between the values of the 97.5th and 2.5th percentiles. As the magnitude of the 95 percent prediction interval increases, variability in the data increases. Figure 5-18 contains the corridor-level and overall results of the 95 percent prediction interval for schedule deviation. The median schedule deviation values represented in the figure decrease between 17 and 33 seconds each time the requesting threshold changes from 3, to 2, to 0 minutes. Additionally, it is important to note that along with improvements for median schedule deviation, the upper bound of the 95th percent prediction interval (the 97.5th percentile value) experienced considerably greater improvements. In the AM NB scenario, for instance, all median values are within 65 seconds of each other while the 97.5th percentile values have a range of 308 seconds (618 seconds for the 5-minute threshold and 309 seconds for the 0-minute threshold).

The remaining figures in this subsection are listed in Table 5-5 and are organized by directional peak scenario and by comparison pair. Figures for the PM peak scenarios are found in Appendix A.3.

In the 95 percent prediction interval analysis, the general trend is that as the requesting threshold approaches zero, the magnitude of the 95 percent prediction interval is reduced, indicating a decrease in variability. In the AM NB scenario this trend is observed quite clearly. For all directional peak scenarios, the magnitudes of the 95 percent prediction interval for the 5-, 3-, 2-, and 0-minute requesting threshold are respectively 553, 582, 510, and 485 seconds.

An interesting observation is lack of adherence to the holding strategy for the AM SB scenario versus fairly strict adherence in the AM NB one. When the 95 percent prediction interval (the shaded region) dips into the negatives, it means that the holding strategy was not adhered to more than 2.5 percent of the time. Additionally, these figures highlight how skewed the data are through observing the relative proximity of the median schedule deviation to the 2.5th percentile (the low end of the shaded region).

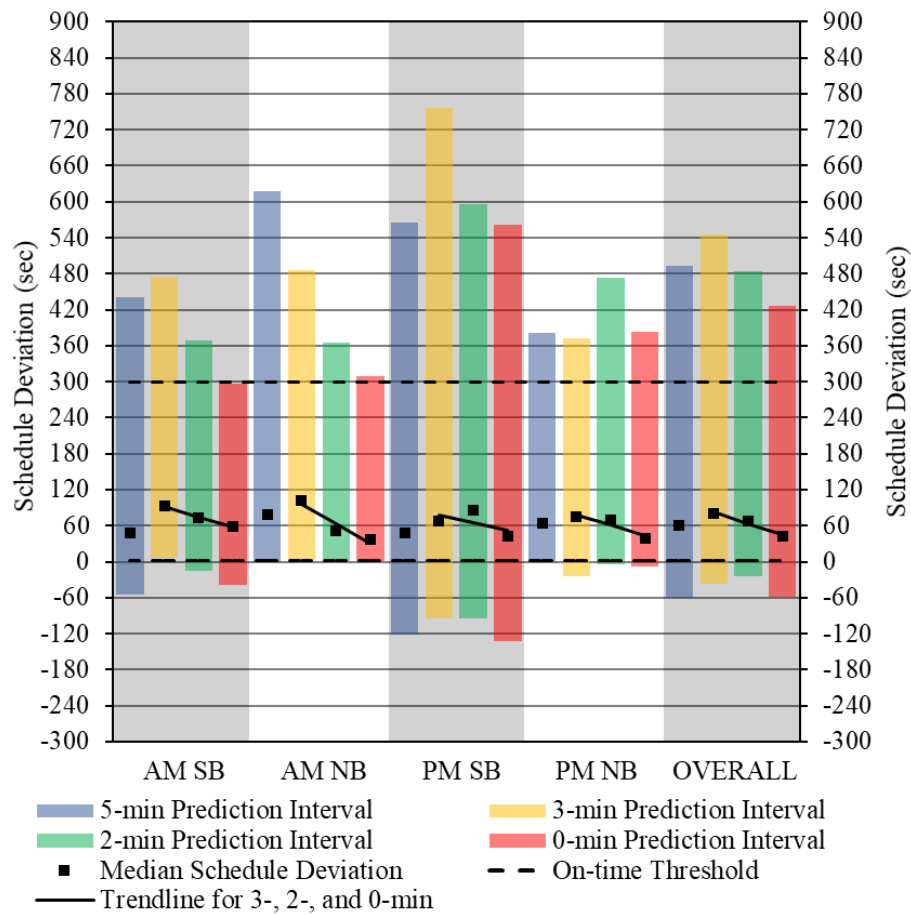


Figure 5-18: Route 217 95 percent prediction interval for schedule deviation at the corridor level and overall.

Table 5-5: Route 217 Schedule Deviation 95 Percent Prediction Interval Figures List

Comparison Pair	AM SB	AM NB
5-min vs 3-min	Figure 5-19	Figure 5-24
5-min vs 2-min	Figure 5-20	Figure 5-25
5-min vs 0-min	Figure 5-21	Figure 5-26
2-min vs 0-min	Figure 5-22	Figure 5-27
All Medians	Figure 5-23	Figure 5-28

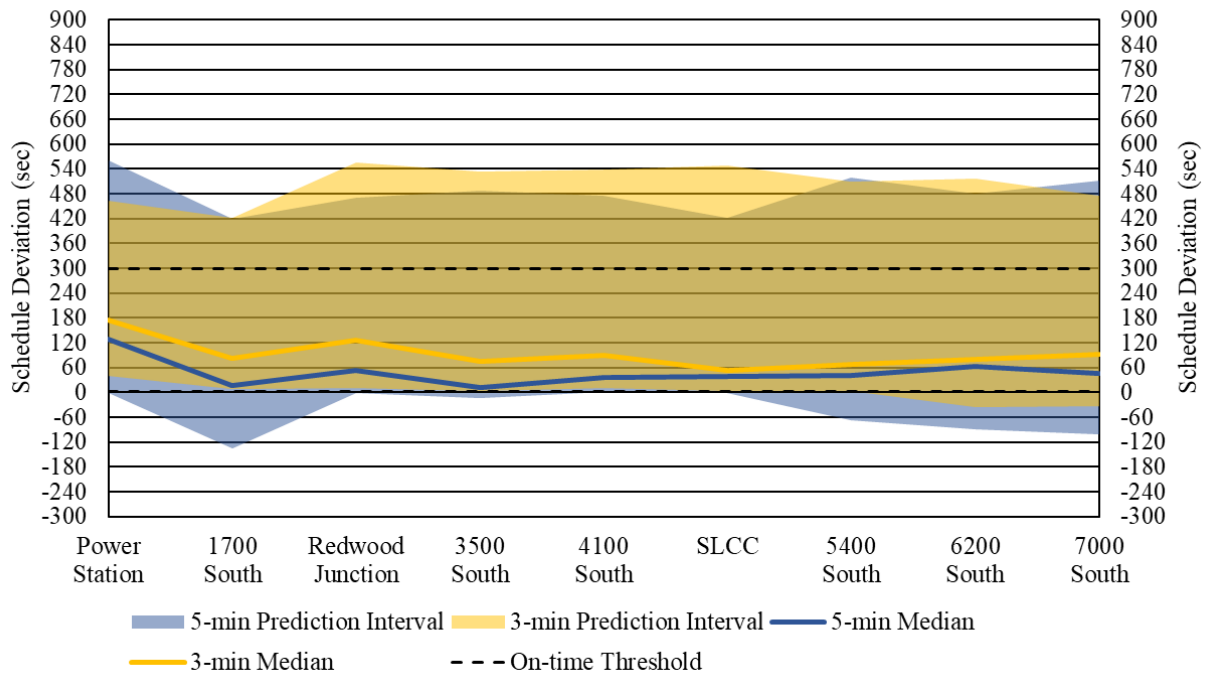


Figure 5-19: Route 217 AM SB schedule deviation prediction interval 5-min vs. 3-min.

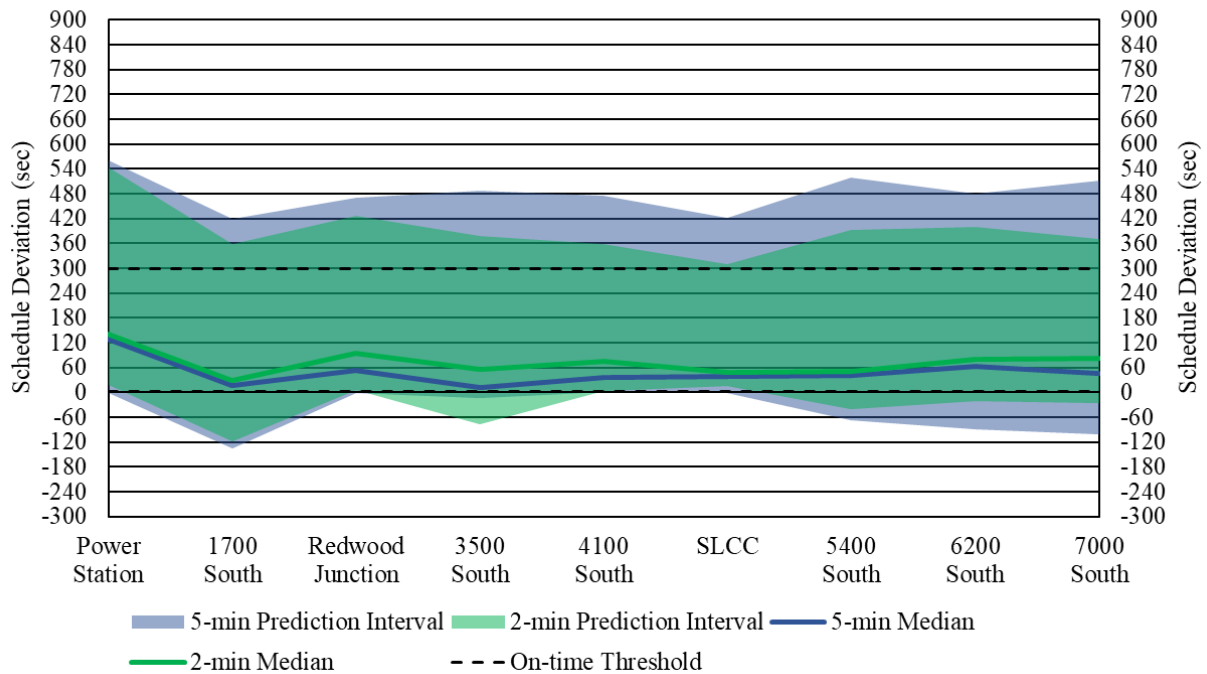


Figure 5-20: Route 217 AM SB schedule deviation prediction interval 5-min vs. 2-min.

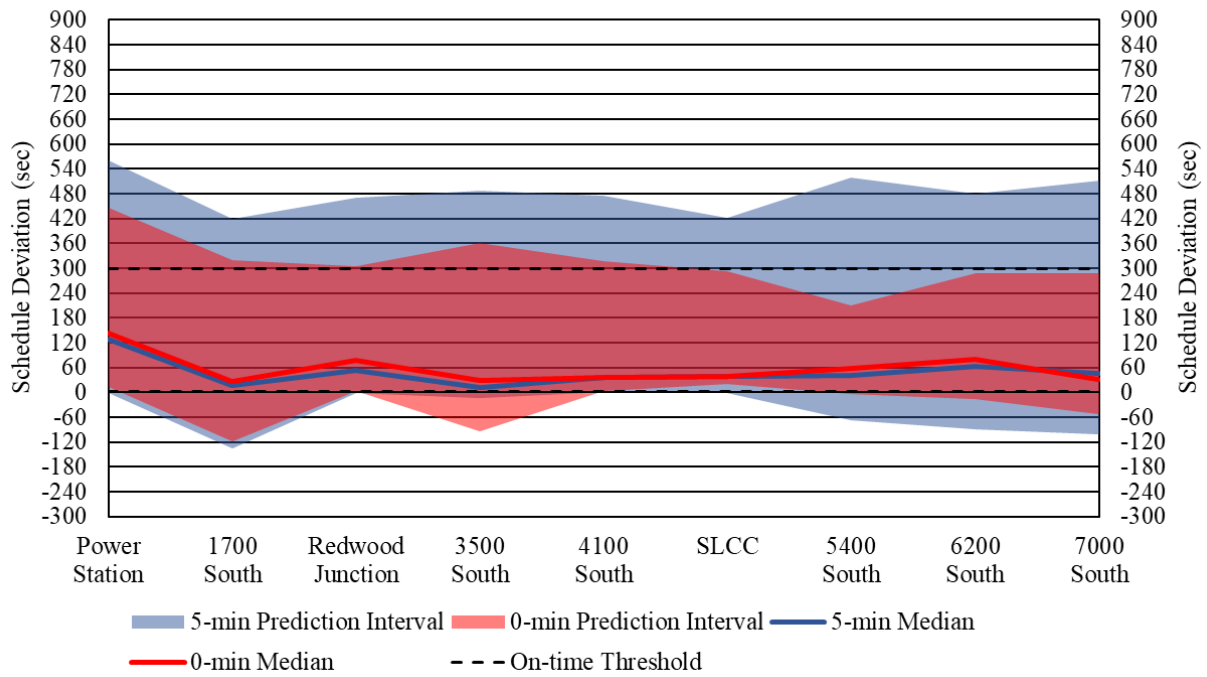


Figure 5-21: Route 217 AM SB schedule deviation prediction interval 5-min vs. 0-min.

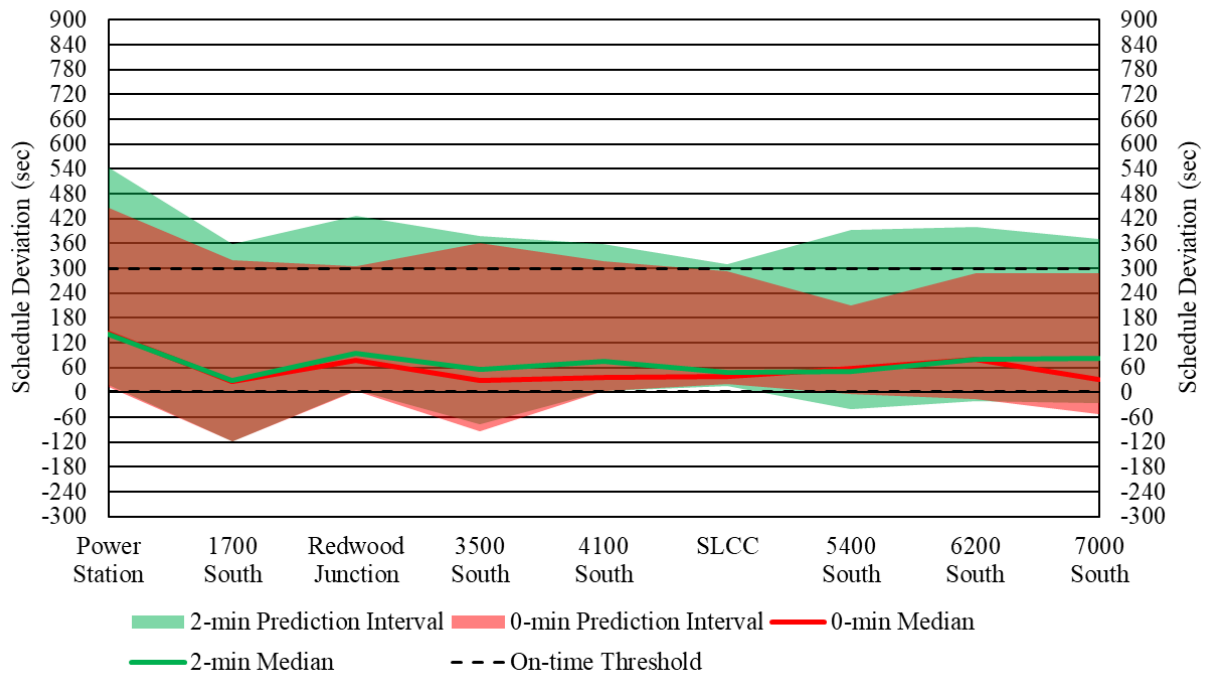


Figure 5-22: Route 217 AM SB schedule deviation prediction interval 2-min vs. 0-min.

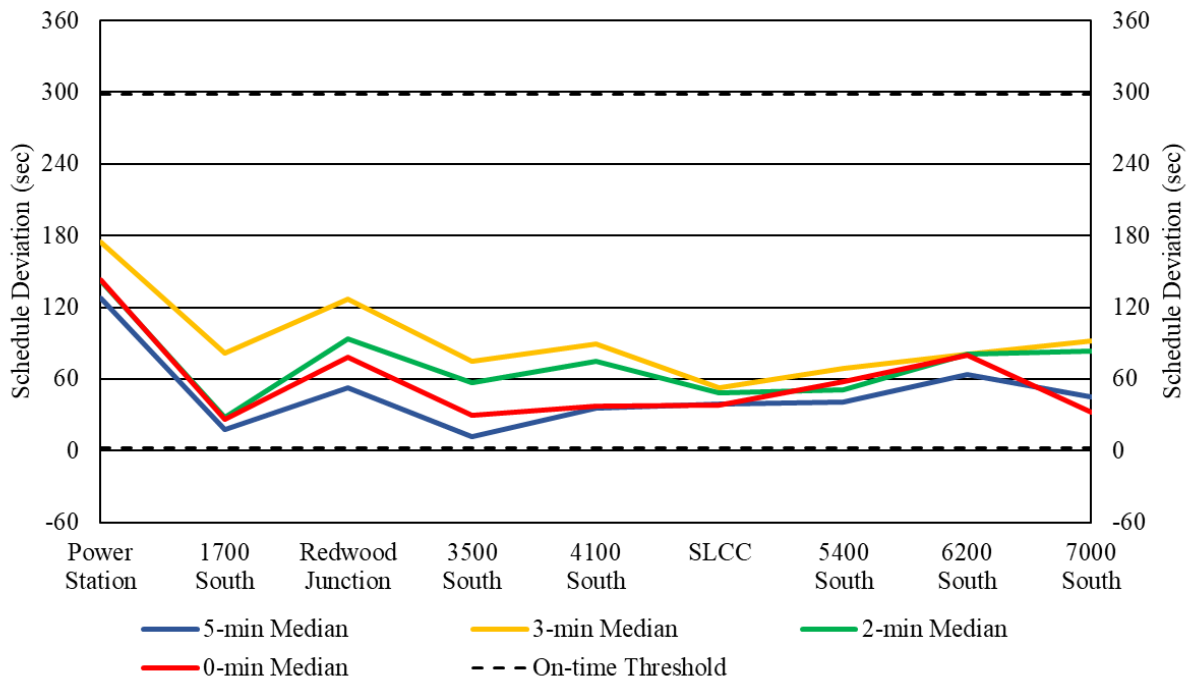


Figure 5-23: Route 217 AM SB median schedule deviation.

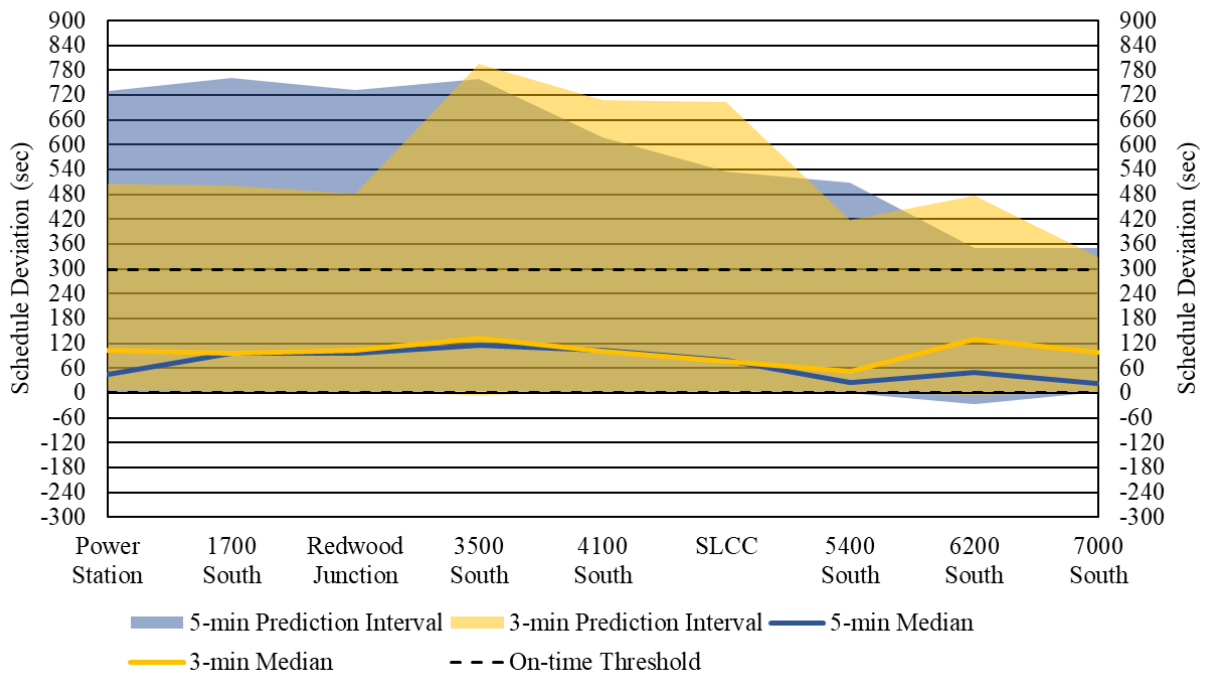


Figure 5-24: Route 217 AM NB schedule deviation prediction interval 5-min vs. 3-min.

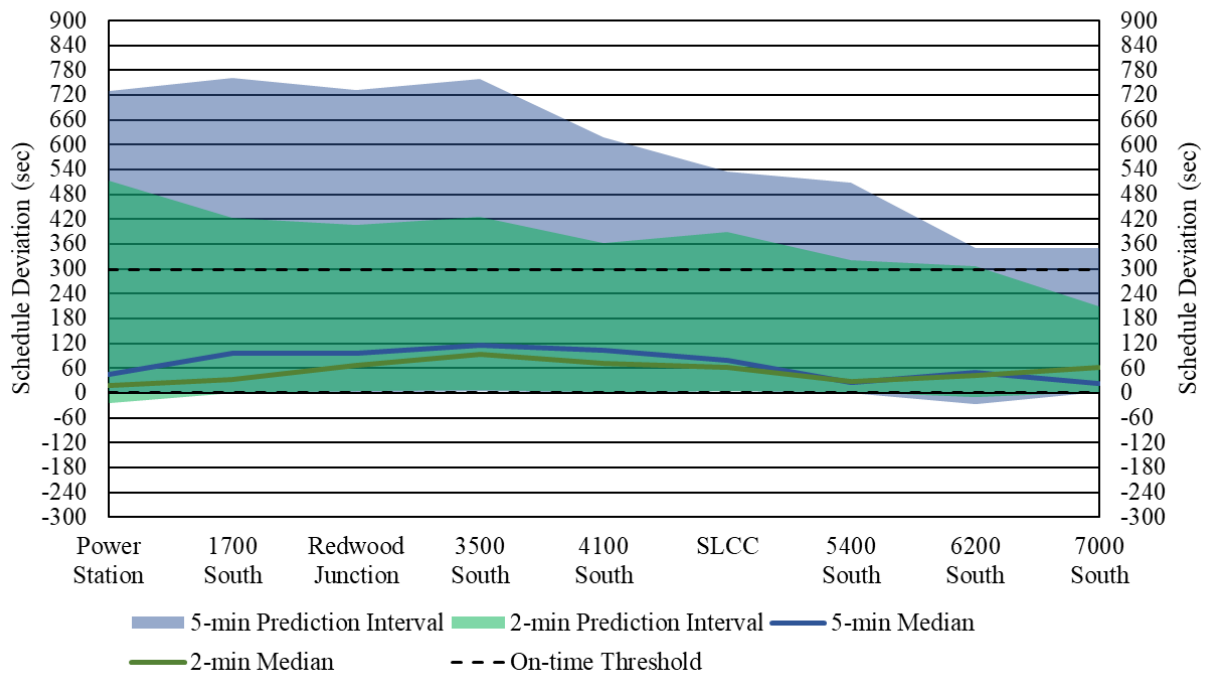


Figure 5-25: Route 217 AM NB schedule deviation prediction interval 5-min vs. 2-min.

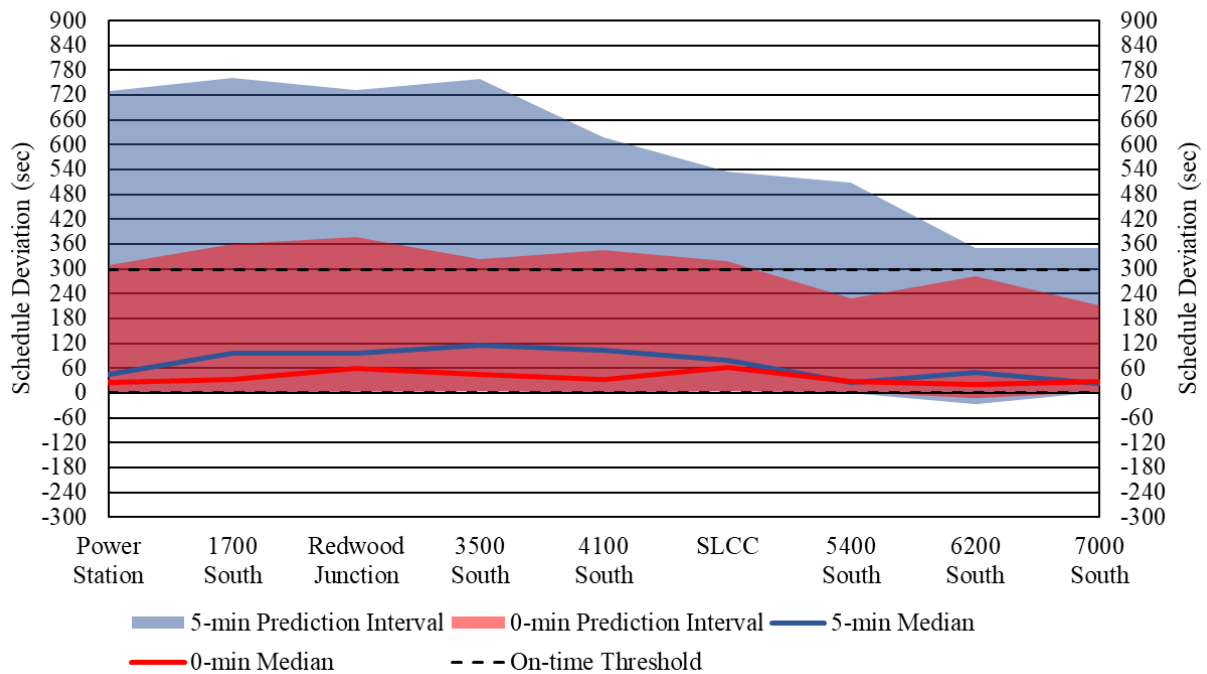


Figure 5-26: Route 217 AM NB schedule deviation prediction interval 5-min vs. 0-min.

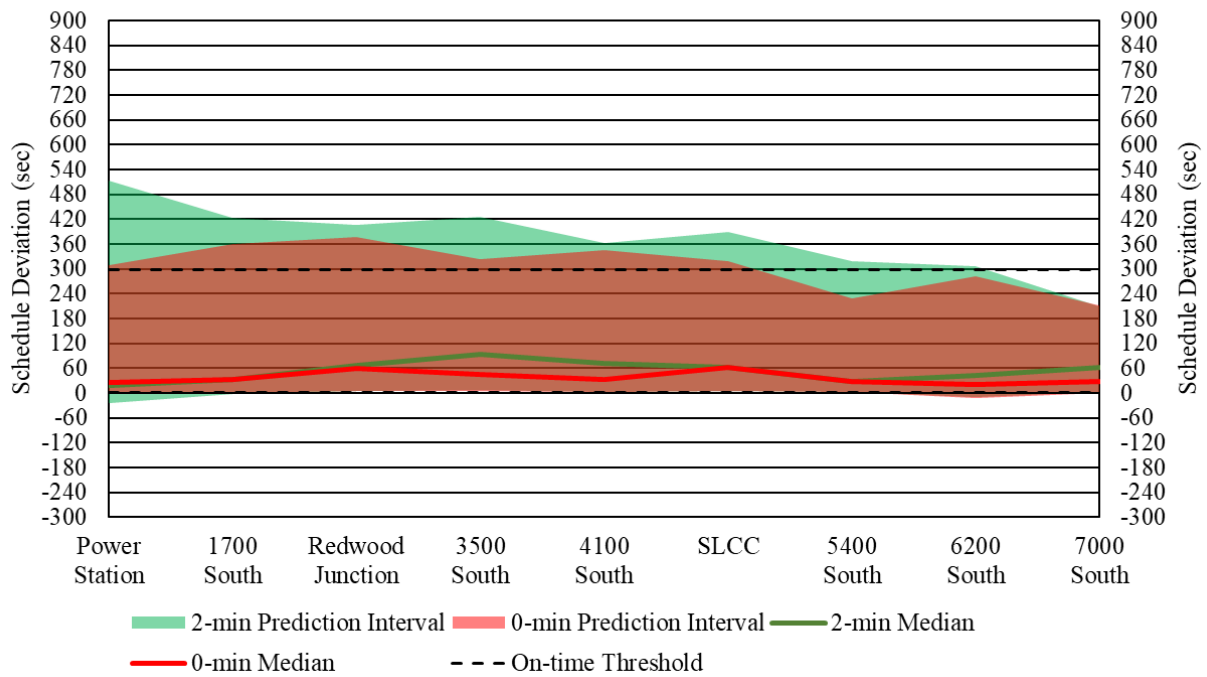


Figure 5-27: Route 217 AM NB schedule deviation prediction interval 2-min vs. 0-min.

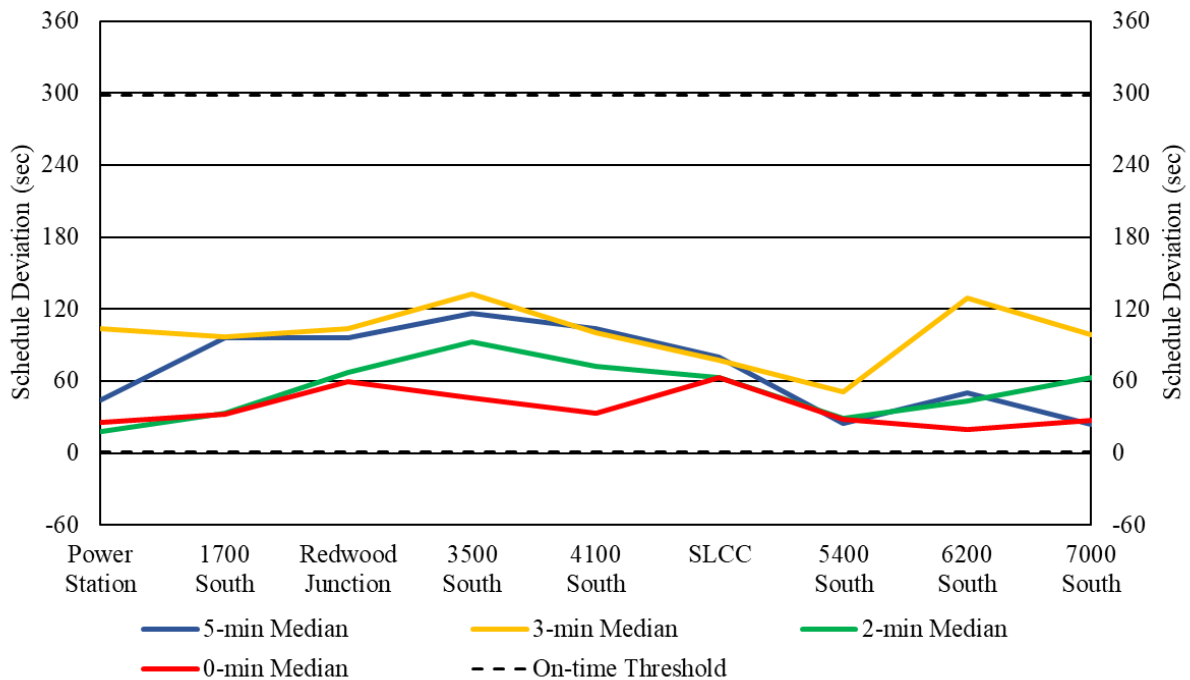


Figure 5-28: Route 217 AM NB median schedule deviation.

As was done with mean schedule deviation, the 95 percent prediction interval graphs are combined for AM SB and AM NB in Figure 5-29 and Figure 5-30, respectively. This display, with the added trendline through the median schedule deviation value for the 3-, 2-, and 0-minute thresholds permits a comparison across requesting thresholds that shows a decrease in the magnitude of the 95 percent prediction interval and a decrease in median schedule deviation as the requesting threshold approaches zero.

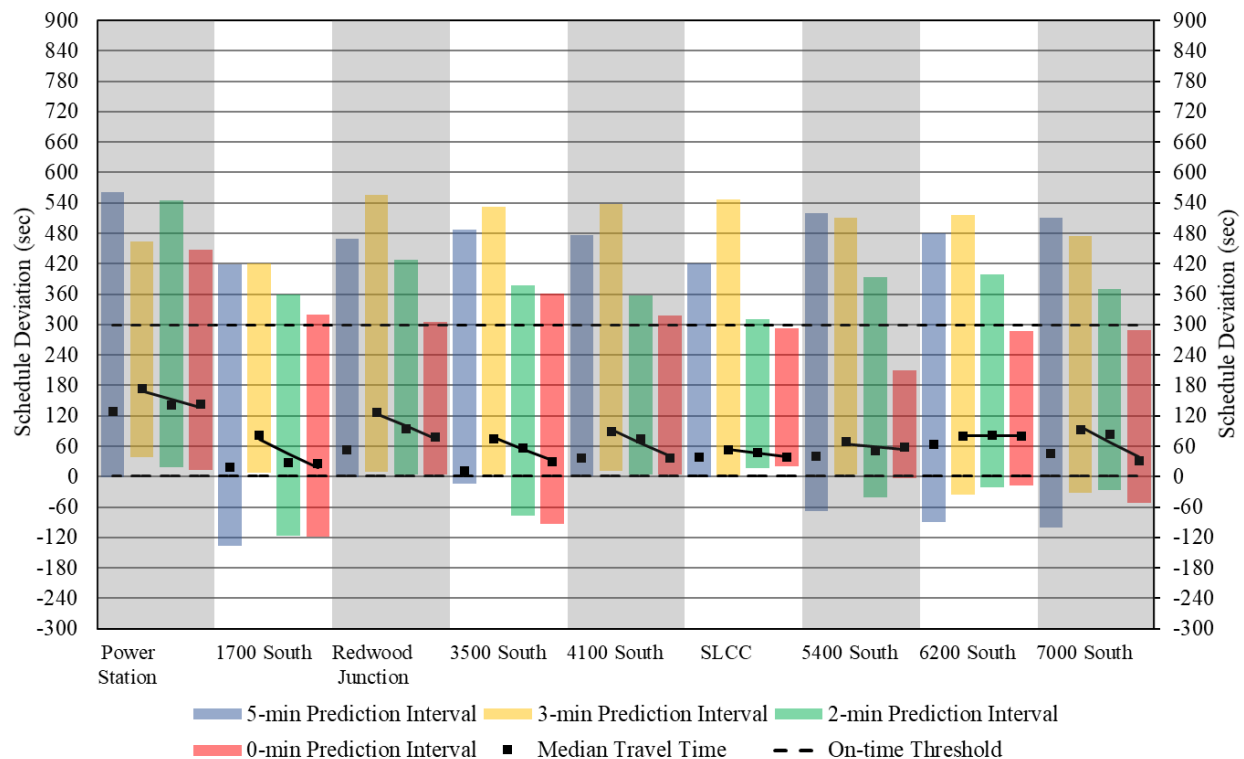


Figure 5-29: Route 217 AM SB schedule deviation prediction interval with all thresholds.

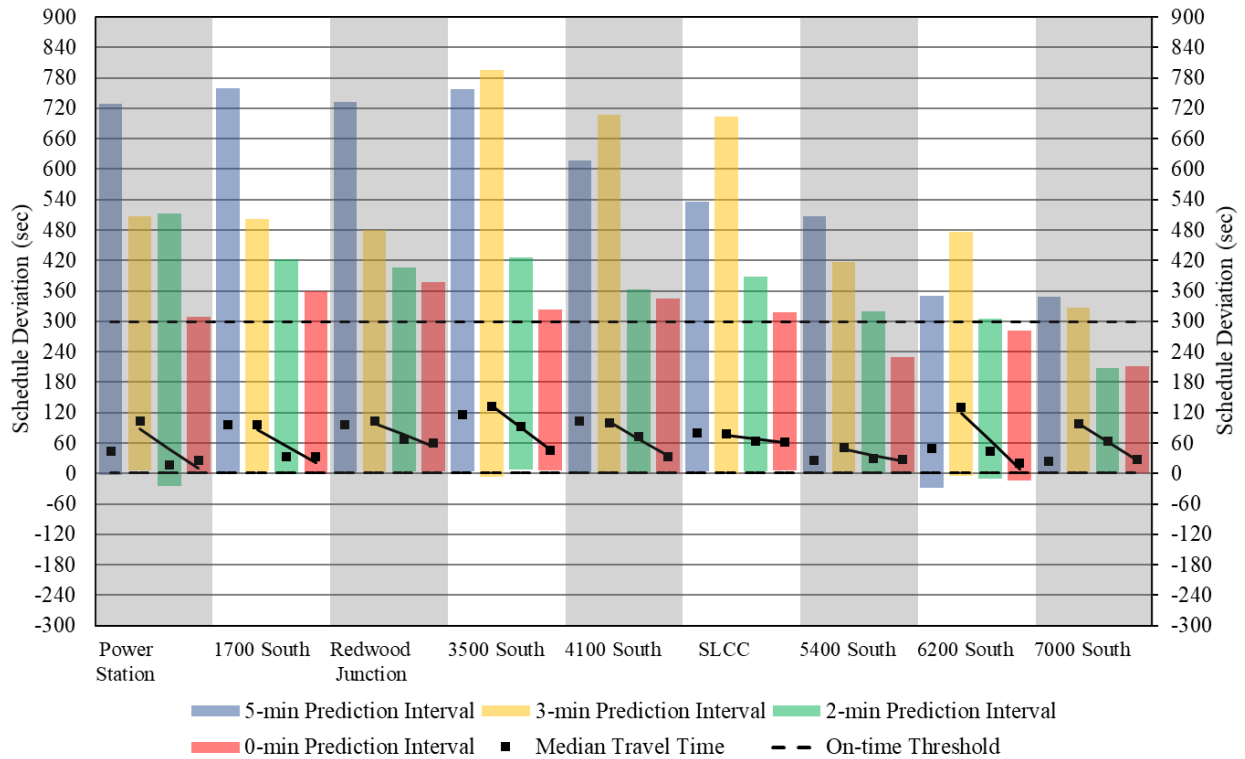


Figure 5-30: Route 217 AM NB schedule deviation prediction interval with all thresholds.

5.2.2.3 Route 217 – Schedule Deviation: Variability

Variability is measured through mean residual SD, where residual means the difference between the schedule deviation of an individual record and the estimated median of all records for the specific timepoint and directional peak scenario to which the individual record belongs. The figures in this subsection are listed in Table 5-6 and are organized by directional peak scenario and by comparison pair.

Table 5-6: Route 217 Schedule Deviation Variability Figures List

Comparison Pair	AM SB	AM NB
5-min vs 3-min	Figure 5-31	Figure 5-35
5-min vs 2-min	Figure 5-32	Figure 5-36
5-min vs 0-min	Figure 5-33	Figure 5-37
2-min vs 0-min	Figure 5-34	Figure 5-38

The figures for schedule deviation variability illustrate the mean residual SD and the corresponding p-value when variability at each timepoint is compared between two thresholds. The p-value for the corridor-level difference in variability is included in the caption of each figure. Table 5-7 and Table 5-8 contain the numerical data plotted in these figures for AM SB and AM NB, respectively, while the tables and figures for the PM peak scenarios are contained in Appendix A.4. Additionally, these tables contain the percent change in variability when each threshold is compared to the 5-minute threshold with negative values indicating less variability. Other than two exceptions, data at every timepoint show less variability when 3-, 2-, and 0-minute requesting thresholds are compared to the 5-minute threshold. Indeed, the corridor-level change in variability data suggest with convincing evidence that variability decreases as the requesting threshold approaches zero.

Table 5-7: Route 217 AM SB Schedule Deviation Variability

Timepoint	Mean Residual SD (sec)				% Change in Variability (p-value)		
	5 min	3 min	2 min	0 min	3 min vs 5 min	2 min vs 5 min	0 min vs 5 min
Power Station	99.0	80.2	86.1	74.5	-19.0% (0.4110)	-13.0% (0.4427)	-24.7% (0.1994)
1700 South	106.8	93.7	91.4	80.8	-12.3% (0.5837)	-14.4% (0.3699)	-24.3% (0.2265)
Redwood Junction	120.7	112.3	98.7	78.1	-6.9% (0.7437)	-18.2% (0.2498)	-35.3% (0.0892)
3500 South	114.5	108.2	91.6	79.6	-5.4% (0.8147)	-20% (0.2763)	-30.5% (0.1999)
4100 South	112.9	107.2	81.6	69.2	-5.0% (0.8296)	-27.7% (0.1510)	-38.7% (0.1161)
SLCC	102.8	107.1	67.9	52.9	4.2% (0.9068)	-34.0% (0.1571)	-48.5% (0.1221)
5400 South	122.8	106.8	89.2	52.9	-13.0% (0.6596)	-27.4% (0.2729)	-56.9% (0.1112)
6200 South	121.3	116.2	98.5	68.9	-4.2% (0.8062)	-18.8% (0.2599)	-43.2% (0.0322)
7000 South	138.5	110.3	103.2	71.8	-20.4% (0.2694)	-25.4% (0.1160)	-48.2% (0.0233)
Corridor	115.6	105.0	90.4	72.5	-9.1% (0.2566)	-21.8% (0.0004)	-37.3% (<0.0001)

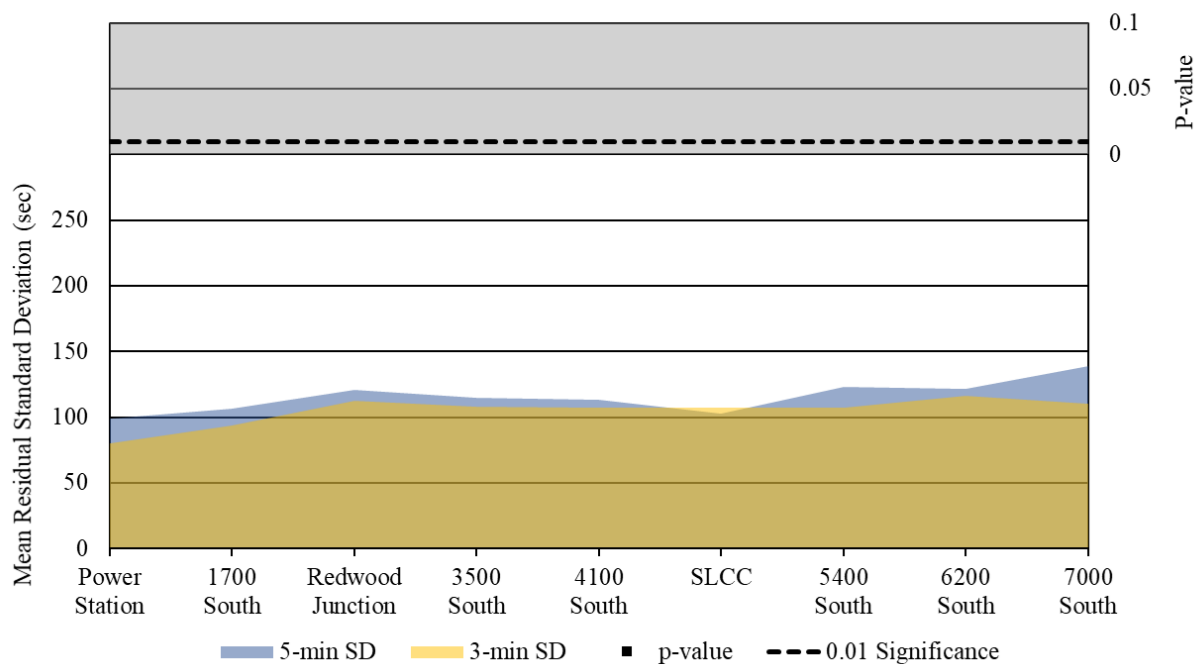


Figure 5-31: Route 217 AM SB schedule deviation variability 5-min vs. 3-min (p-value=0.2566).

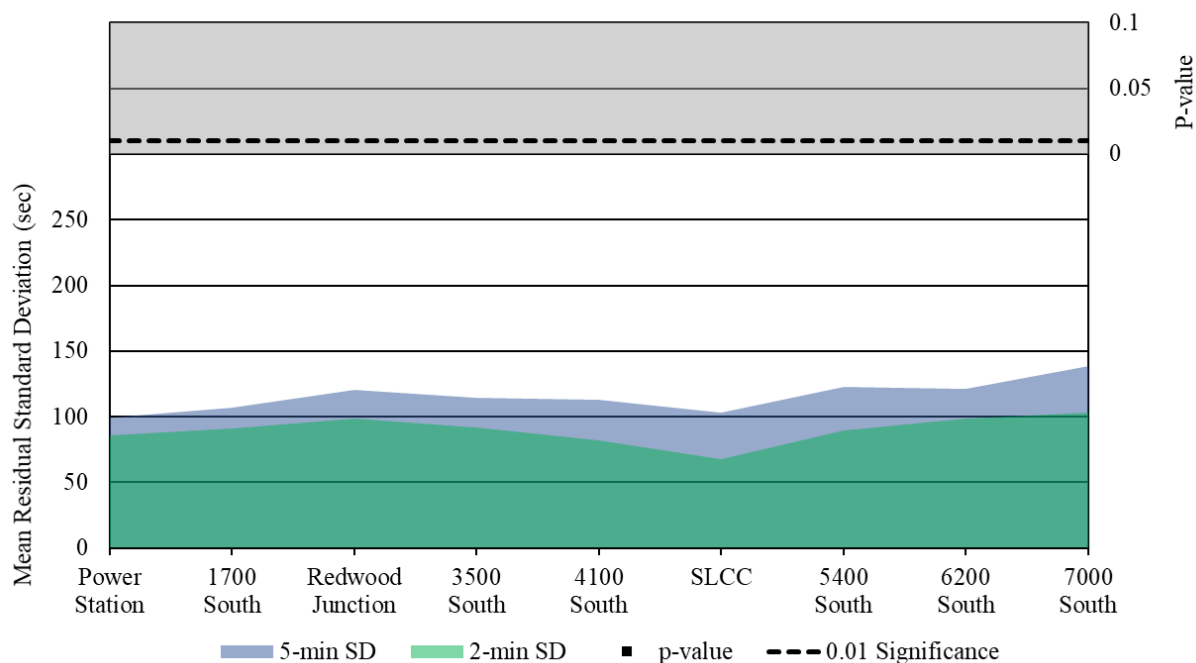


Figure 5-32: Route 217 AM SB schedule deviation variability 5-min vs. 2-min (p-value=0.0004).

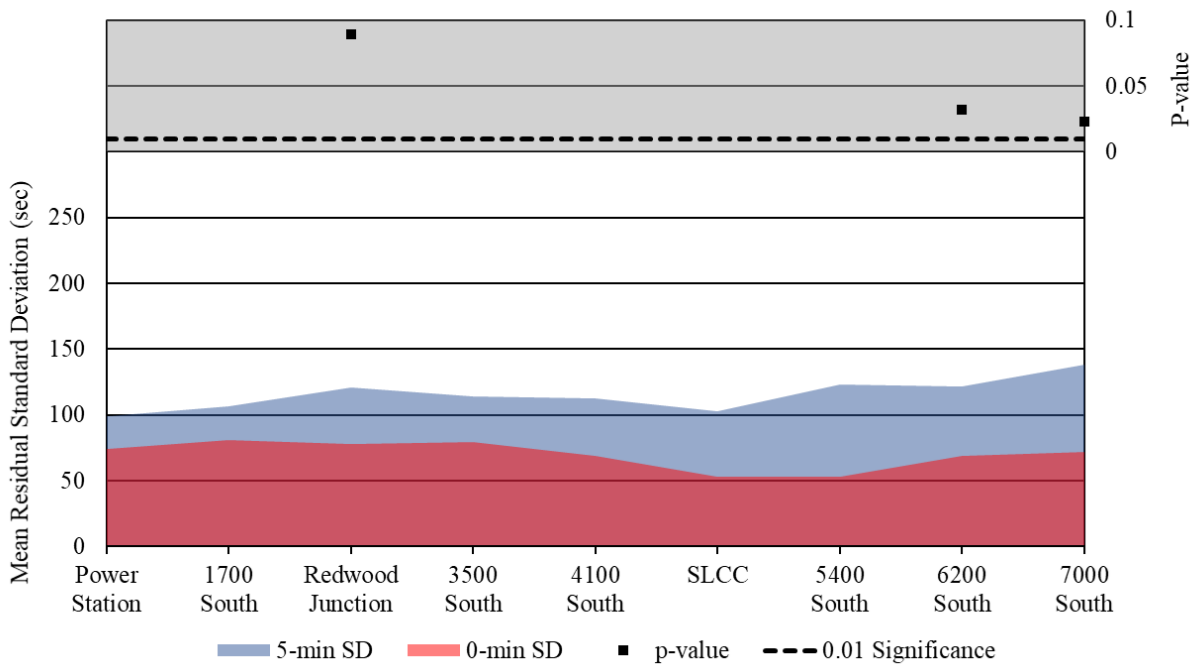


Figure 5-33: Route 217 AM SB schedule deviation variability 5-min vs. 0-min (p-value=<0.0001).

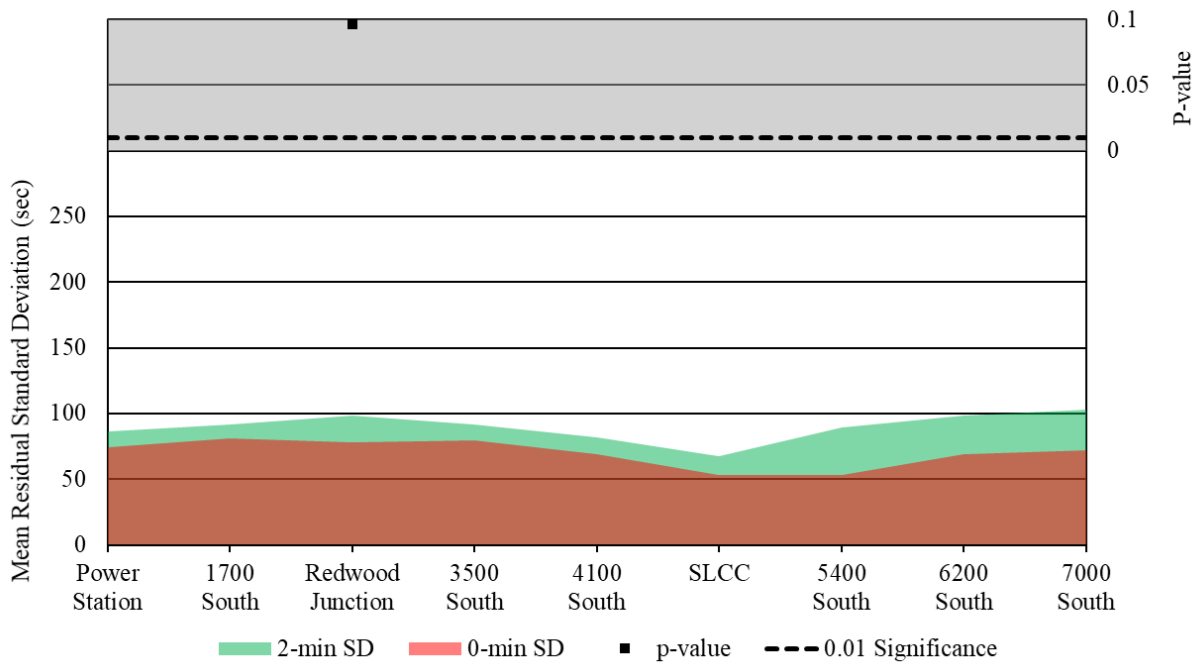


Figure 5-34: Route 217 AM SB schedule deviation variability 2-min vs. 0-min (p-value=0.0007).

Furthermore, the data consistently show that there is less and less variability as the requesting threshold changes from 5 minutes, to 3 minutes, to 2 minutes, and to 0 minutes. Analyses for OTP, mean schedule deviation, and the 95 percent prediction interval for schedule deviation were unable to decisively conclude that the detected trends applied as the requesting threshold changed from 5 minutes, to 3 minutes, to 2 minutes, and to 0 minutes; they only detected trends from 3 minutes, to 2 minutes, to 0 minutes.

Table 5-8: Route 217 AM NB Schedule Deviation Variability

Timepoint	Mean Residual SD (sec)				% Change in Variability (p-value)		
	5 min	3 min	2 min	0 min	3 min vs 5 min	2 min vs 5 min	0 min vs 5 min
Power Station	172.6	120.4	136.1	74.5	-30.2% (0.3757)	-21.1% (0.2594)	-56.8% (0.0144)
1700 South	159.7	111.7	108.5	75.4	-30.1% (0.3201)	-32.1% (0.0706)	-52.8% (0.0127)
Redwood Junction	152.7	107.1	101.9	95.7	-29.9% (0.3193)	-33.2% (0.0393)	-37.3% (0.0490)
3500 South	159.2	139.3	81.3	80.5	-12.4% (0.6295)	-48.9% (0.0017)	-49.4% (0.0129)
4100 South	140.0	125.5	83.2	79.7	-10.3% (0.6743)	-40.6% (0.0068)	-43.1% (0.0259)
SLCC	134.9	138.4	83.0	72.3	2.6% (0.9533)	-38.5% (0.0112)	-46.4% (0.0229)
5400 South	133.1	90.5	74.2	64.6	-32.0% (0.3593)	-44.3% (0.0340)	-51.5% (0.0700)
6200 South	106.6	98.7	80.2	65.2	-7.5% (0.6885)	-24.8% (0.0505)	-38.9% (0.0279)
7000 South	103.2	64.1	49.3	58.7	-37.9% (0.3776)	-52.2% (0.0482)	-43.1% (0.1863)
Corridor	141.8	111.4	91.3	75.6	-21.4% (0.0352)	-35.7% (<0.0001)	-46.7% (<0.0001)

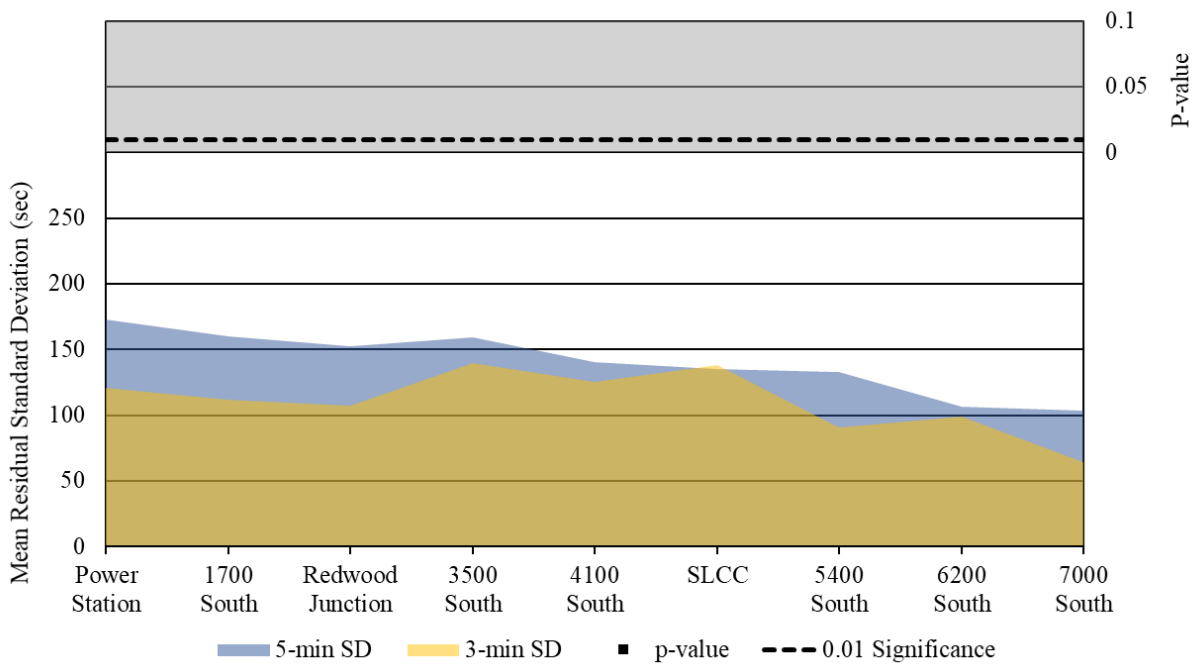


Figure 5-35: Route 217 AM NB schedule deviation variability 5-min vs. 3-min (p-value=0.0352).

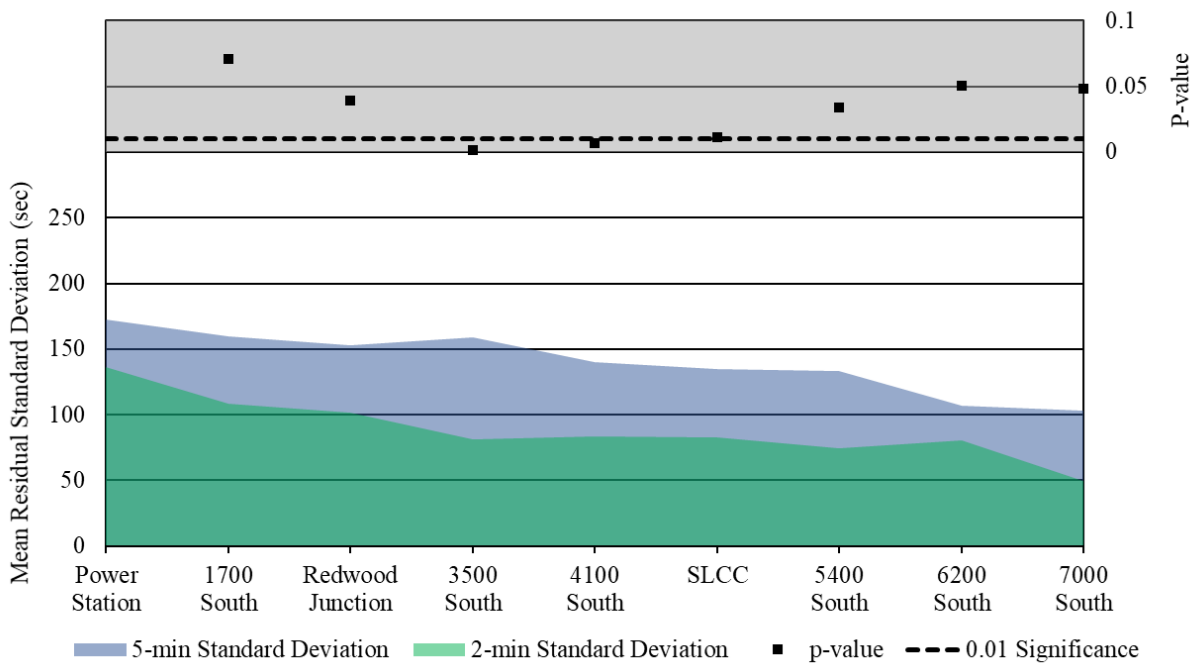


Figure 5-36: Route 217 AM NB schedule deviation variability 5-min vs. 2-min (p-value=<0.0001).

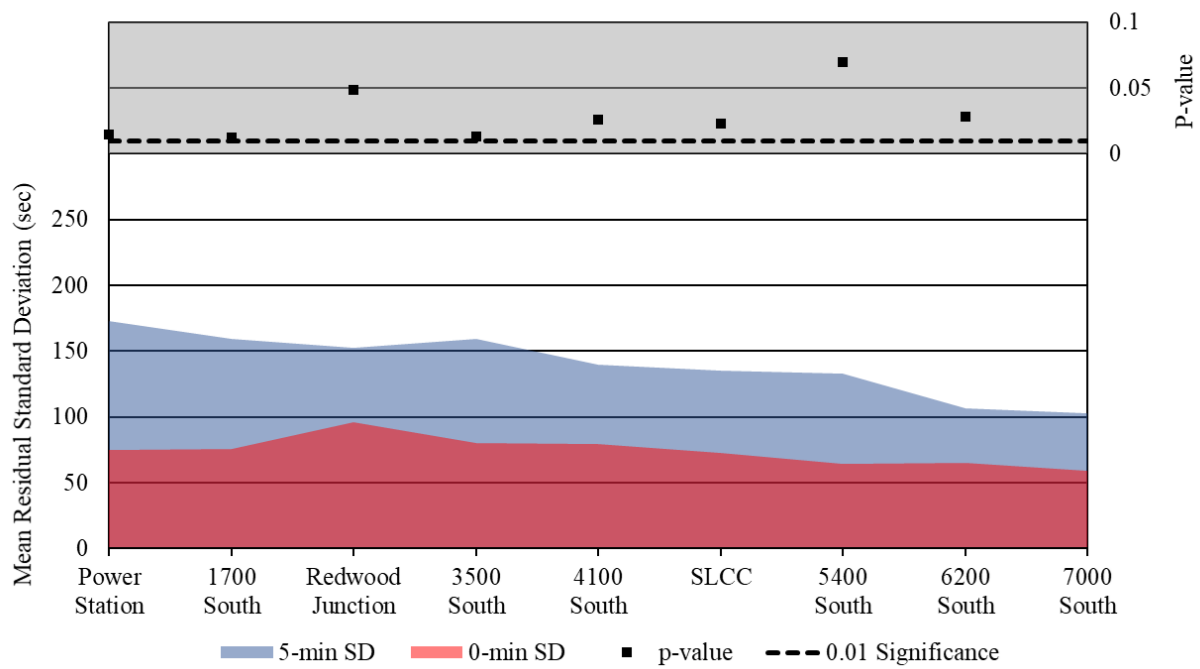


Figure 5-37: Route 217 AM NB schedule deviation variability 5-min vs. 0-min (p-value=<0.0001).

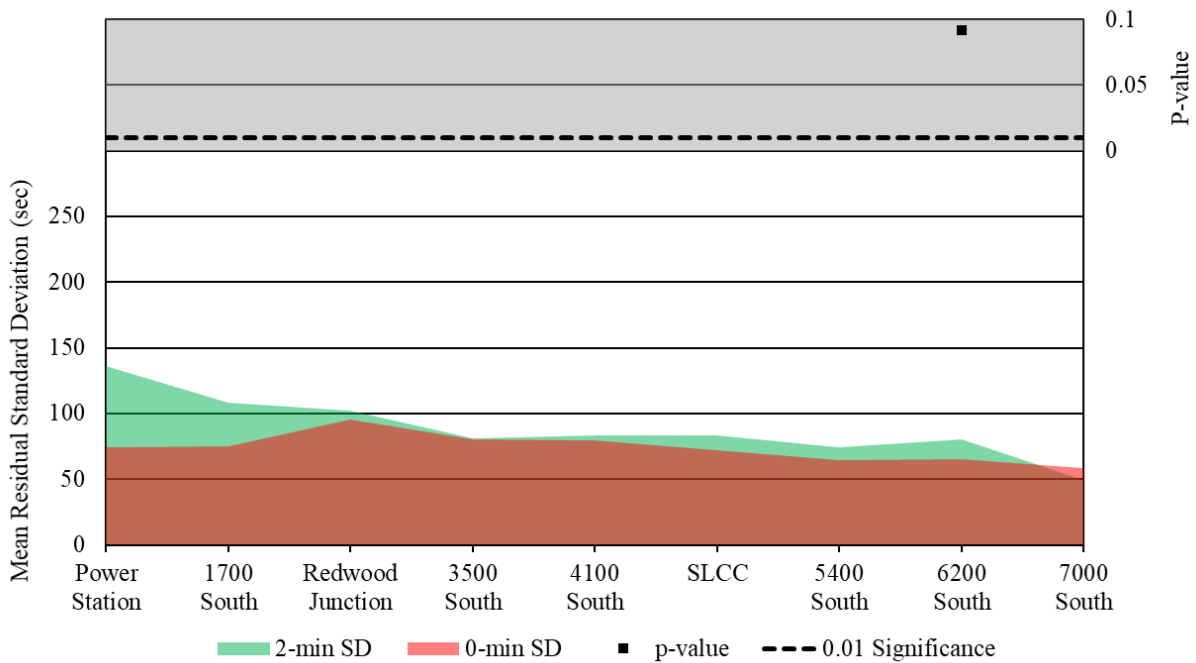


Figure 5-38: Route 217 AM NB schedule deviation variability 2-min vs. 0-min (p-value=0.0293).

5.2.3 Route 217 – Travel Time

While OTP and schedule deviation are extremely dependent on the schedule, travel time is much more independent of the schedule. The travel-time values represent the elapsed time from departure of the previous timepoint to arrival at the current timepoint the bus had just left. In other words, for SB buses, travel time recorded at the 4100 South timepoint represents the elapsed time since departing the 3500 South timepoint to arriving at the 4100 South timepoint. Travel time was only analyzed at the timepoint level through the 95 percent prediction interval and through variability, the results of which are summarized in the following subsections.

5.2.3.1 Route 217 – Travel Time: 95 Percent Prediction Interval

The 95 percent prediction interval is the range of expected values based on the value of the 2.5th and 97.5th percentiles and represents the middle 95 percent of data. As the magnitude of the 95 percent prediction interval increases, variability in the data increases. Figure 5-39 and Figure 5-40 contain graphs of the 95 percent prediction interval for travel time under the AM SB and AM NB scenarios, respectively, while figures for the PM peak scenarios are found in Appendix A.5. Also plotted is the median travel time, a trendline for the median travel time at each timepoint, and the scheduled travel time.

Several inferences can be made from displaying the travel-time data using the 95 percent prediction interval. First, the slope of the trendline is negative at eight of nine timepoints in the AM SB scenario and seven of nine timepoints in the AM NB scenario, which suggests that as the requesting threshold approaches zero, travel time decreases. As the requesting threshold changed from 5, to 3, to 2, to 0 minutes, each change resulted in an average decrease in travel time of 3.6 seconds for the AM SB directional peak scenario and 6.1 seconds for the AM NB. Across all directional peak scenarios, the trendline through the median travel time was negative at 26 of the 36 timepoints (nine for each directional peak scenario) with an average median travel-time decrease of 2.1 seconds each time the requesting threshold changed.

However, while the median travel time usually decreased as the requesting threshold approached zero, there is not a clear change in the magnitude of the 95 percent prediction interval, or a suggested change in variability. Indeed, the magnitudes of the 95 percent prediction

interval for the 5-, 3-, 2-, and 0-minute requesting threshold are respectively 242, 257, 243, and 244 seconds.

Another inference that can be made from these graphs are locations with schedule deficiencies. For example, at the Redwood Junction timepoint in Figure 5-39, the median travel time values are approximately 60 seconds above the allowed travel time set by the schedule. This means that as AM SB buses travel from 1700 South to Redwood Junction they will most likely fall further behind schedule. In fact, 81.1 percent of SB buses fall further behind schedule as they travel to Redwood Junction (13.5 percent fall 2 minutes or more behind schedule). However, it is only when falling further behind causes the bus to cross the lateness threshold (5 minutes behind schedule) that OTP is affected. On average, OTP drops 3.0 percent at this point in the route. If the schedule were adjusted to allow one more minute of travel time, only 41.6 percent of buses would fall further behind schedule at this timepoint (3.5 percent would fall 2 minutes or more behind schedule). The opposite is true at West Jordan City Center, where the recovery time built into the schedule is quite apparent from this figure; the schedule allows for 9 minutes of travel time when the median travel time is only about 3.5 minutes.

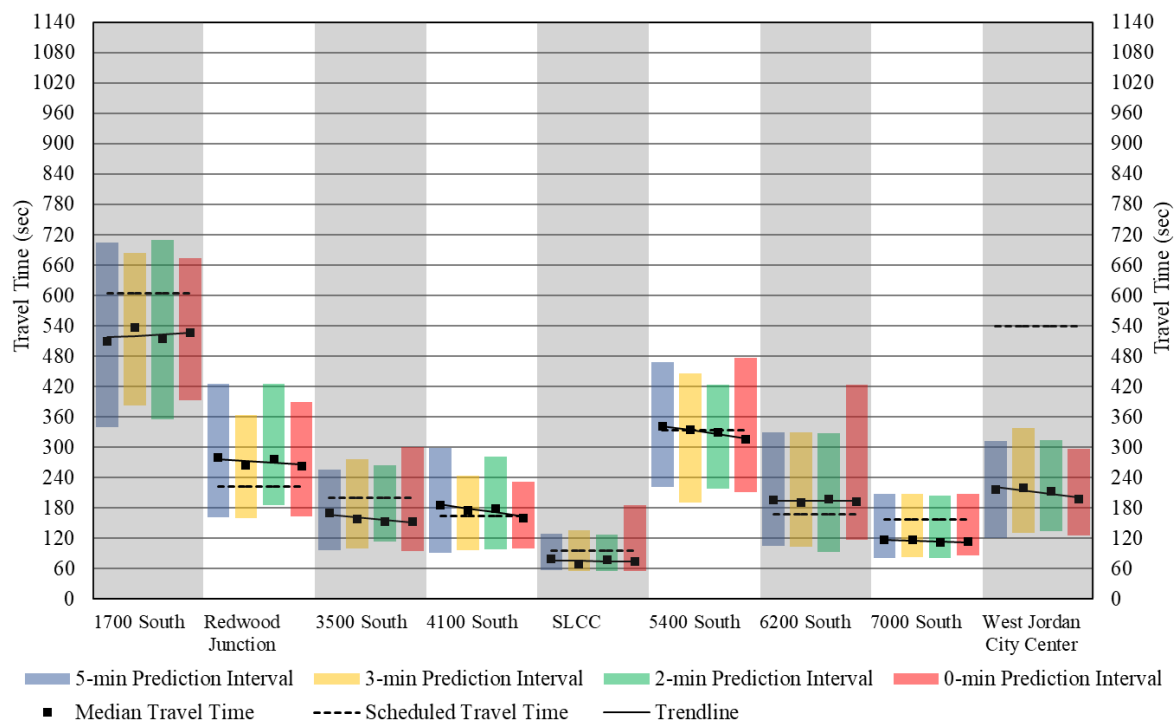


Figure 5-39: Route 217 AM SB travel time 95 percent prediction interval.

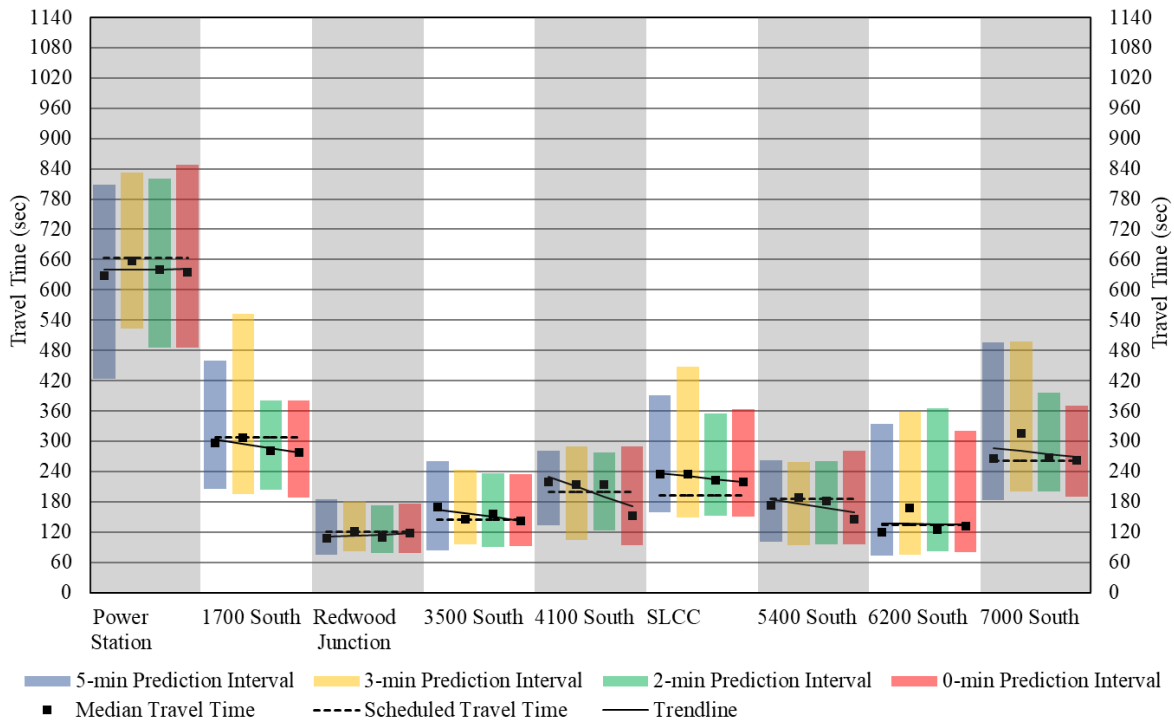


Figure 5-40: Route 217 AM NB travel time 95 percent prediction interval.

5.2.3.2 Route 217 – Travel Time: Variability

Variability is measured through mean residual SD, where residual is defined as the difference between the schedule deviation of an individual record and the median of all records for the specific timepoint and directional peak scenario to which the individual record belongs. The SD of the residual is used to evaluate the difference in variability between thresholds. The figures in this subsection are listed in Table 5-9 and are organized by directional peak scenario and by comparison pair.

Table 5-9: Route 217 Travel-Time Variability List of Figures

Comparison Pair	AM SB	AM NB
5-min vs 3-min	Figure 5-41	Figure 5-45
5-min vs 2-min	Figure 5-42	Figure 5-46
5-min vs 0-min	Figure 5-43	Figure 5-47
2-min vs 0-min	Figure 5-44	Figure 5-48

The figures for travel-time variability illustrate the mean residual SD and the corresponding p-value when variability at each timepoint is compared between two thresholds. Table 5-10 and Table 5-11 contain the numerical data plotted in these figures for AM SB and AM NB, respectively, while the tables and figures for the PM peak scenarios are contained in Appendix A.6. Additionally, these tables contain the percent change in variability when each threshold is compared to the 5-minute threshold with negative values indicating less variability. The research team was unable to find consistent trends when comparing variability among two different requesting thresholds; compared to schedule deviation, travel-time values are much more uniform and the data are less variable.

Table 5-10: Route 217 AM SB Travel-Time Variability

Timepoint	Mean Residual SD (sec)				% Change in Variability (p-value)		
	5 min	3 min	2 min	0 min	3 min vs 5 min	2 min vs 5 min	0 min vs 5 min
1700 South	84.1	65.8	82.5	70.8	-21.8% (0.1094)	-1.9% (0.8607)	-15.8% (0.1505)
Redwood Junction	58.7	47.5	54.1	51.3	-19% (0.0789)	-7.8% (0.3982)	-12.6% (0.1687)
3500 South	36.9	40.1	36.5	36.9	8.7% (0.5531)	-1.1% (0.9249)	0.0% (0.9825)
4100 South	41.3	30.1	38.8	34.2	-27.2% (0.1026)	-6.1% (0.6323)	-17.3% (0.1933)
SLCC	17.9	17.2	18.3	28.8	-3.7% (0.7647)	2.6% (0.8114)	61.3% (0.0797)
5400 South	61.8	62.5	49.6	62.0	1.0% (0.9780)	-19.8% (0.0825)	0.2% (0.9846)
6200 South	64.0	58.0	52.4	61.3	-9.4% (0.3219)	-18.1% (0.0418)	-4.1% (0.7489)
7000 South	42.7	41.6	39.5	30.6	-2.5% (0.6811)	-7.7% (0.3114)	-28.3% (0.0005)
West Jordan City Center	58.7	45.8	45.1	39.1	-22.1% (0.4210)	-23.2% (0.3091)	-33.4% (0.2617)

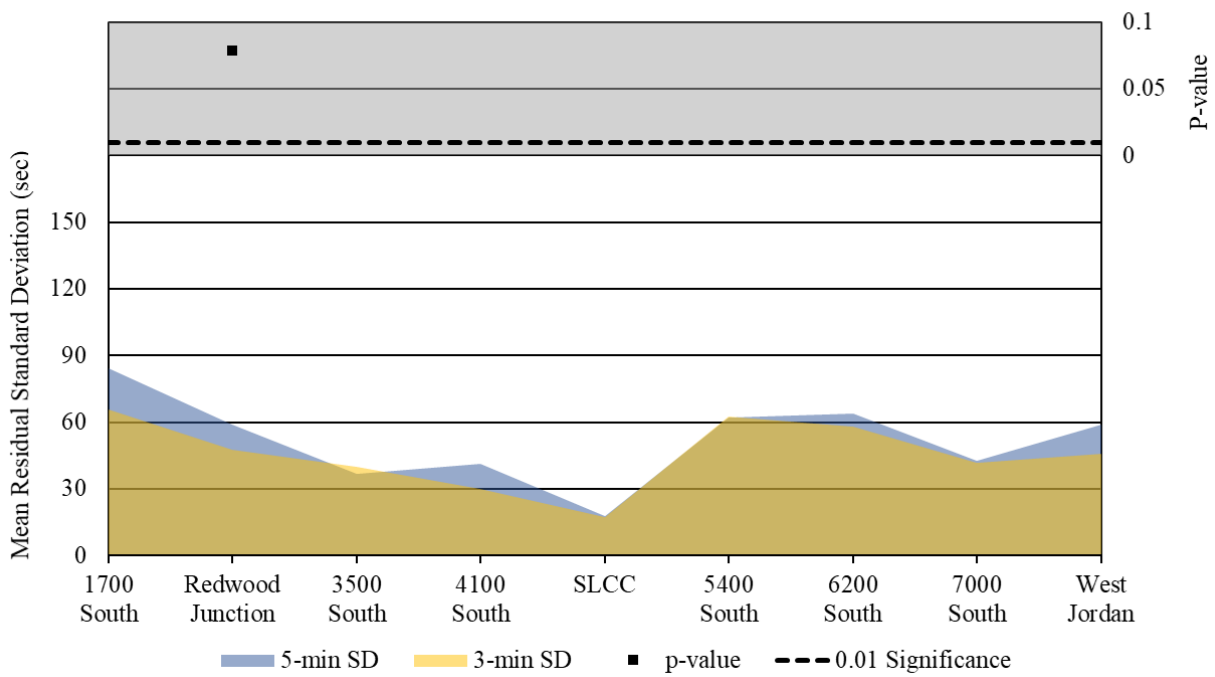


Figure 5-41: Route 217 AM SB travel-time variability 5-min vs. 3-min.

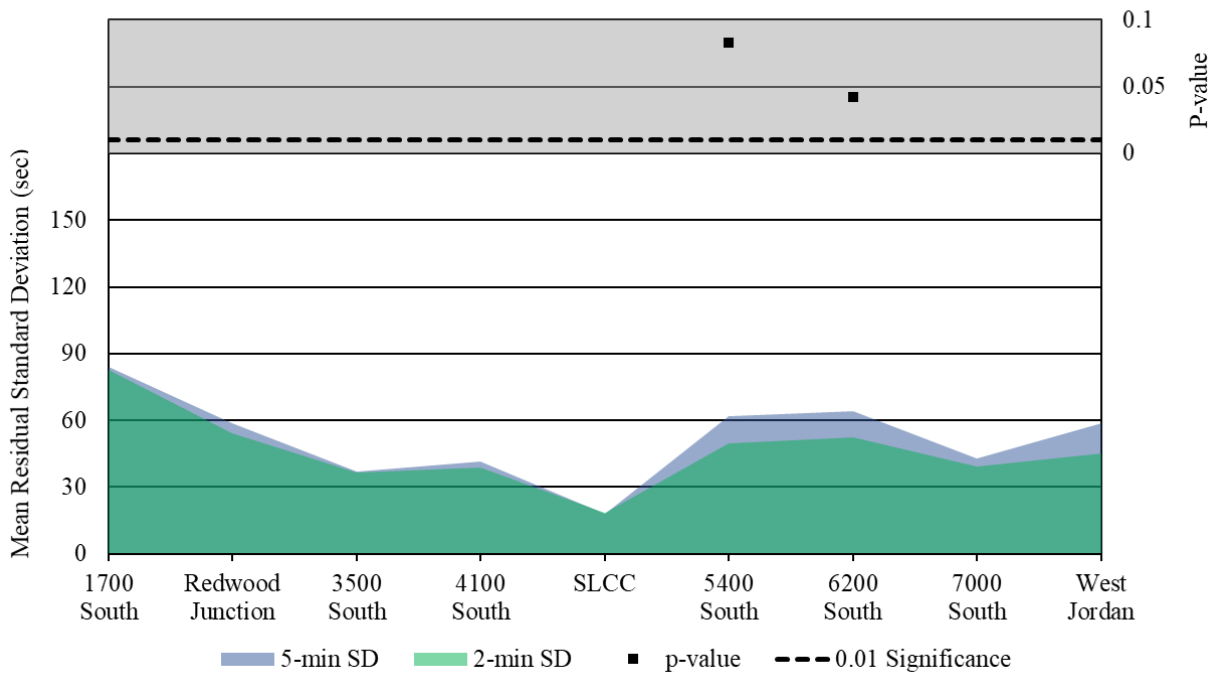


Figure 5-42: Route 217 AM SB travel-time variability 5-min vs. 2-min.

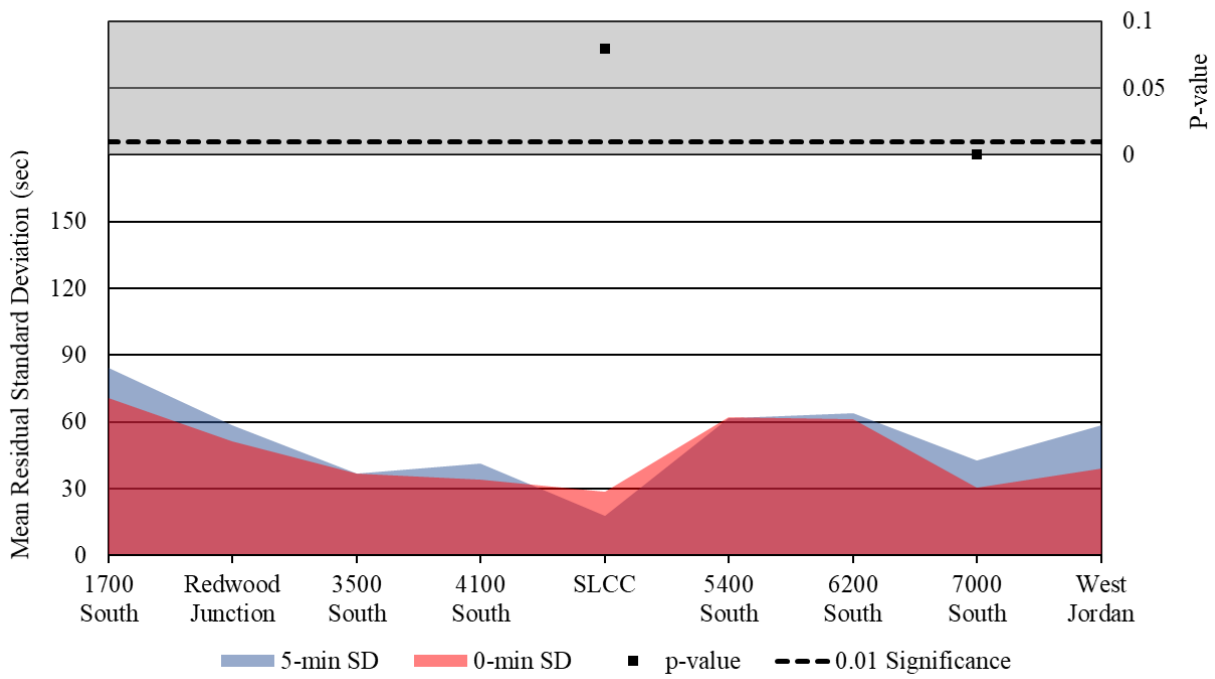


Figure 5-43: Route 217 AM SB travel-time variability 5-min vs. 0-min.

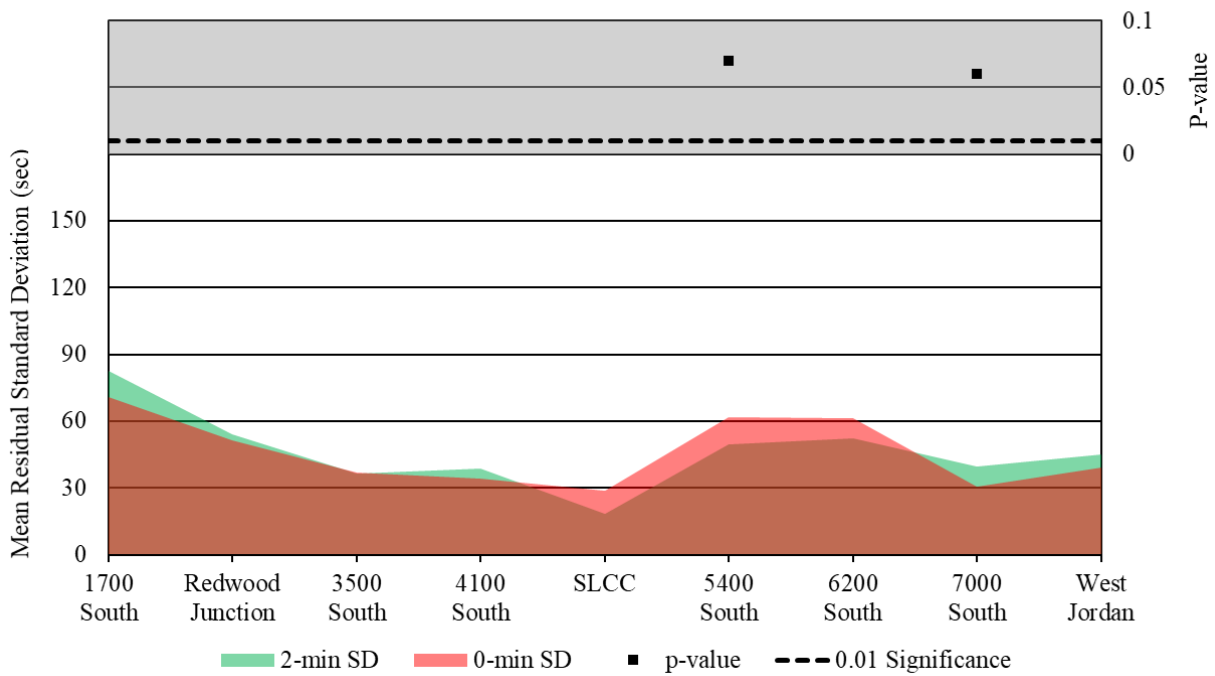


Figure 5-44: Route 217 AM SB travel-time variability 2-min vs. 0-min.

Table 5-11: Route 217 AM NB Travel-Time Variability

Timepoint	Mean Residual SD (sec)				% Change in Variability (p-value)		
	5 min	3 min	2 min	0 min	3 min vs 5 min	2 min vs 5 min	0 min vs 5 min
Power Station	85.6	69.2	70.2	75.3	-19.2% (0.3301)	-17.9% (0.0839)	-12% (0.3115)
1700 South	55.4	65.3	40.1	46.8	17.8% (0.4423)	-27.7% (0.0095)	-15.5% (0.2032)
Redwood Junction	35.5	28.6	28.3	36.9	-19.2% (0.4562)	-20.3% (0.1040)	4.1% (0.8771)
3500 South	50.9	40.6	42.7	37.1	-20.2% (0.2764)	-16.1% (0.0776)	-27.2% (0.0265)
4100 South	40.8	44.8	50.1	50.5	9.7% (0.6759)	22.9% (0.0495)	23.9% (0.1131)
SLCC	50.6	74.6	49.6	46.7	47.4% (0.0016)	-2.1% (0.8539)	-7.8% (0.4547)
5400 South	53.1	47.3	47.6	52.0	-11.1% (0.3381)	-10.4% (0.1752)	-2.2% (0.8087)
6200 South	60.8	82.5	73.7	61.8	35.6% (0.0281)	21.3% (0.1046)	1.6% (0.9191)
7000 South	60.8	50.5	47.1	42.5	-17.0% (0.2800)	-22.6% (0.0223)	-30.2% (0.0203)

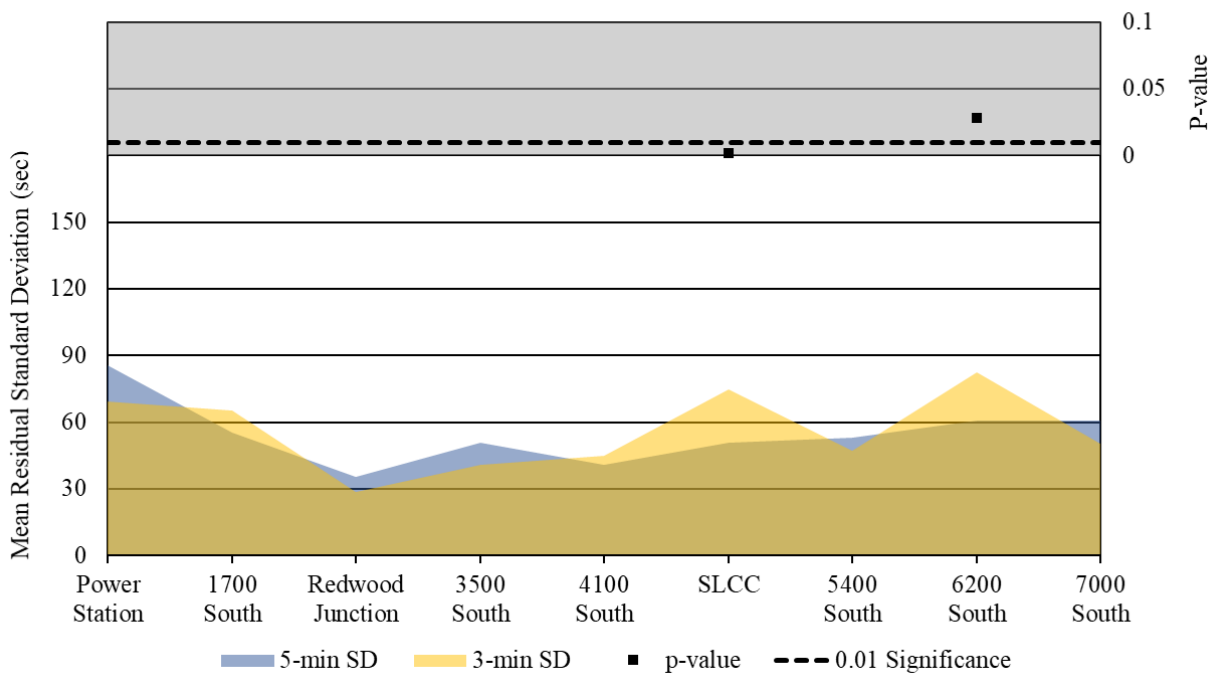


Figure 5-45: Route 217 AM NB travel-time variability 5-min vs. 3-min.

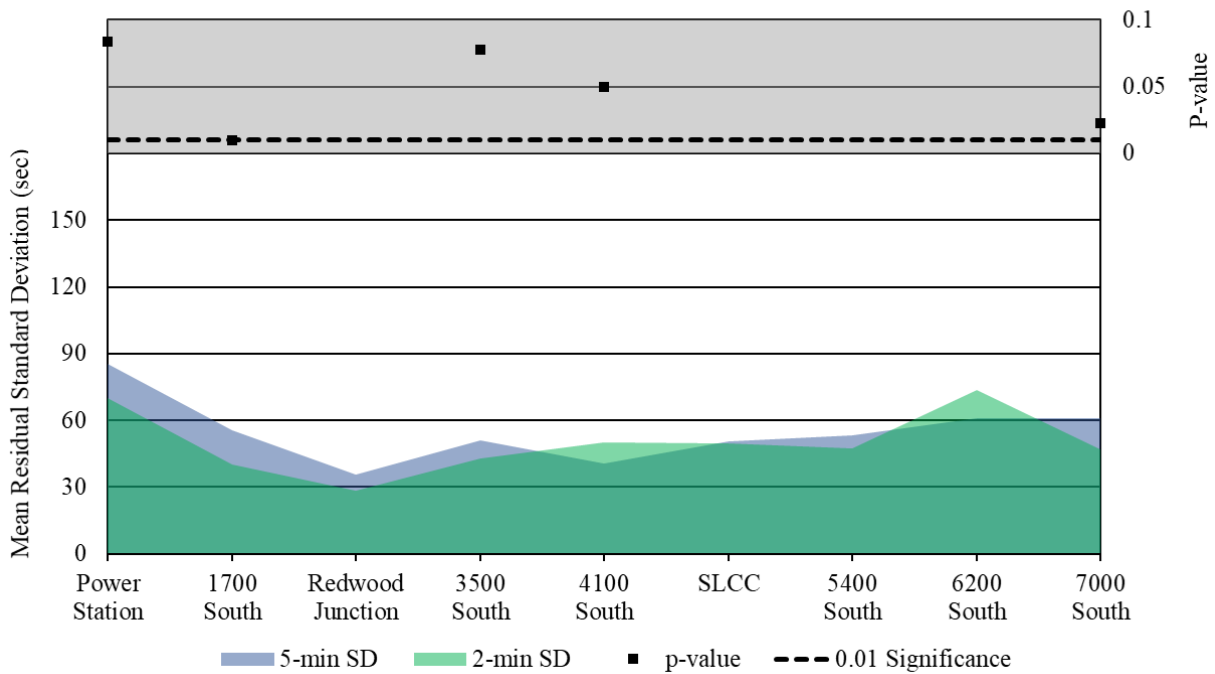


Figure 5-46: Route 217 AM NB travel-time variability 5-min vs. 2-min.

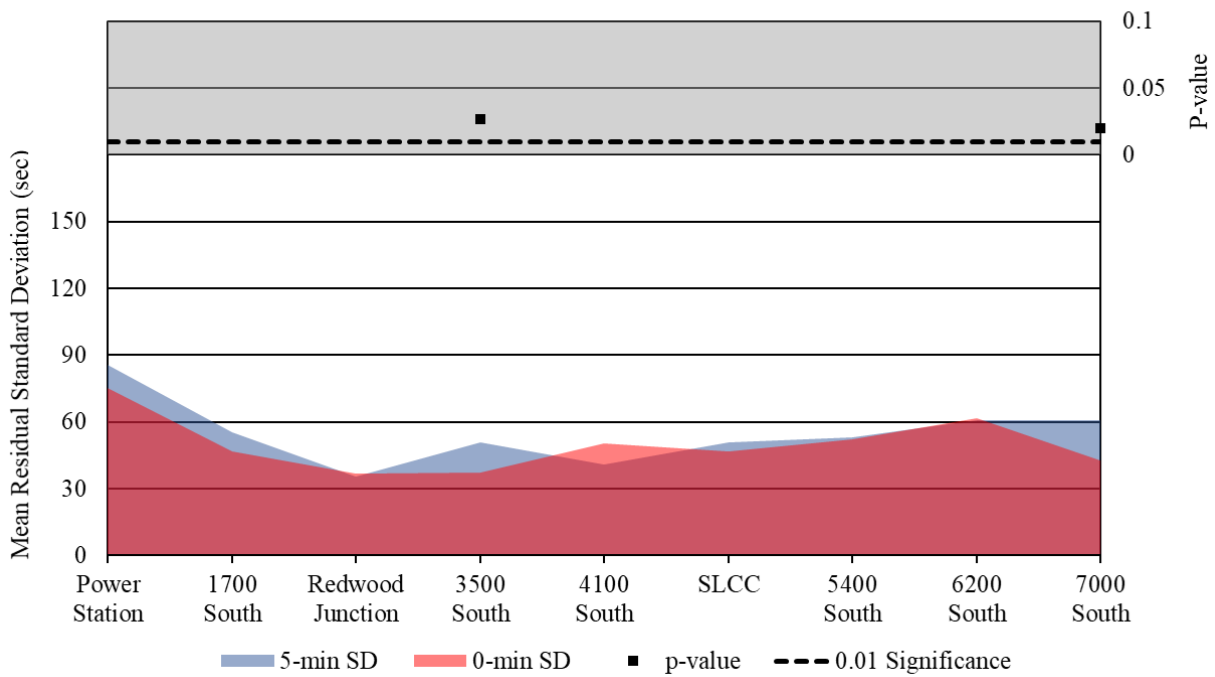


Figure 5-47: Route 217 AM NB travel-time variability 5-min vs. 0-min.

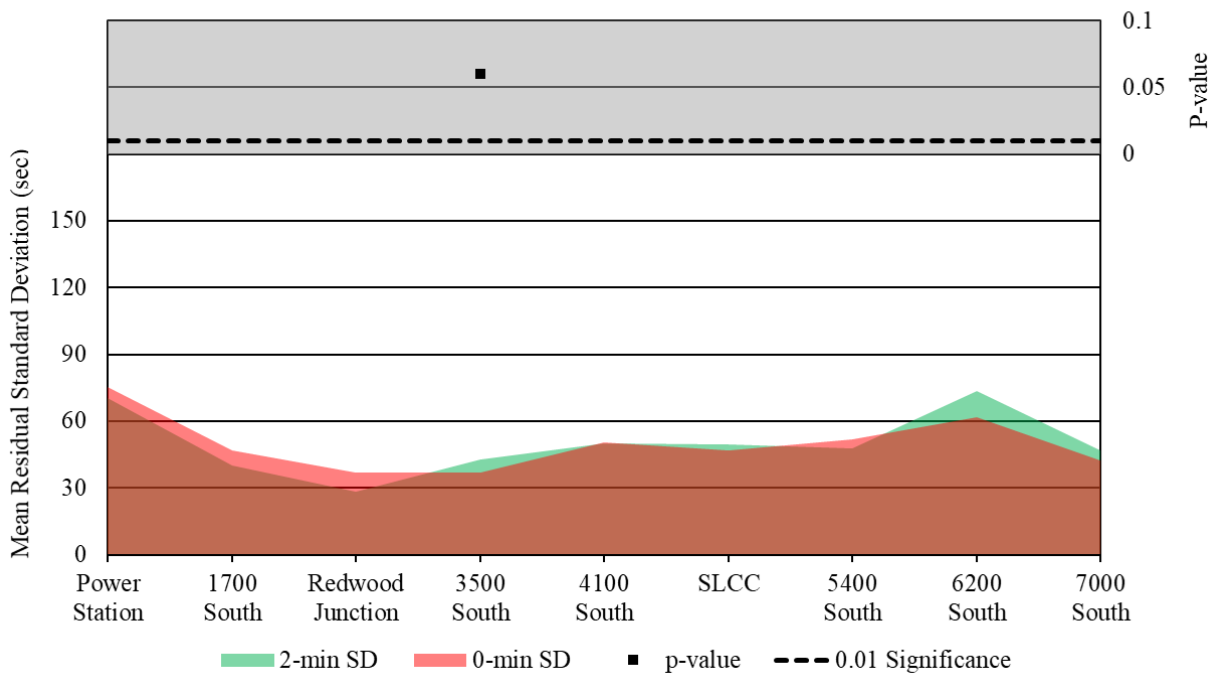


Figure 5-48: Route 217 AM NB travel-time variability 2-min vs. 0-min.

5.2.4 Route 217 – Dwell Time

An observed negative impact to buses that is theorized to be attributed to TSP is increased dwell time at timepoints due to holding buses that are early. The TCQSM defines dwell time as “the time spent at a stop or station serving passenger movements, including the time required to open and close the doors. Time spent at a stop for any other reasons, such as waiting for a traffic signal, waiting for another transit vehicle to move, or waiting for a late-arriving passenger is considered delay and is not counted as part of dwell time” (Ryus et al. 2013). Likewise, the *Highway Capacity Manual* (HCM) defines dwell time as “the sum of the time required to serve passengers at a transit stop and the time required to open and close the vehicle doors” (TRB 2010). There are several contributing factors to dwell time, including boarding and alighting volumes, fare payment method, vehicle type and size, number of passengers with wheelchairs or bicycles, operator interactions with passengers (e.g., answering questions or fare disputes), and many more (Ryus et al. 2013).

Discussions with UTA personnel revealed that UTA records “dwell time” as the time from which a bus enters a geofence around a stop to the time at which it leaves the geofence. This makes it impossible to determine how much of the recorded time was actual dwell time, as defined by the TCQSM and the HCM, delay, or due to the holding of early buses. Nevertheless, if a relatively small number of buses have to hold, it would be appropriate that the time spent holding be treated as additional dwell time for the purposes of calculating dwell-time variability (Ryus et al. 2013). Therefore, the “dwell time” that UTA records is a sum of all time a bus spends at a stop regardless of the reason, which could include actual dwell time, delay from difficulties re-entering the traffic stream, or time spent holding at a stop because the bus is early.

While it is reasonable that actual dwell time or other sources of delay could be considered constant for each requesting threshold, it was determined to be unreasonable to consider holding time constant. At the 0-minute threshold, a bus that is only 1 second behind schedule will request TSP as it travels to the next timepoint. These requests, if served, make the bus more likely to arrive early at the subsequent timepoint and have to hold, thus increasing the recorded dwell time. At the 2-minute threshold, a bus would have to gain more than 2 minutes to necessitate holding at the subsequent timepoint for TSP to have an effect on dwell time. Likewise, a bus

requesting TSP at the 5-minute threshold would need to gain more than 5 minutes to have the need to hold at a timepoint, a scenario highly unlikely at the next timepoint but could occur at a timepoint further down the route.

Therefore, it would be expected that as the requesting threshold approaches zero, the recorded dwell time would increase due to TSP helping the bus so much that it becomes early and needs to hold at subsequent timepoints. Indeed it is observed that for each directional peak scenario, with the exception of the AM SB scenario, buses at the 0-minute threshold have higher cumulative dwell time and dwell time per timepoint through the equipped corridor as shown in Table 5-12 and Table 5-13, respectively.

Table 5-12: Route 217 Average Cumulative Dwell Time (sec)

Requesting Threshold	AM NB	AM SB	PM NB	PM SB
5-min	417	378	548	584
3-min	386	318	509	581
2-min	413	355	547	542
0-min	477	374	632	616

Table 5-13: Route 217 Average Timepoint Dwell Time (sec)

Requesting Threshold	AM NB	AM SB	PM NB	PM SB
5-min	46.3	49.2	60.6	72.7
3-min	42.3	39.4	56.2	75.8
2-min	45.6	46.5	60.8	70.3
0-min	53.2	48.5	70.2	79.9

Figure 5-49, Figure 5-50, Figure 5-51, and Figure 5-52 (AM SB, AM NB, PM SB, and PM NB, respectively) are figures depicting the average dwell time at each timepoint as columns and the cumulative dwell time as the line graphs. While not true at every timepoint nor for every directional peak scenario, dwell time at individual timepoints for the 0-minute threshold is generally higher than it is for the other thresholds, often with little difference in dwell time among the 5-, 3-, and 2-minute requesting thresholds. This indicates that the 0-minute threshold generally leads to higher dwell time than the other requesting thresholds, which is likely due to receiving TSP when the bus is only slightly behind schedule.

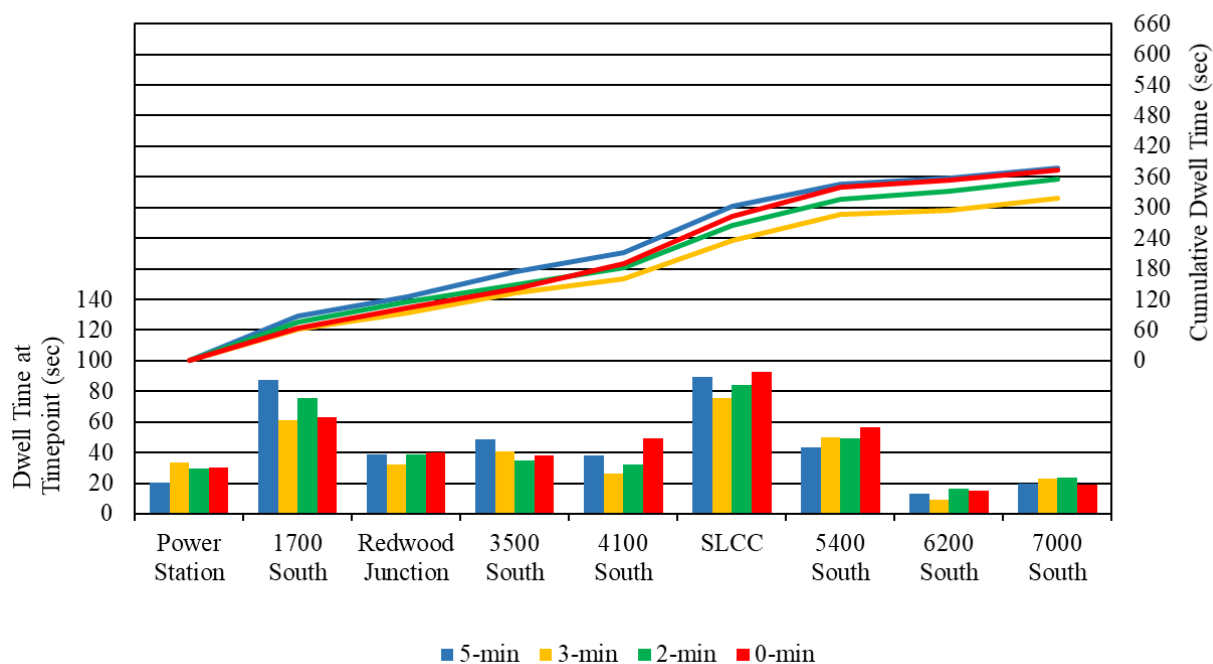


Figure 5-49: Route 217 AM SB dwell time.

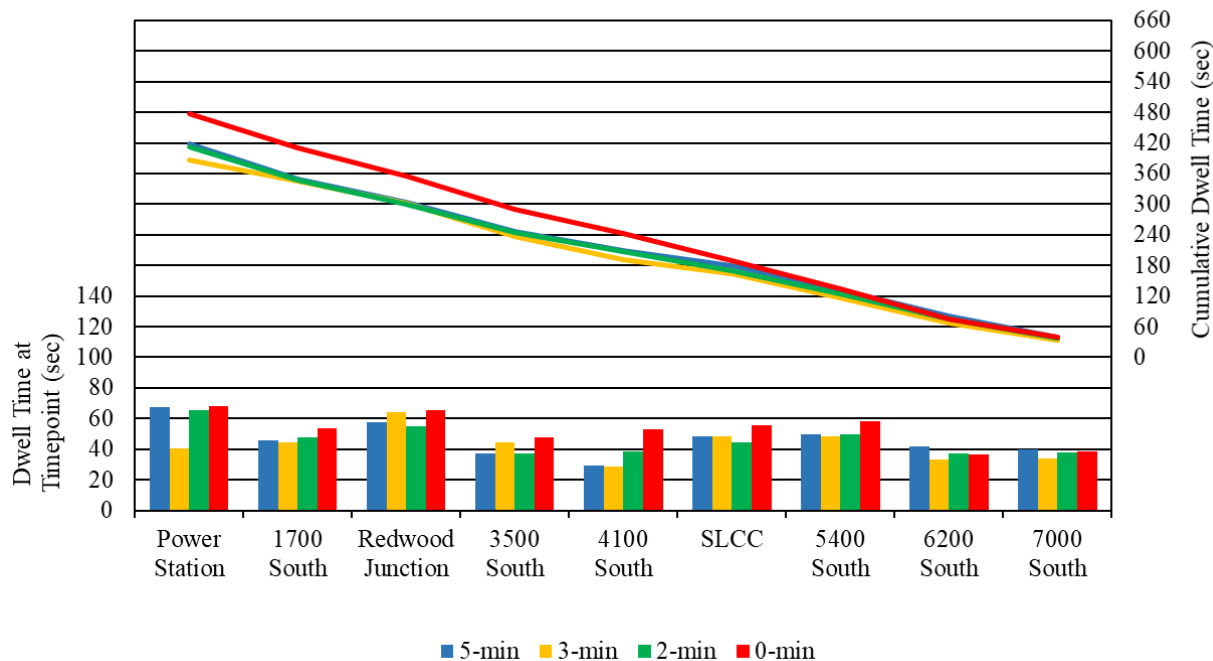


Figure 5-50: Route 217 AM NB dwell time.

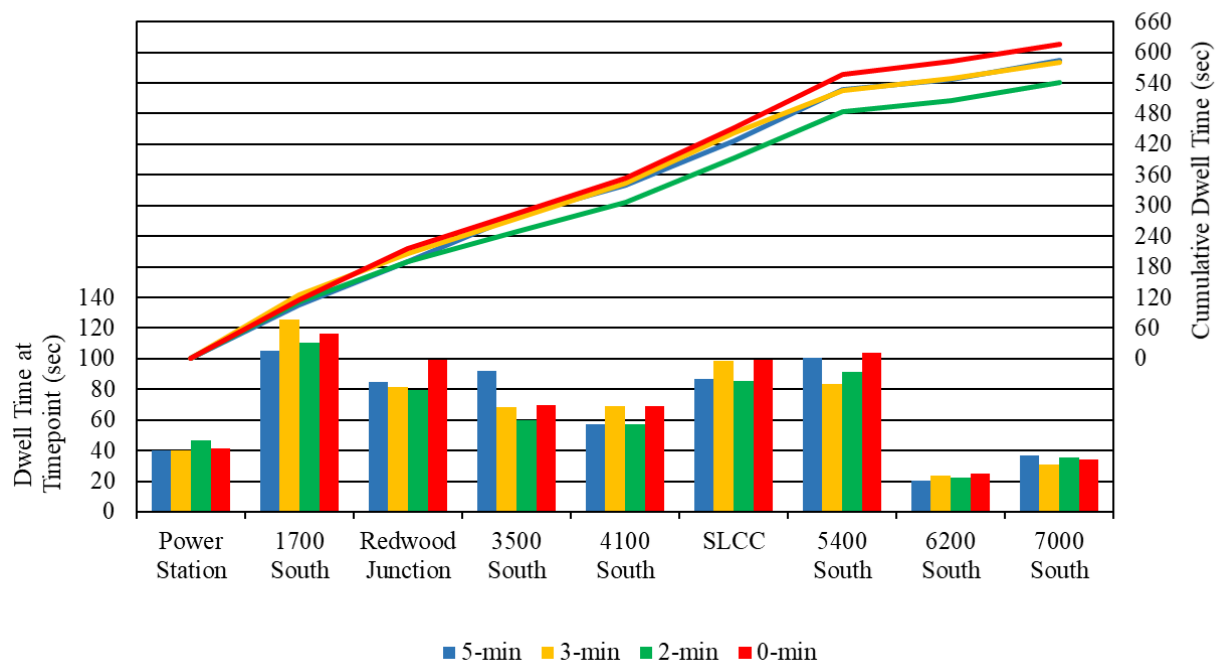


Figure 5-51: Route 217 PM SB dwell time.

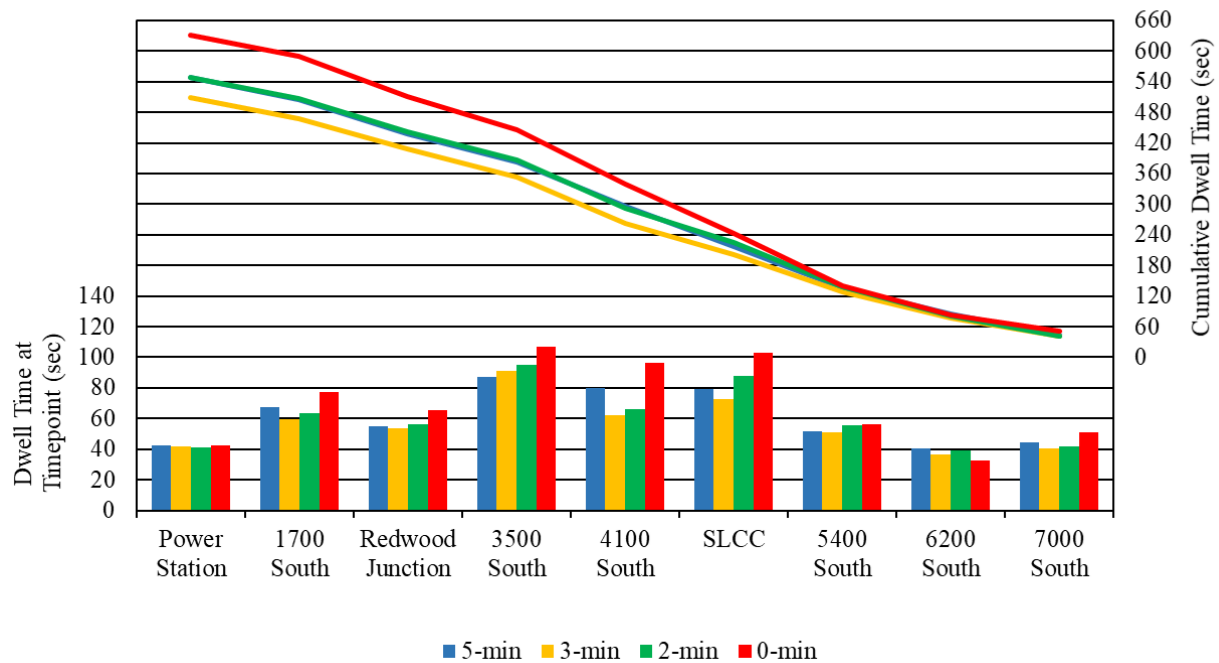


Figure 5-52: Route 217 PM NB dwell time.

While the 0-minute requesting threshold usually resulted in the best bus performance, consideration should be given to whether this improved bus performance offsets passenger frustration due to increased dwell time. When cumulative dwell time at the 0-minute threshold is compared to the other requesting thresholds evaluated, the average cumulative dwell time is 60 seconds higher at the 0-minute threshold.

5.3 Route 217 General Traffic Results

The following subsections contain the results of the general traffic analyses for the frequency at which TSP is served, split fail, and change in green time. Contrary to how bus performance was analyzed, the traffic analysis evaluates the impact of changing the requesting threshold by AM and PM peak, thereby combining instances in which TSP was served for NB and SB buses.

5.3.1 Route 217 – Transit Signal Priority Frequency

For all equipped intersections capable of serving TSP, the percent of cycles served with TSP is displayed in Figure 5-53 with the frequency of TSP served per hour shown in Figure 5-54 with averages by peak period shown in parentheses along the x-axis. It is clear that the 2-minute and 3-minute requesting thresholds are very similar with respect to the percent of cycles that are impacted (numerical difference of 0.2 percent) and how many times per hour TSP is served (difference of 0.03 times per hour). However, the results for both metrics are much lower for the 5-minute threshold and much higher for the 0-minute threshold. For both metrics, the average of the 2-minute and 3-minute thresholds is compared to the 5-minute and 0-minute requesting thresholds. For percent of cycles served with TSP, the 5-minute threshold is 87 percent lower while the 0-minute threshold is 307 percent higher. For the number of times TSP is served per hour, the 5-minute threshold is 86 percent lower while the 0-minute threshold is 284 percent higher.

Results for the percent of cycles served with TSP and the frequency at which TSP is served per hour at the timepoint level are shown in Figure 5-55 for the AM peak and in Figure 5-56 for the PM peak. These figures illustrate that certain intersections are much more likely to

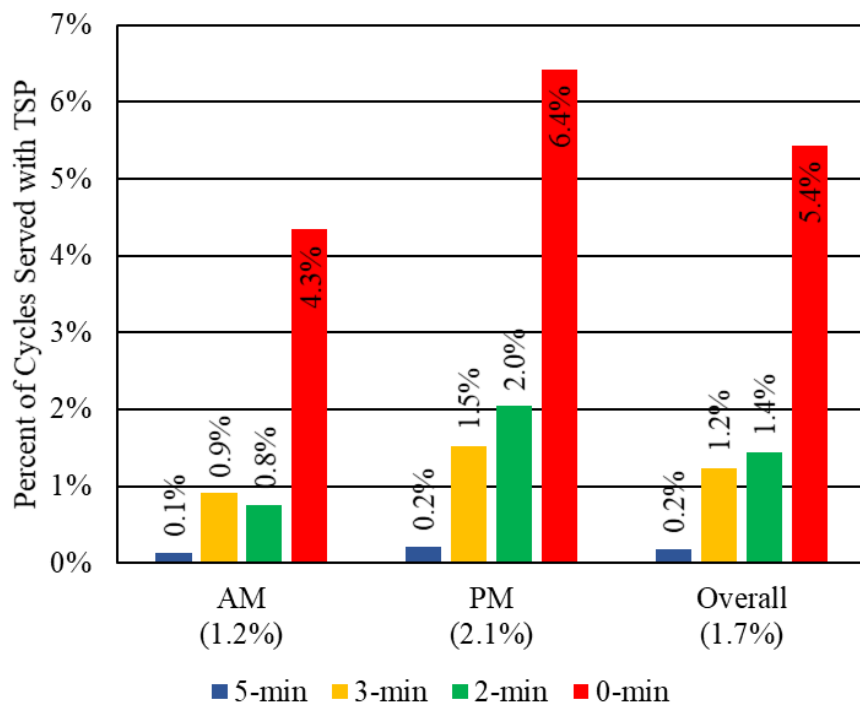


Figure 5-53: Corridor-level percent of cycles served with TSP.

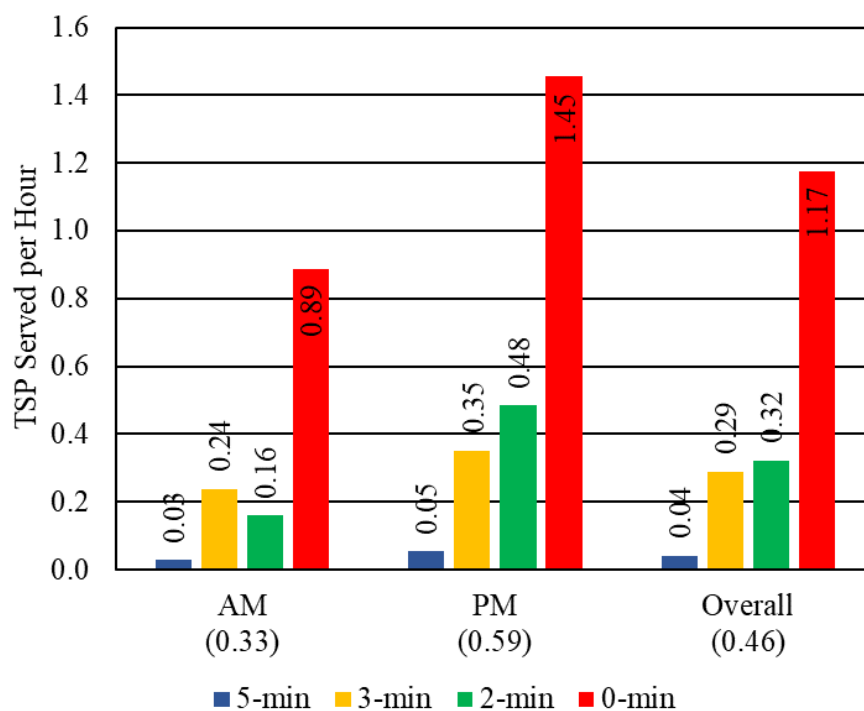


Figure 5-54: Corridor-level frequency of TSP served per hour.

serve TSP, although none come close to serving TSP at the maximum possible frequency of 10 per hour (Route 217 runs at 15-minute headways, which results in five NB and five SB buses per hour). It should be noted that an error occurred when evaluating 1500 South for the 3-minute requesting threshold and the results do not accurately represent the frequency at which TSP is served.

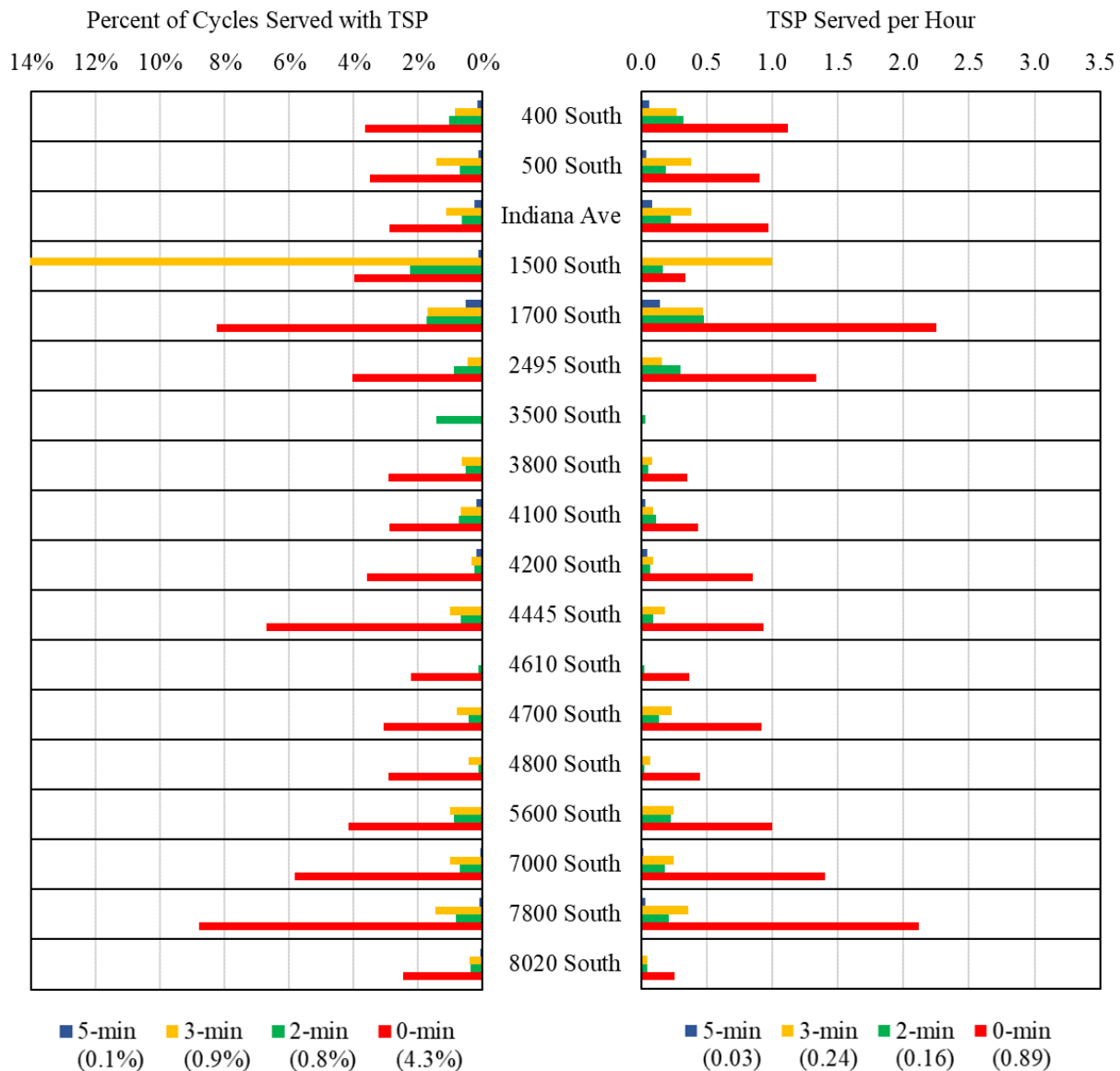


Figure 5-55: AM peak intersection-level frequency of TSP served.

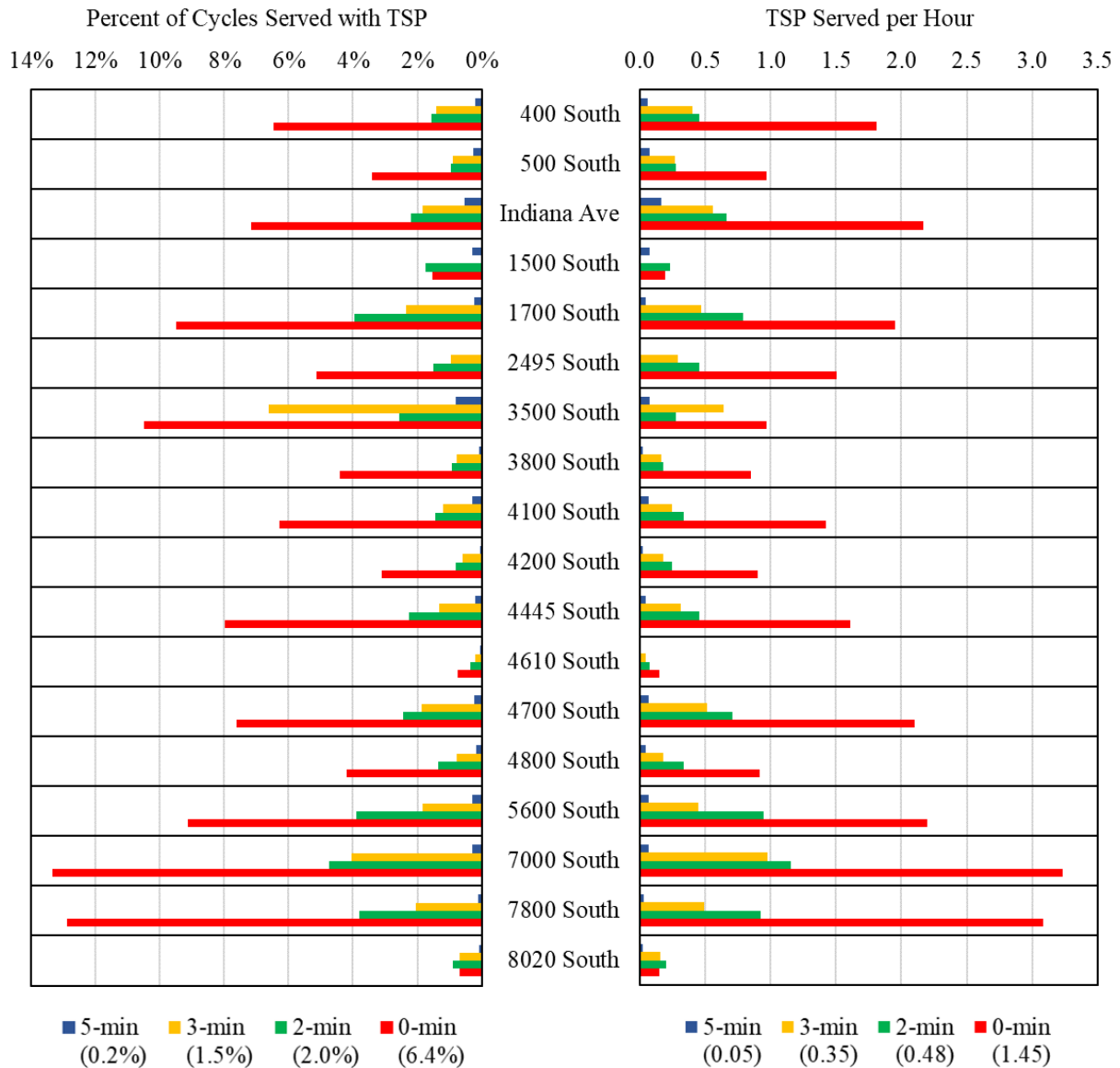


Figure 5-56: PM peak intersection-level frequency of TSP served.

5.3.2 Route 217 – Split Fail

Split fail occurs when the duration of green for a movement at a signalized intersection is insufficient to serve the amount of demand present. It is determined that split failure has occurred

when vehicle occupancy exceeded 85 percent of both green time and the first 5 seconds of red time. The figures in this section represent how split fail was affected when TSP was served. Figure 5-57 shows the corridor-level results of the split-fail analysis with the intersection-level results shown in Figure 5-58 for the AM Peak and Figure 5-59 for the PM peak. It was unexpected to see that split fail improved as the requesting threshold approaches zero. Although the cause of this phenomena was not verified, the research team believes that this occurred because when TSP was served at the 5-minute threshold, traffic was more congested. That is not to say that traffic was inherently worse during the weeks that the 5-minute data were collected, but rather because the bus was 5 minutes behind schedule it was likely that traffic was worse.

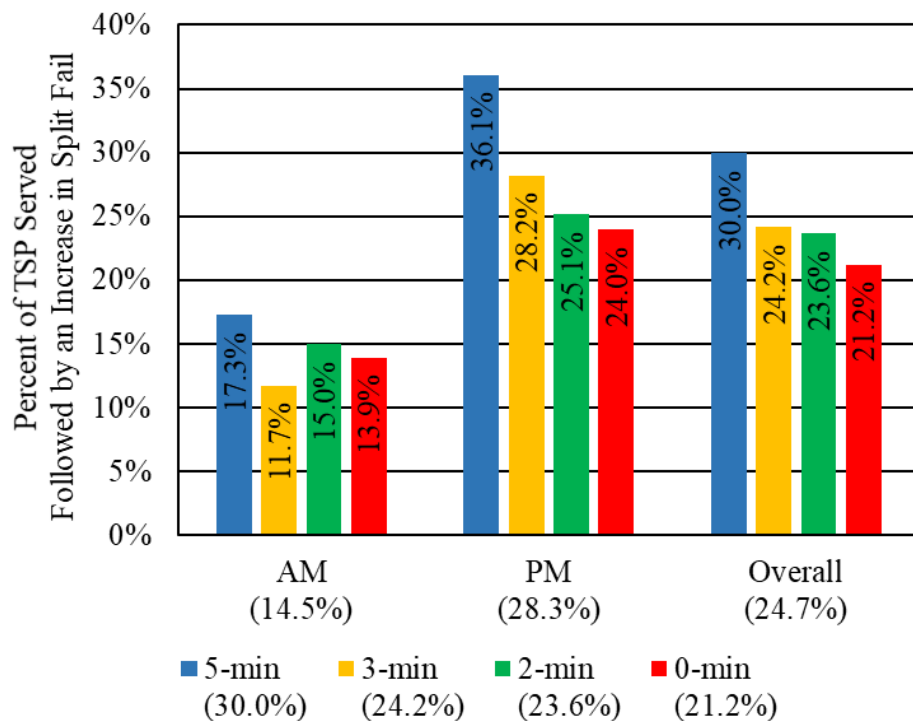


Figure 5-57: Corridor-level split fail results.

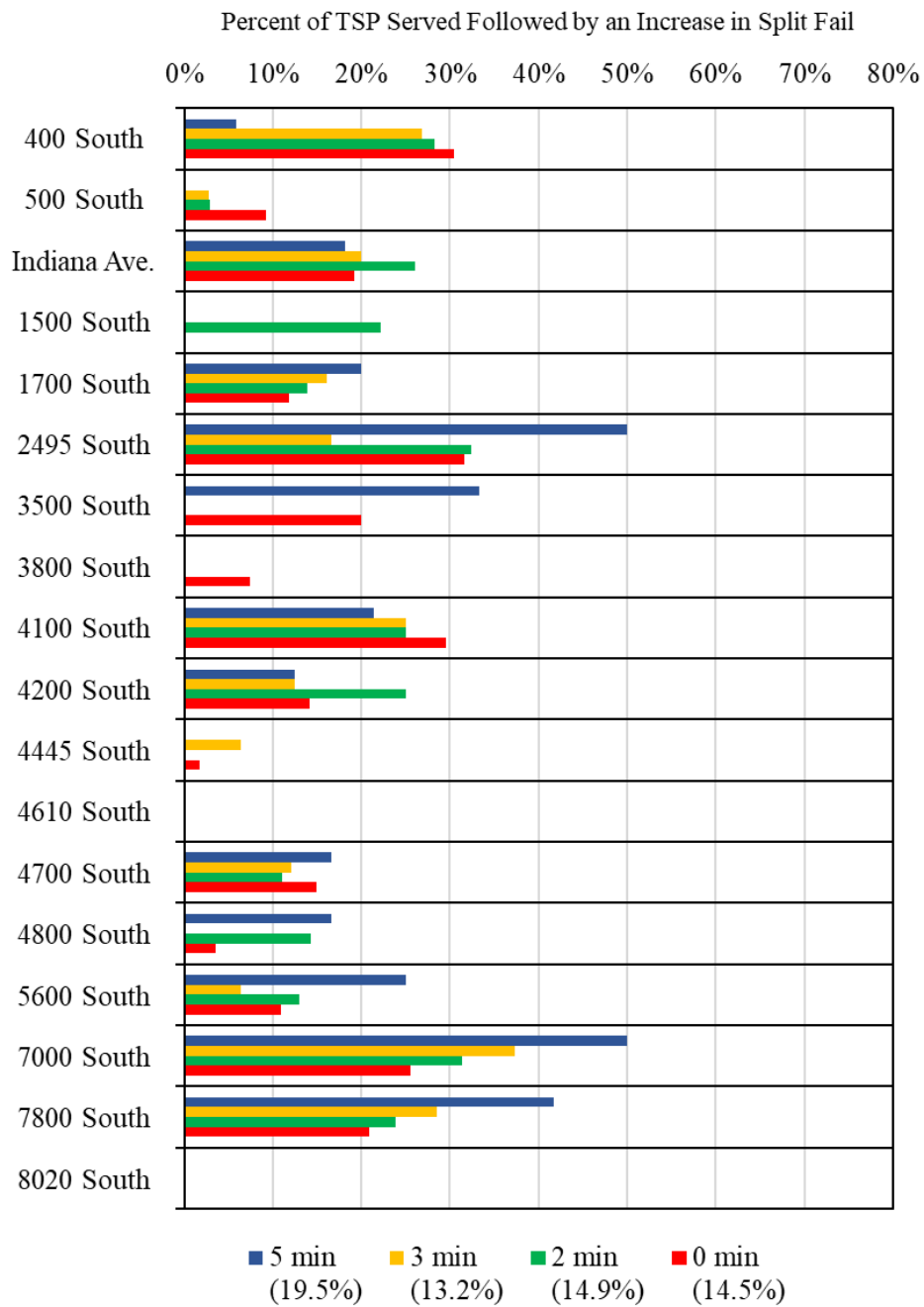


Figure 5-58: AM peak intersection-level split fail results.

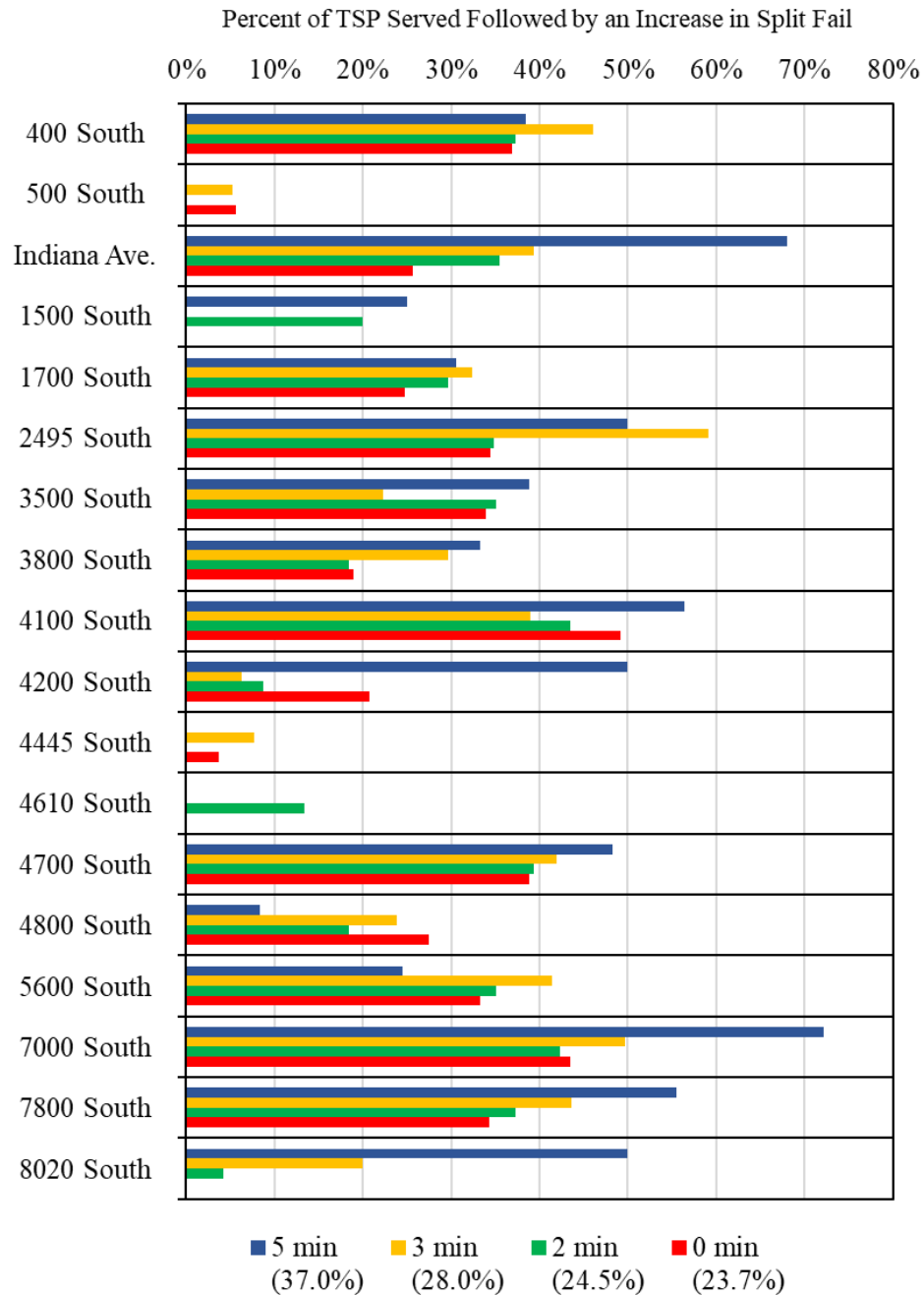


Figure 5-59: PM peak intersection-level split fail results.

The frequency at which TSP is served metric was multiplied by the percent of TSP served followed by an increase in split-fail metric to obtain the frequency at which it is suggested that TSP negatively impacted general traffic. Table 5-14 contains the results of this analysis by peak period and indicates that inconsequential negative impacts to general traffic occur when

TSP is served. For the 3-minute requesting threshold during the AM peak, for example, TSP was served an average of 0.24 times per hour while an average of 11.7 percent of those events resulted in an increase in split fail, or negative impacts to general traffic. Multiplying the two together suggests that, on average, TSP causes negative impacts to general traffic 0.028 times per hour, or once every 2,158 minutes. The PM peak during the 0-minute requesting threshold had the greatest impact with TSP negatively impacting general traffic once every 172 minutes, or approximately once every 3 hours. Overall, when the AM and PM peak data are combined, it is suggested that TSP causes negative impact to general traffic once every 241 minutes, or once every 4 hours, when the 0-minute threshold was implemented.

Table 5-14: Impacts of TSP on General Traffic by Peak Period

Serving TSP Negatively Impacts General Traffic Every X Minutes				
Peak	5 min	3 min	2 min	0 min
AM	12,139	2,156	2,519	485
PM	3,112	605	493	172
Overall	4,840	859	787	241

The results of general traffic impacts analysis at the intersection level are shown in Table 5-15. This table is overlaid with a 3-color scale heatmap where the green, yellow, and red shadings correspond to the 90th, 50th, and 10th percentile of all values in the table for the given peak period. This means that dark red shading highlights lower values, which indicates that traffic is negatively impacted at a higher frequency, and dark green indicates the intersections where there is the least potential for traffic to be negatively impacted. The white areas indicate scenarios where no increase in split failure was recorded during the study period.

The intersection and scenario with the greatest suggested impact to general traffic is 7000 South during the PM peak at the 0-minute threshold, which indicates that TSP negatively impacts traffic once every 43 minutes. The heatmap also illustrates that negative impacts to general traffic occurred more frequently during the 0-minute threshold and during the PM peak.

Table 5-15: General Traffic Impacts by Peak Period and Intersection (heatmap by table)

Cross Street	Serving TSP Negatively Impacts General Traffic Every X Minutes							
	AM				PM			
	5 min	3 min	2 min	0 min	5 min	3 min	2 min	0 min
400 South	17871	839	659	176	2732	326	354	90
500 South		5713	10804	720		4277		1097
Indiana Ave	3851	794	1035	323	545	274	253	108
1500 South			1620		3150		1306	
1700 South	2099	797	904	226	4125	397	257	125
2495 South	12632	2313	617	142	12632	351	379	116
3500 South					2025	417	616	183
3800 South				2313	9475	1215	1832	373
4100 South	9790	2700	2160	469	1595	630	414	86
4200 South	10084	5399	3598	499	6316	5399	2822	322
4445 South		5075		3695		2464		1027
4610 South							5786	
4700 South	37887	2127	4051	440	1866	277	214	74
4800 South	37887		18913	3735	15132	1417	979	239
5600 South	25263	3806	2071	551	3673	326	181	82
7000 South	6316	658	1077	168	1246	123	123	43
7800 South	5035	591	1194	136	3776	282	175	57
8020 South					6316	1928	7194	

Table 5-16 contains the same data as Table 5-15, but generates the heatmap separately for each column. This highlights that the cross streets 7000 South and 7800 South were typically where TSP was most likely to negatively impact traffic regardless of the requesting threshold. A thorough understanding of the corridor is needed before conclusions are drawn, however, because these two intersections are also some of the most congested intersections along the corridor. Thus, the heavier congestion results in the increased likelihood that minor adjustments to signal timing, such as those permitted by TSP, will lead to negative impacts to general traffic.

Table 5-16: General Traffic Impacts by Peak Period and Intersection (heatmap by column)

Cross Street	Serving TSP Negatively Impacts General Traffic Every X Minutes							
	AM				PM			
	5 min	3 min	2 min	0 min	5 min	3 min	2 min	0 min
400 South	17871	839	659	176	2732	326	354	90
500 South		5713	10804	720		4277		1097
Indiana Ave	3851	794	1035	323	545	274	253	108
1500 South			1620		3150		1306	
1700 South	2099	797	904	226	4125	397	257	125
2495 South	12632	2313	617	142	12632	351	379	116
3500 South					2025	417	616	183
3800 South				2313	9475	1215	1832	373
4100 South	9790	2700	2160	469	1595	630	414	86
4200 South	10084	5399	3598	499	6316	5399	2822	322
4445 South		5075		3695		2464		1027
4610 South							5786	
4700 South	37887	2127	4051	440	1866	277	214	74
4800 South	37887		18913	3735	15132	1417	979	239
5600 South	25263	3806	2071	551	3673	326	181	82
7000 South	6316	658	1077	168	1246	123	123	43
7800 South	5035	591	1194	136	3776	282	175	57
8020 South					6316	1928	7194	

It is noteworthy that all of the 10 lowest values occurred during the PM peak, while eight of the 10 were during the PM peak under the 0-minute requesting threshold. Nevertheless, negatively impacting traffic on average once every 43 minutes or 57 minutes, the two lowest values, is still quite infrequent. It is also observed that there are more white areas during the AM peak and in the middle portion of the route.

5.3.3 Route 217 – Change in Green Time

The amount of extra green provided when TSP is served is dependent on when in the cycle the bus enters the pre-defined geofence of the intersection. Consequently, it is reasonable that the change in requesting threshold would not impact how much extra green time is allocated to a bus requesting TSP. Figure 5-60 (AM peak) and Figure 5-61 (PM peak) show the change in green time for the phases served with TSP as a percentage of total cycle length. There is often a

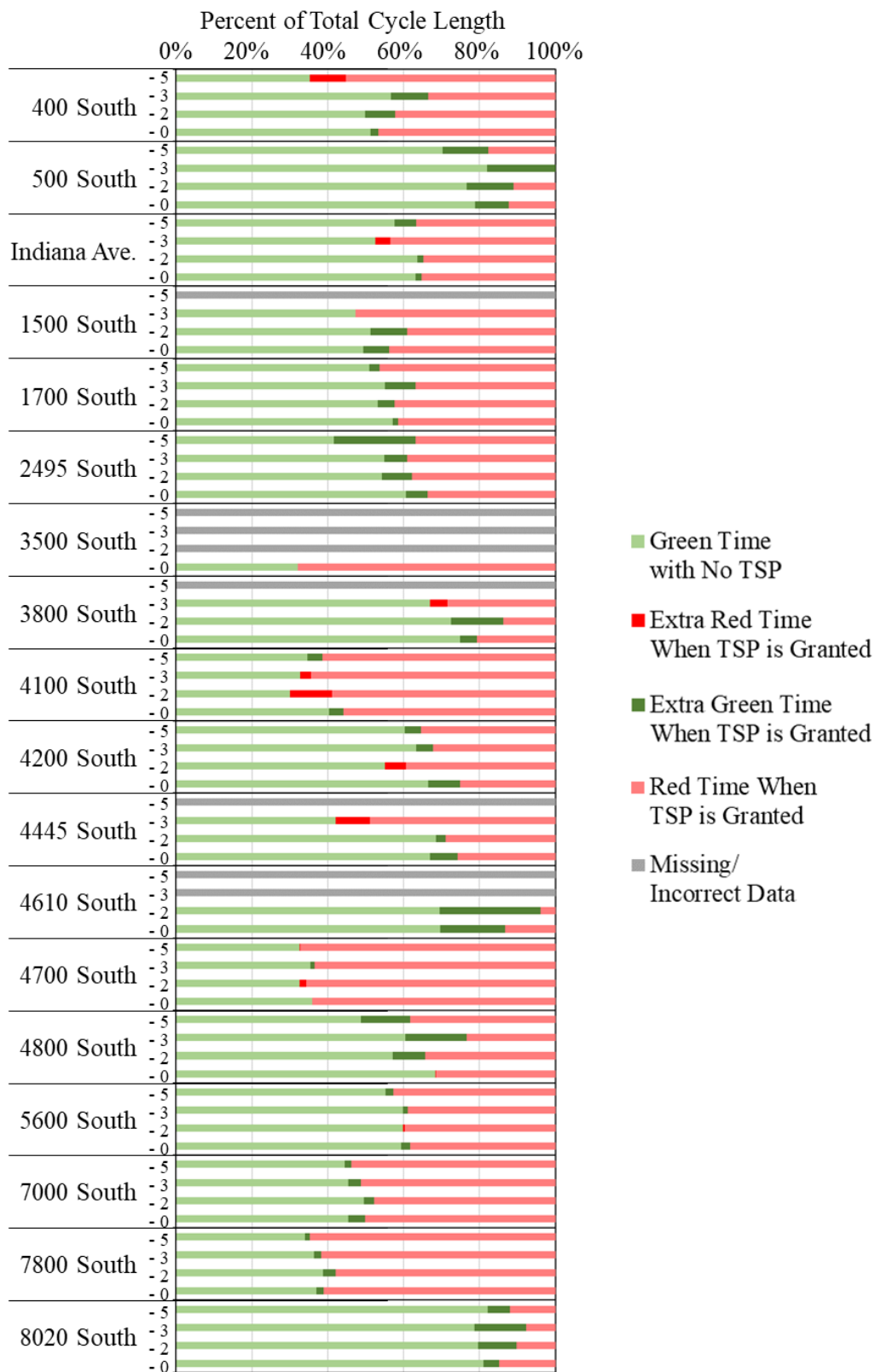


Figure 5-60: Route 217 AM peak change in green time by intersection.

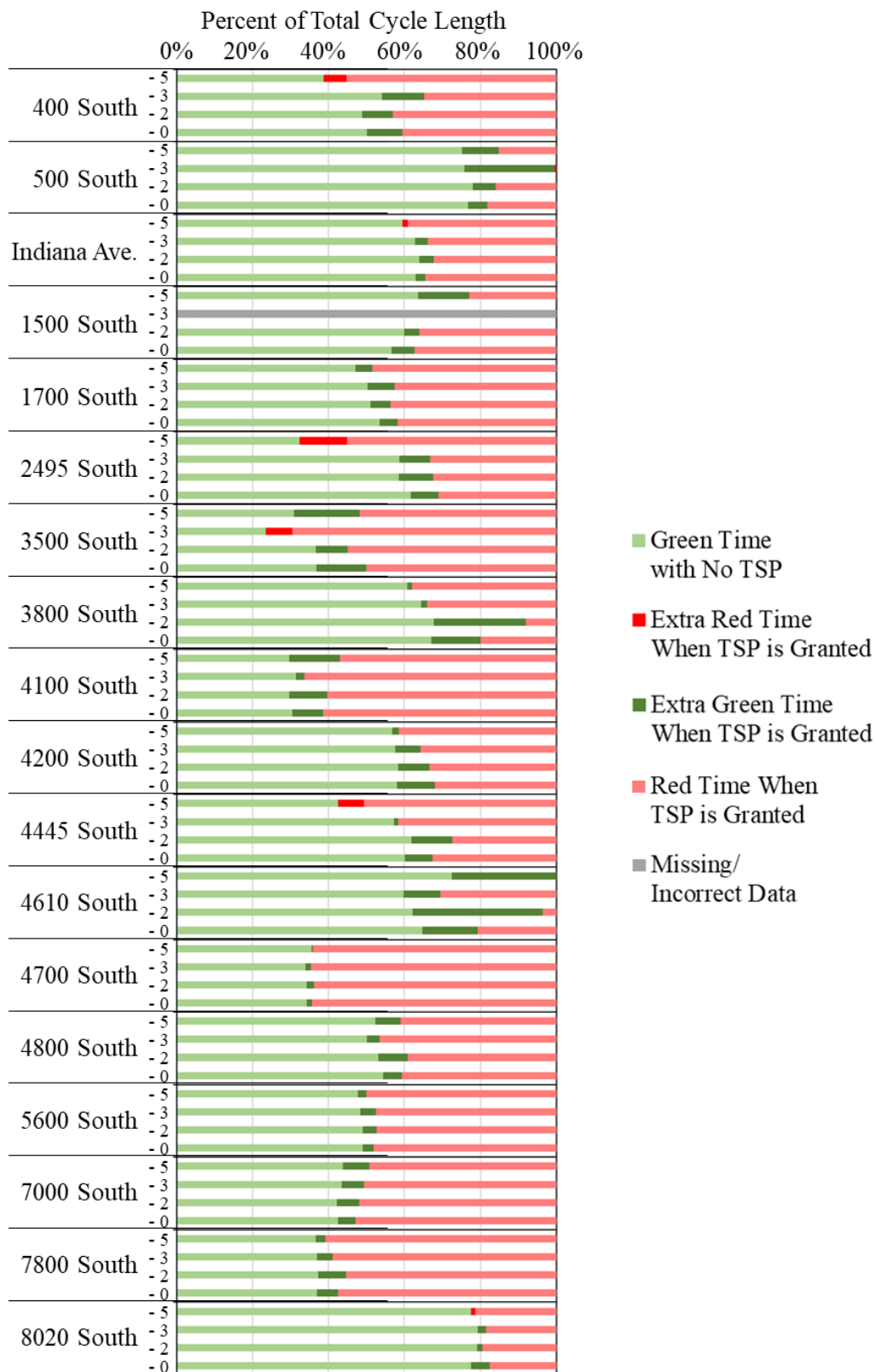


Figure 5-61: Route 217 PM peak change in green time by intersection.

correlation where intersections with more green time as a percentage of total cycle length also have some of the lowest frequency of TSP served. The cross street of 4610 South is green for north and southbound traffic for nearly 70 percent of the cycle length. This makes it very likely that a bus requesting TSP will arrive on green and will not actually be served with TSP. Indeed, 4610 South is among the cross streets with the lowest frequency of TSP served and lowest percent of TSP served that is followed by an increase in split fail.

5.4 UVX Bus Performance Results

It is noted that there are striking differences in the bus performance results between UVX and Route 217. One of the most obvious differences is OTP; OTP for Route 217 usually has percentages between the mid-80s to mid-90s while OTP for UVX is considerably lower and frequently dips below 60 percent. There are two possible explanations as to why OTP for UVX is considerably lower than that of Route 217. First, the lateness threshold for UVX is 2 minutes whereas the lateness threshold is 5 minutes for Route 217. In fact, if UVX OTP is calculated using a 5-minute lateness threshold (a bus is only considered late if it is 5 minutes or more behind schedule), UVX outperforms Route 217 for nearly all directional peak scenarios. Second, UVX is a new route with a schedule that is not fully understood as can be observed through the large changes in OTP and schedule deviation from one timepoint to the next and throughout the route.

To illustrate, it should first be recognized that UVX travel time is quite consistent. The average magnitude of the 95 percent prediction interval for each requesting threshold and each directional peak scenario is 105 seconds for UVX while it is 246 seconds for Route 217. This can likely be attributed to the dedicated lanes on which UVX operates and less distance between timepoints. More consistent travel time should correspond to more consistent schedule deviation, however UVX mean schedule deviation changes an average of 36 seconds from one timepoint to the next while the average for Route 217 is 27 seconds, a 33 percent increase for UVX. Furthermore, for each requesting threshold and each directional peak scenario, the difference between the timepoints with the highest and lowest mean schedule deviation averages 101 seconds for Route 217 and 217 seconds for UVX, a 115 percent increase for UVX. Because the lateness threshold is only 2 minutes, OTP is more susceptible to the large schedule deviation

fluctuations that are observed. Collectively, these characteristics produce an amplified effect on UVX OTP and cause it to be considerably lower than that which is observed for Route 217.

Another obvious difference between these two routes is that between requesting thresholds, there is much less variability on UVX. This is believed to most strongly result from the dedicated lanes, which makes the bus relatively impervious to variations in general traffic and immune to reentry delay, and the absence of a holding strategy, which makes dwell time mostly a function of number of boardings and alightings. Route 217 buses, on the other hand, operate in mixed traffic, are greatly impacted by variations in general traffic, and have a dwell time that is also impacted by schedule deviation and the holding strategy (if ahead of schedule, the bus must wait so that it leaves on time).

The subsections contained herein cover the results of OTP, schedule deviation, and travel-time analyses for UVX.

5.4.1 UVX – On-Time Performance

The corridor-level results of the observational OTP evaluation for each directional peak scenario are shown in Figure 5-62. The requesting thresholds are displayed in ascending order according to anticipated frequency of TSP requests. As expected, and across all directional peak

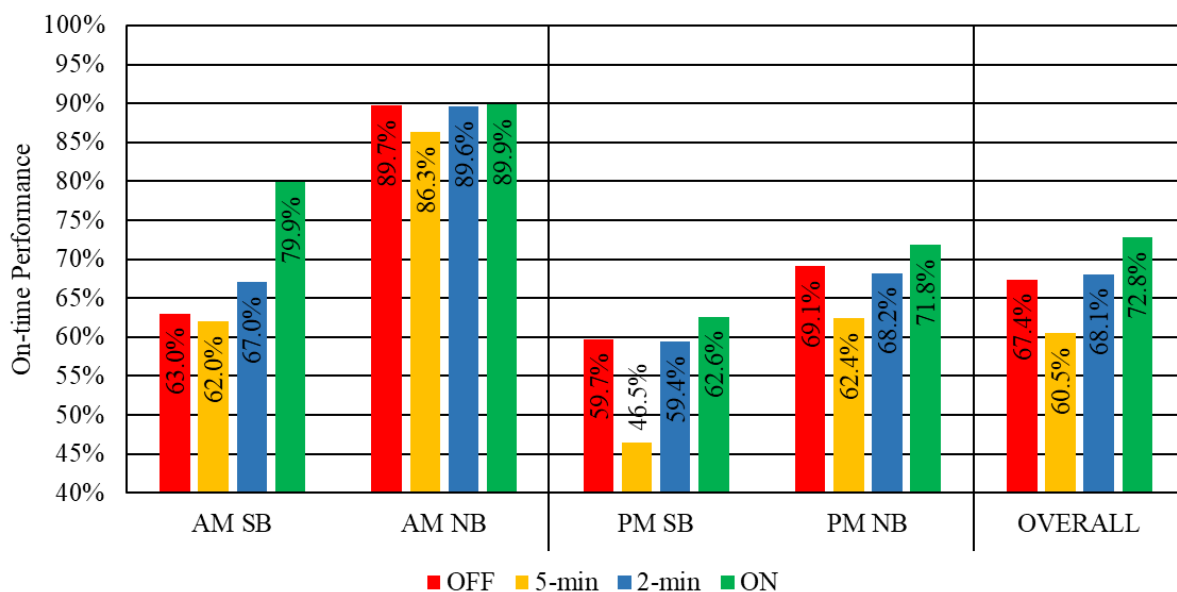


Figure 5-62: UVX corridor-level and overall OTP.

scenarios, the ON requesting threshold resulted in the highest OTP and was followed in descending order by the 2-minute threshold, then OFF, and then the 5-minute threshold. It was unexpected to see that OTP for the OFF requesting threshold was often higher than OTP for the 5-minute and 2-minute requesting thresholds, a phenomena that cannot be conclusively explained by the research team. Overall, OTP improved 7.6 percent as the requesting threshold changed from 5 minutes to 2 minutes and improved 4.7 percent as the requesting threshold changed from 2 minutes to ON.

The timepoint-level OTP results are shown in Figure 5-63 for the AM peak and in Figure 5-64 for the PM peak with the corridor-level results displayed in parentheses as part of the legend. The NB direction showed surprising consistency regardless of the requesting threshold while the SB direction often had large differences between thresholds.

As previously alluded to in the introduction of this section (Section 5.4), OTP throughout most of this route is low when compared to Route 217. The PM NB OTP results in Figure 5-64 illustrate what appears to be a schedule deficiency for several consecutive timepoints near the beginning of the route. It is observed that OTP is approximately 90 percent at the 400 South timepoint, drops to almost 30 percent two timepoints later at 300 North, and then returns back up to approximately 90 percent at the BYU Campus timepoint.

5.4.2 UVX – Schedule Deviation

Schedule deviation measures the difference between the actual and scheduled departure time in seconds, a more granular way to measure schedule adherence than OTP which is binary (on time or late). Subsections include the results of evaluating schedule deviation through the difference in means analysis, the 95 percent prediction interval, and the analysis of variability.

5.4.2.1 UVX – Schedule Deviation: Difference in Means

The statistical model was used to estimate the mean schedule deviation and the SE of the mean for each directional peak scenario. The comparison of means between two requesting thresholds was performed through a two-sided t-test, which measures whether there is a statistically significant difference in mean schedule deviation. The results are shown graphically by plotting the estimated mean and the SE range at each timepoint, with the SE range being

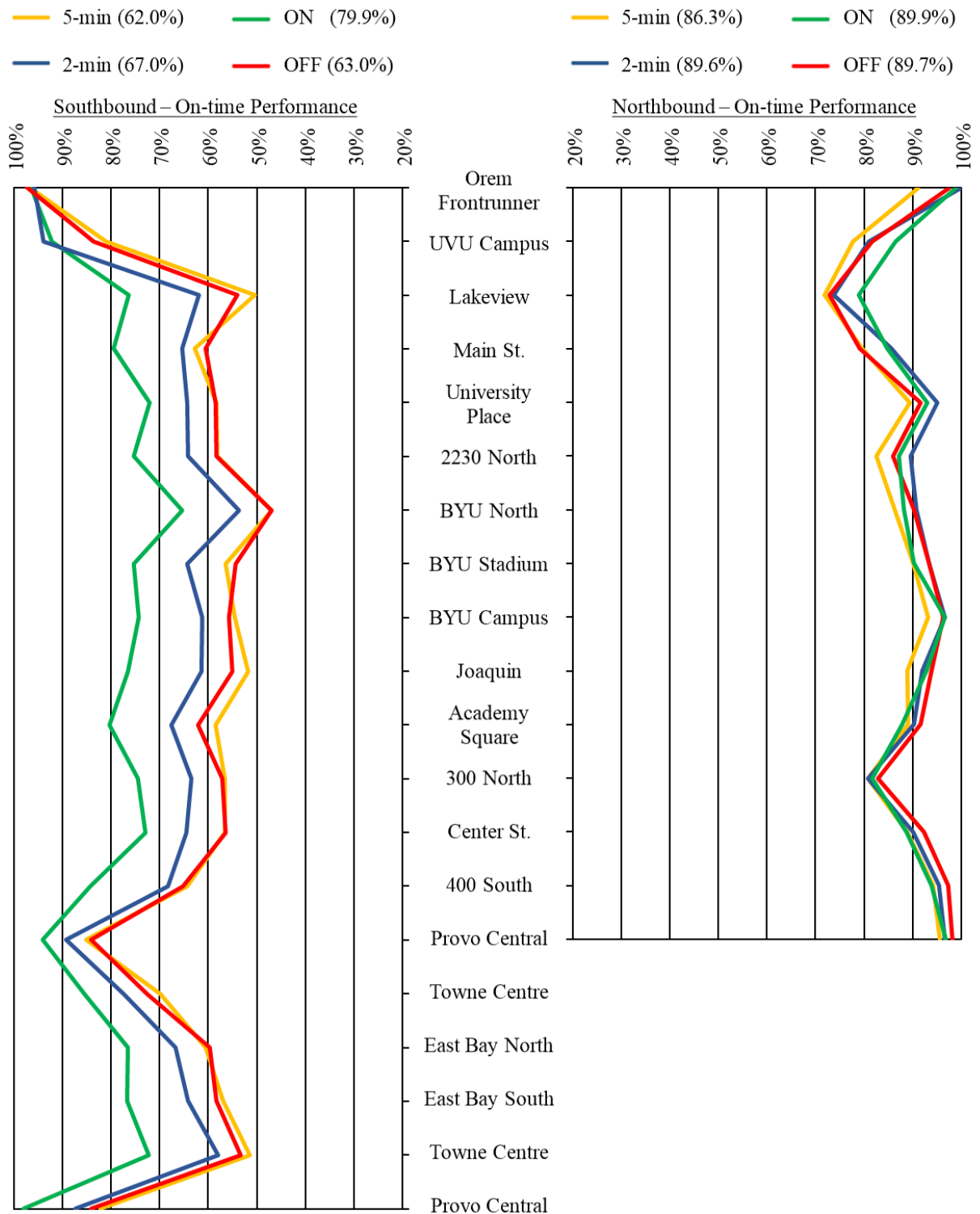


Figure 5-63: UVX AM peak OTP.

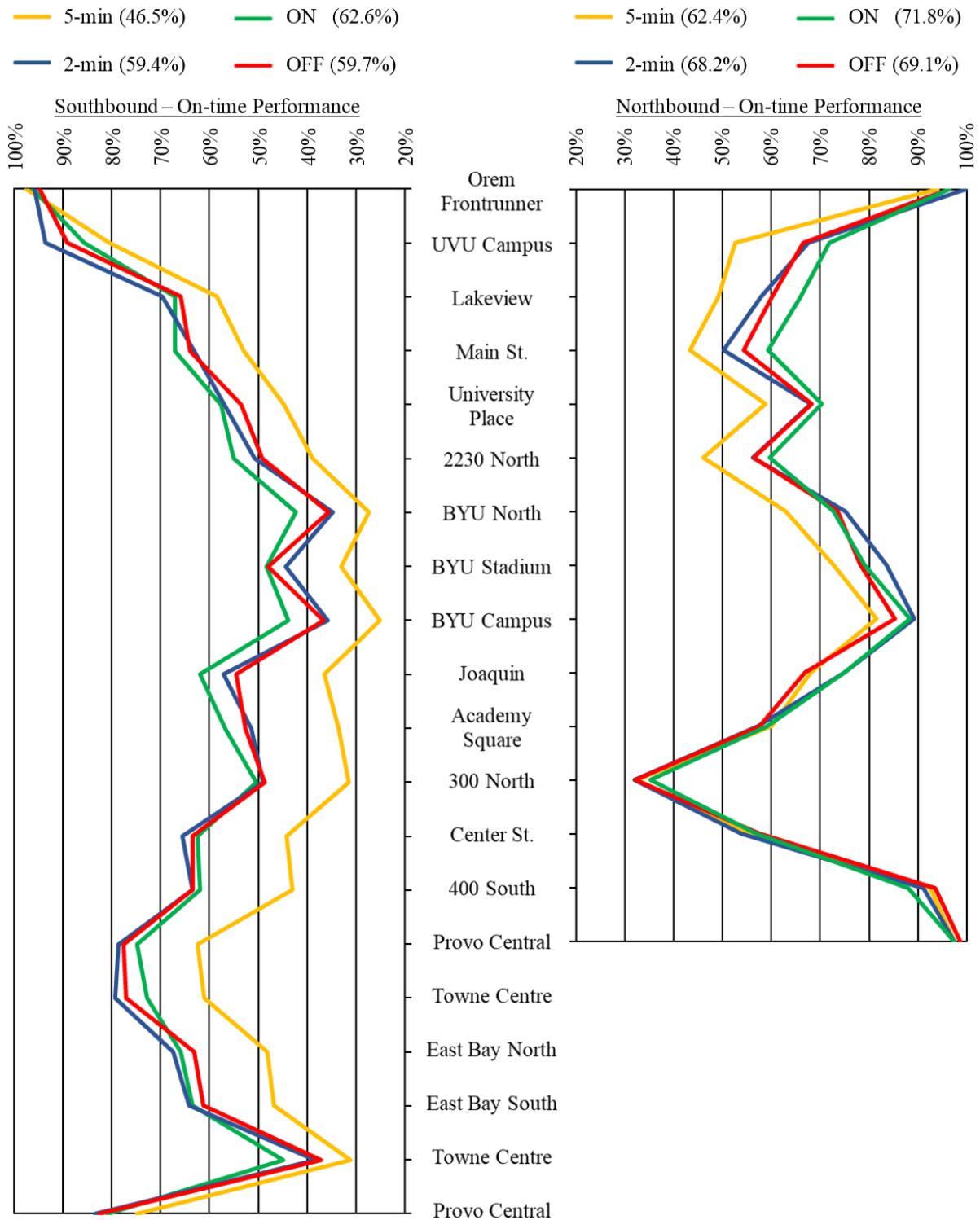


Figure 5-64: UVX PM peak OTP.

calculated using Equation 5-3. Four comparison pairs were evaluated for UVX; each requesting threshold was compared to the baseline 2-minute requesting threshold and then the OFF and ON thresholds were compared against each other.

Figure 5-65 contains the corridor-level estimates of the mean schedule deviation for each directional peak scenario. Overall, mean schedule deviation improved and decreased 24.3 seconds when the requesting threshold changed from 5 minutes to 2 minutes ($p < 0.0001$) and decreased 15.0 seconds when the threshold changed from 2 minutes to ON ($p < 0.0001$). These results effectively parallel the findings observed in the OTP analysis, although there are contrasts that highlight the inherent differences in analyzing bus performance through OTP versus schedule deviation. For example, in the corridor-level OTP analysis the ON requesting threshold performed the best across all the directional peak scenarios, but the corridor-level mean schedule deviation analysis shows that it was outperformed in the PM SB by the OFF and 2-minute thresholds.

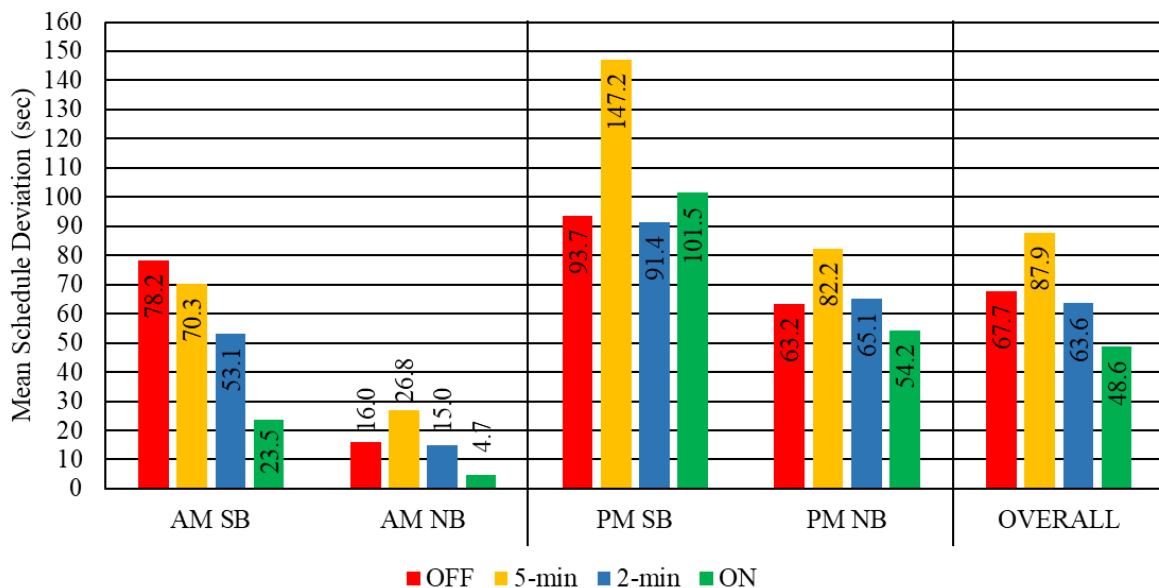


Figure 5-65: UVX mean corridor-level and overall schedule deviation.

The overall and corridor-level p-values from the difference in means statistical analysis are displayed in Table 5-17 and are organized by comparison pair and directional peak scenario. Through Equation 5-1 and Equation 5-2, the p-values in this table have been converted from the

original, two-sided t-test p-values to one-sided t-test p-values that reflect the anticipated decrease in mean schedule deviation as the requesting threshold approaches zero, the null hypothesis. The shaded results emphasize p-values less than 0.01 (the pseudo-Bonferroni adjustment) and indicate that a statistically significant improvement in mean schedule deviation exists for the given comparison pair and directional peak scenario according to the null hypothesis.

Across all directional peak scenarios, there is convincing evidence that mean schedule deviation improves from the 5-minute to the 2-minute requesting threshold and again from the 2-minute to the ON requesting threshold. The only exception is in the PM SB where the mean schedule deviation at the 2-minute and OFF requesting thresholds are lower than the ON requesting threshold.

Table 5-17: UVX Corridor-Level Difference in Means P-Values

Comparison Pair	AM SB	AM NB	PM SB	PM NB	OVERALL
2-min vs OFF	<0.0001	0.3508	0.23785	0.7041	0.1011
2-min vs 5-min	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
2-min vs ON	<0.0001	<0.0001	0.99925	0.00095	<0.0001
OFF vs ON	<0.0001	<0.0001	0.98885	0.00705	<0.0001

The remaining figures in this subsection display results at the timepoint level for each directional peak scenario as outlined in Table 5-18. The “all means” figures present the estimated mean schedule deviation at each timepoint by requesting threshold. The “all SE ranges” figures show the SE range, mean schedule deviation, and a trendline of the mean (from OFF, to 5 minute, to 2 minute, to ON) for each timepoint. The tabulated results of the difference in means statistical analysis at the timepoint level are found in Appendix B.2.

All 20 SB timepoints and all 15 NB timepoints were evaluated during the AM and PM peaks with four comparison pairs per timepoint, which totals 280 comparisons. The timepoint-level analysis shows a statistically significant difference in mean schedule deviation for only 12.5 percent of the comparison pairs (35 of 280). Unlike Route 217, there was consistency in which comparison pairs and directional peak scenarios had statistically significant results. Out of the 35 comparisons with statistically significant results, 24 came from the 2-minute vs 5-minute comparison pair, 10 came from the OFF vs ON comparison pair, and one came from the 2-

minute vs OFF comparison pair. When grouped by directional peak scenario, 16 of the 35 came from PM SB, 13 from AM SB, and 6 from PM NB.

Although a statistically significant difference in mean schedule deviation occurred at 12.5 percent of the comparison pairs, evaluating schedule deviation through the trendline shows that mean schedule deviation consistently decreased as the requesting threshold changed from OFF, to 5-minute, to 2-minute, to ON. In fact, for the 70 timepoints evaluated (20 SB timepoints and 15 NB timepoints for both the AM and PM peaks), the trendline is negative at 62 of them, or 89 percent. The trendline is negative at 19 of 20 AM SB timepoints, 14 of 15 for AM NB, 18 of 20 for PM SB, and 11 of 15 for PM NB.

Table 5-18: UVX Schedule Deviation Difference in Means Timepoint-Level Figures

Figure	AM SB	AM NB	PM SB	PM NB
All Means	Figure 5-66	Figure 5-68	Figure 5-70	Figure 5-72
ALL SE Ranges	Figure 5-67	Figure 5-69	Figure 5-71	Figure 5-73

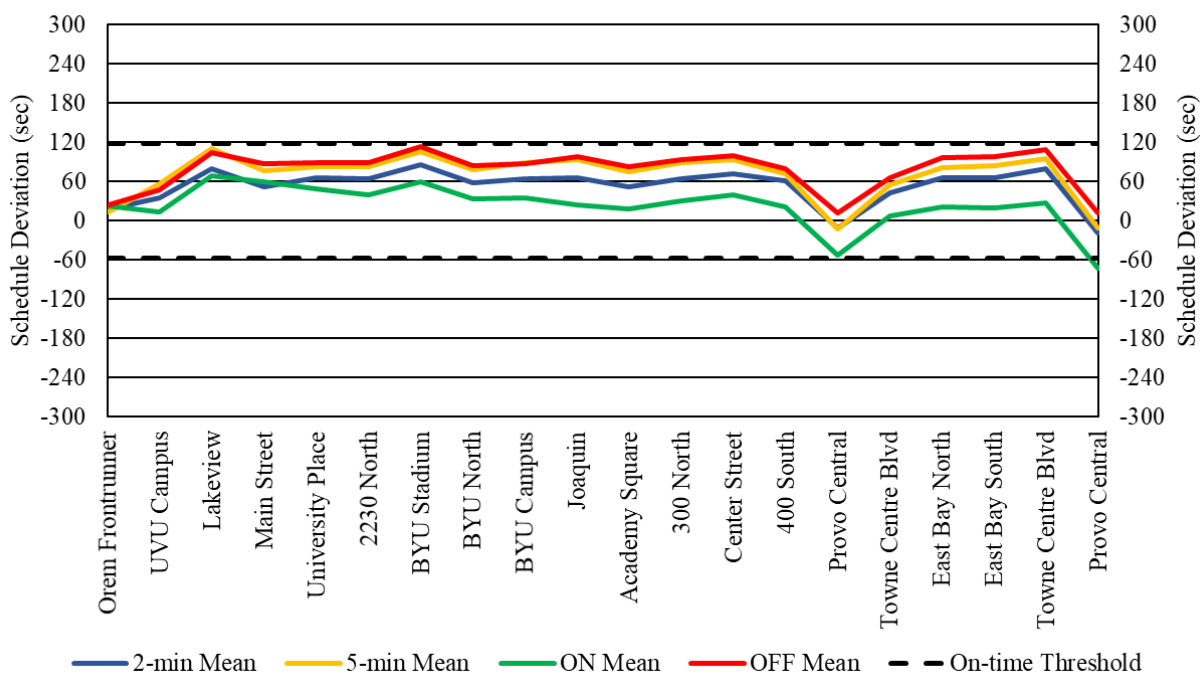


Figure 5-66: UVX AM SB mean schedule deviation.

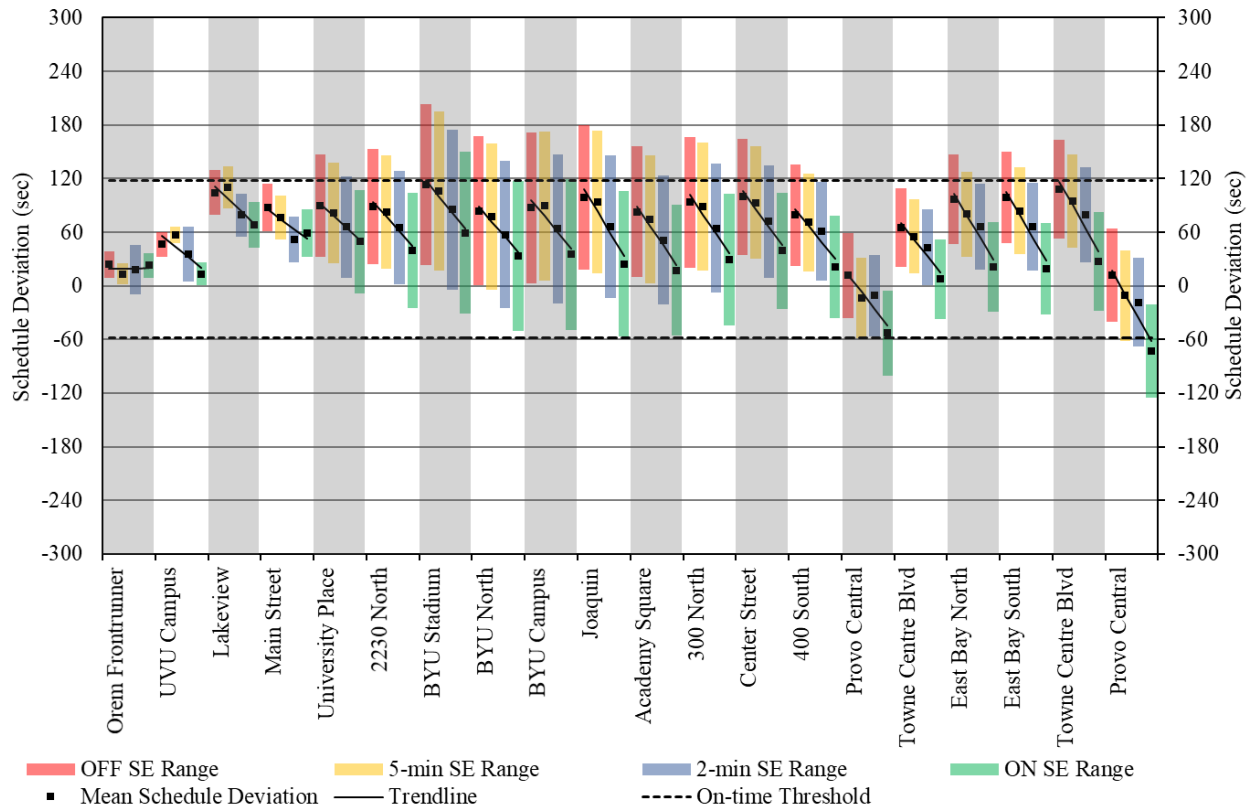


Figure 5-67: UVX AM SB mean schedule deviation with all thresholds.

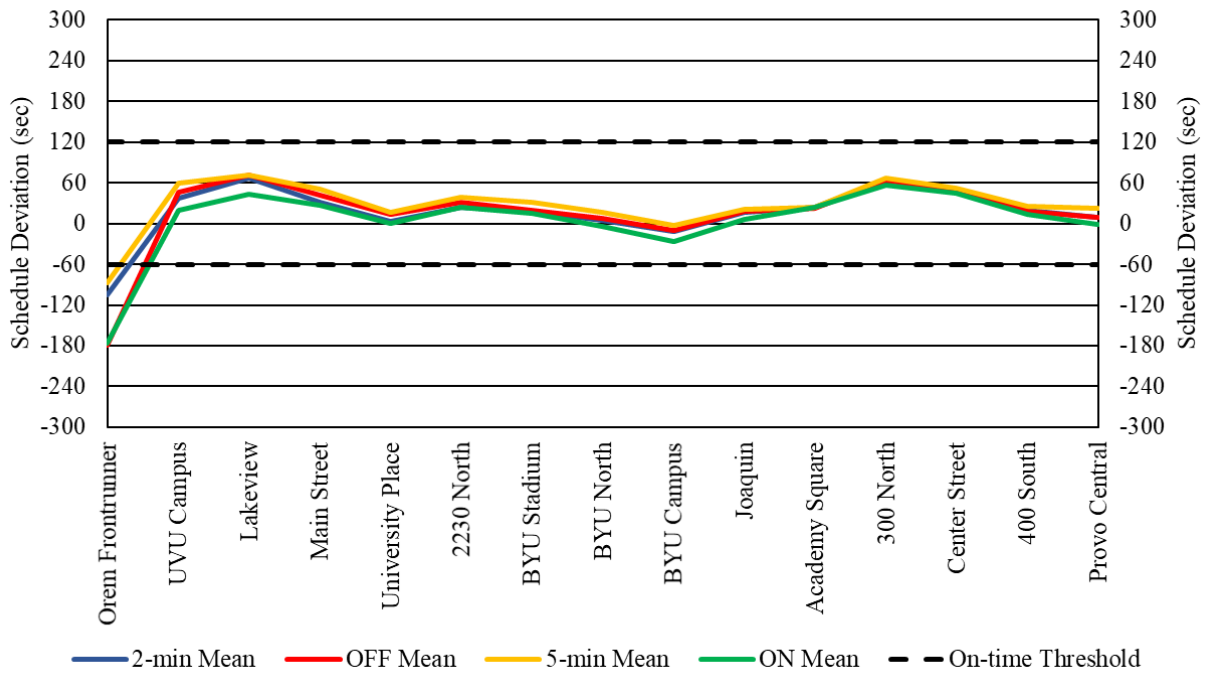


Figure 5-68: UVX AM NB mean schedule deviation.

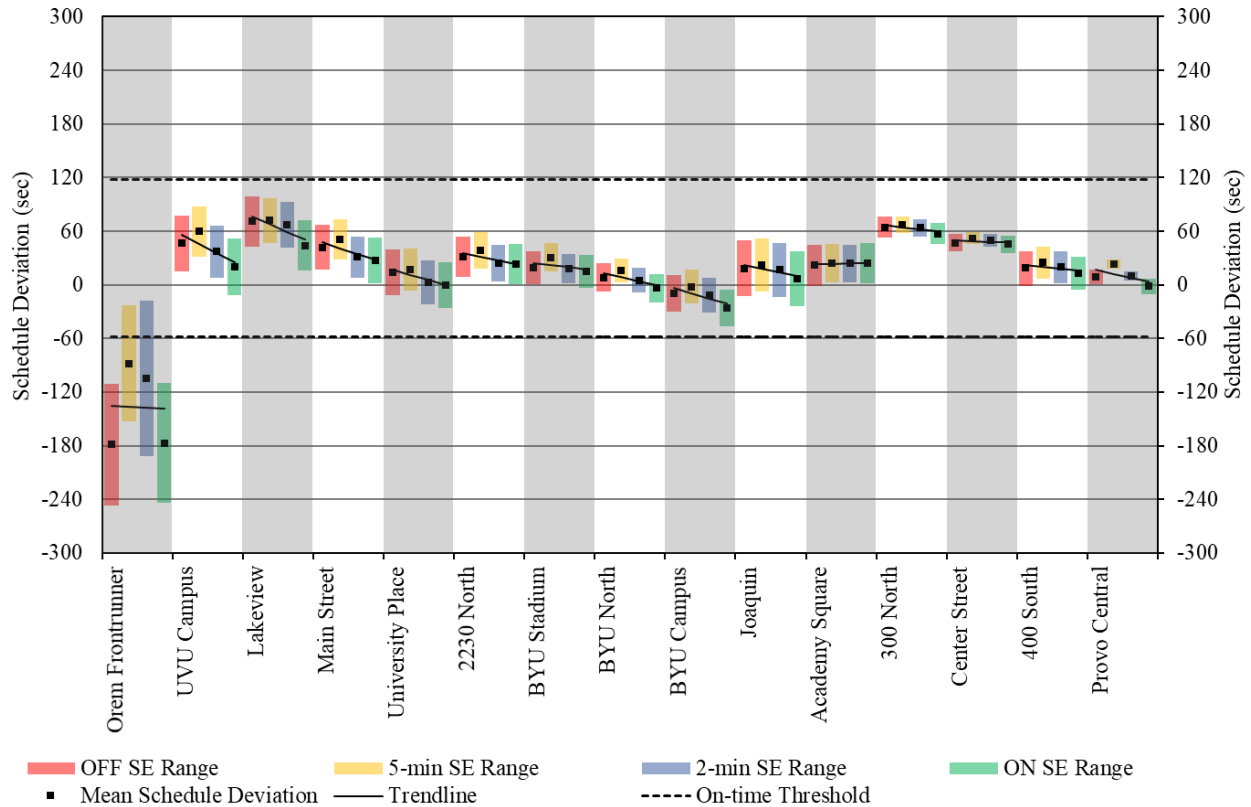


Figure 5-69: UVX AM NB mean schedule deviation with all thresholds.

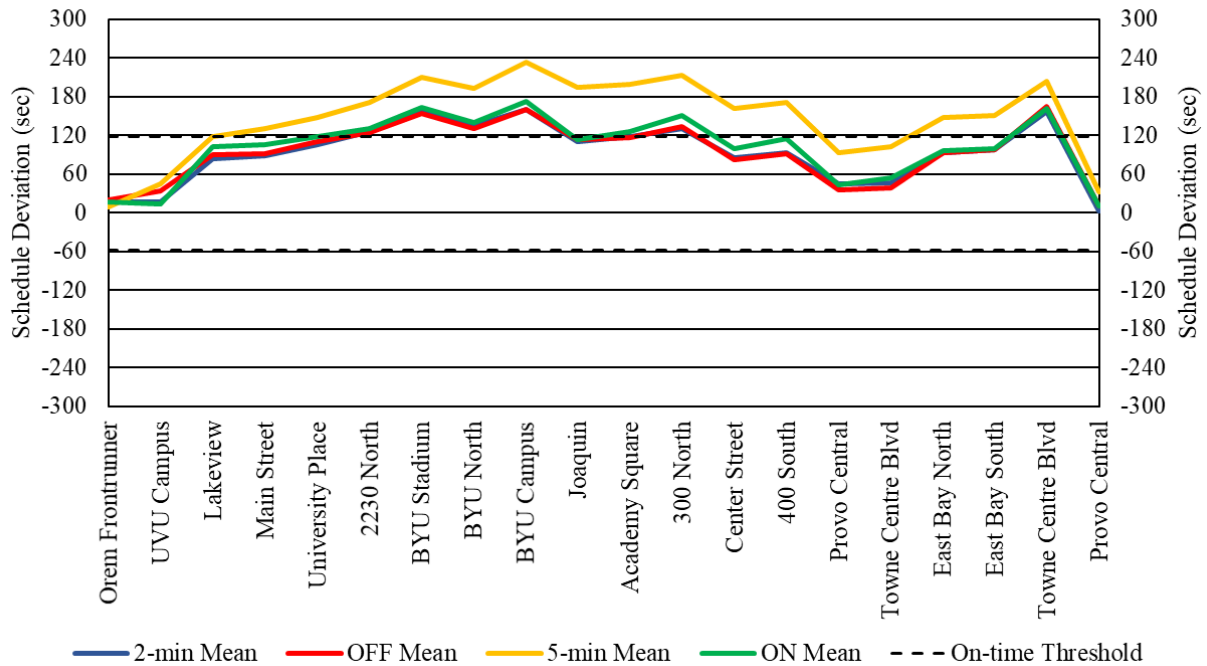


Figure 5-70: UVX PM SB mean schedule deviation.

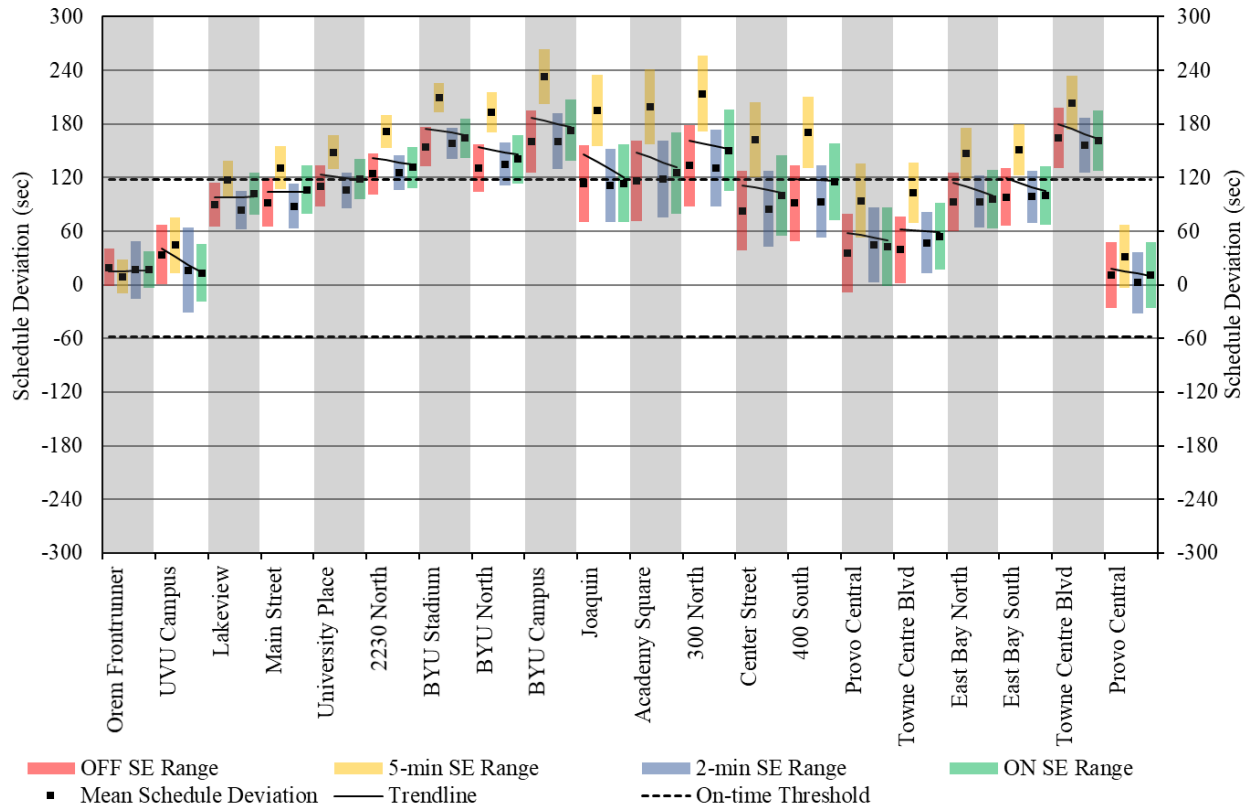


Figure 5-71: UVX PM SB mean schedule deviation with all thresholds.

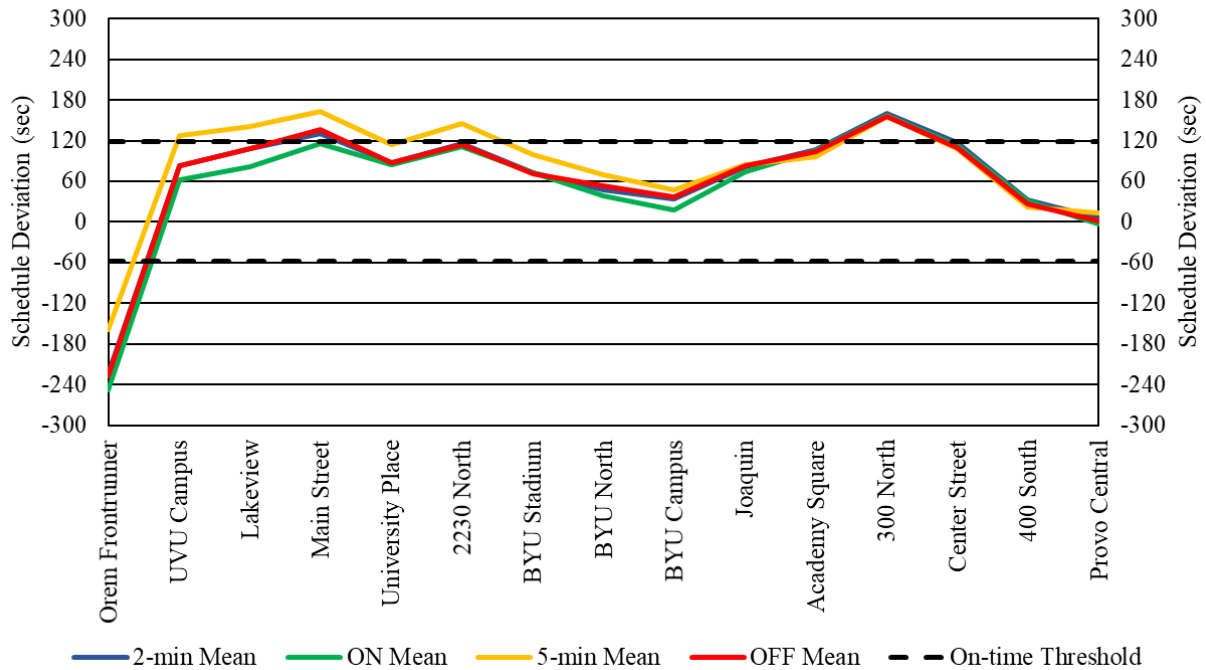


Figure 5-72: UVX PM NB mean schedule deviation.

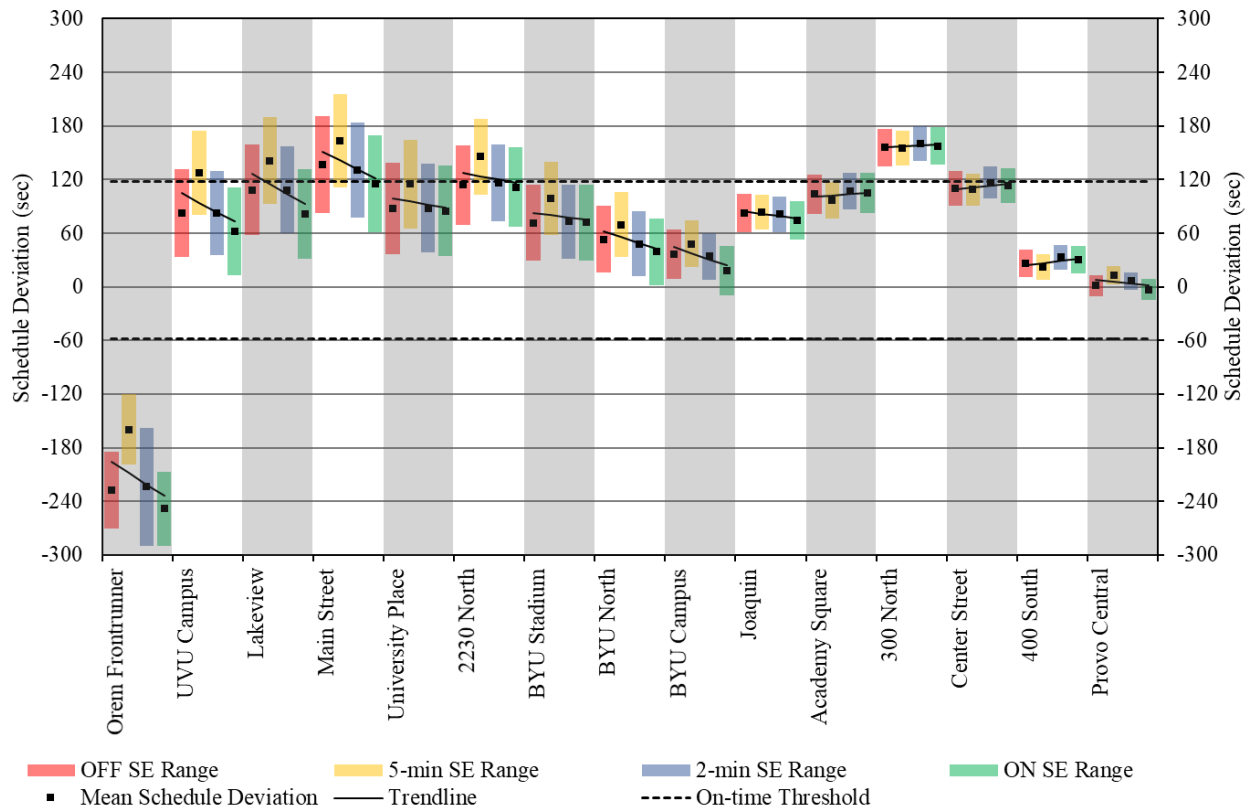


Figure 5-73: UVX PM NB mean schedule deviation with all thresholds.

5.4.2.2 UVX – Schedule Deviation: 95 percent prediction interval

The 95 percent prediction interval is the range of expected values based on the value of the 2.5th and 97.5th percentiles, thus representing the middle 95 percent of data. As the magnitude of the 95 percent prediction interval increases, variability in the data increases. The figures in this subsection show the 95 percent prediction intervals for each requesting threshold by directional peak scenario. Figure 5-74 contains the corridor-level results, while the timepoint-level results are shown for the AM SB in Figure 5-75; AM NB in Figure 5-76; PM SB in Figure 5-77; and PM NB in Figure 5-78.

Overall, and in order from OFF, 5 minute, 2 minute, and ON, the magnitude of the 95 percent prediction interval is 455, 524, 409, and 575 seconds. Thus, the 2-minute requesting threshold outperforms the other requesting thresholds with the ON threshold performing worst of all. Although the magnitude of the 95 percent prediction interval does not consistently decrease as the requesting threshold changes from OFF, to 5-minute, to 2-minute, to ON, the juxtaposition is that trendline for the median schedule deviation does. Out of the 70 timepoints evaluated (20 SB timepoints and 15 NB timepoints for both the AM and PM peaks), the trendline is negative at 67 of them, or 96 percent.

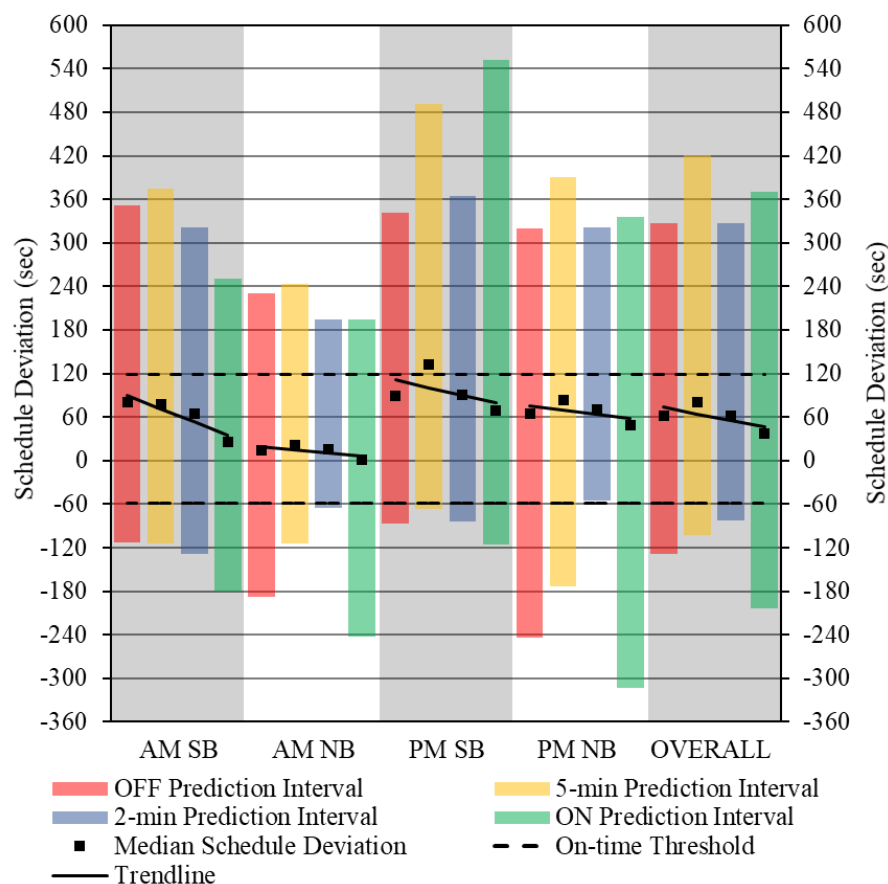


Figure 5-74: UVX 95 percent prediction interval for schedule deviation at the corridor-level and overall.

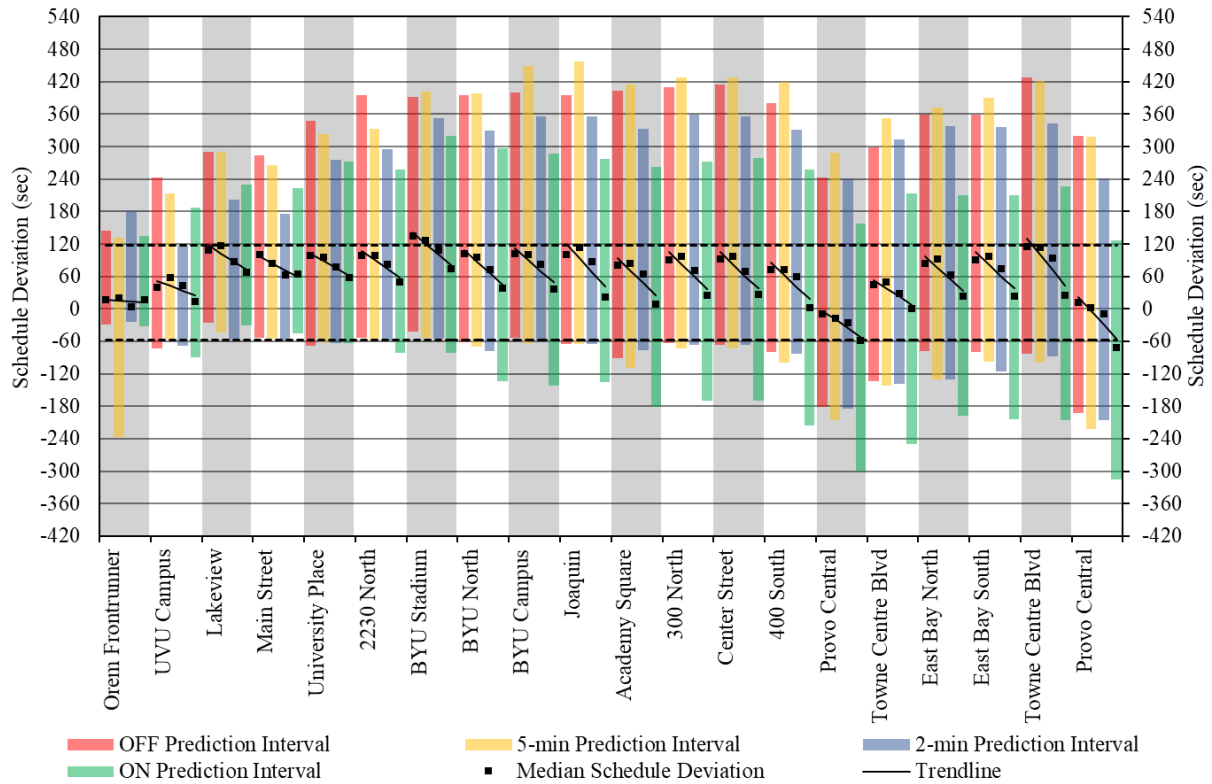


Figure 5-75: UVX AM SB schedule deviation prediction interval with all thresholds.

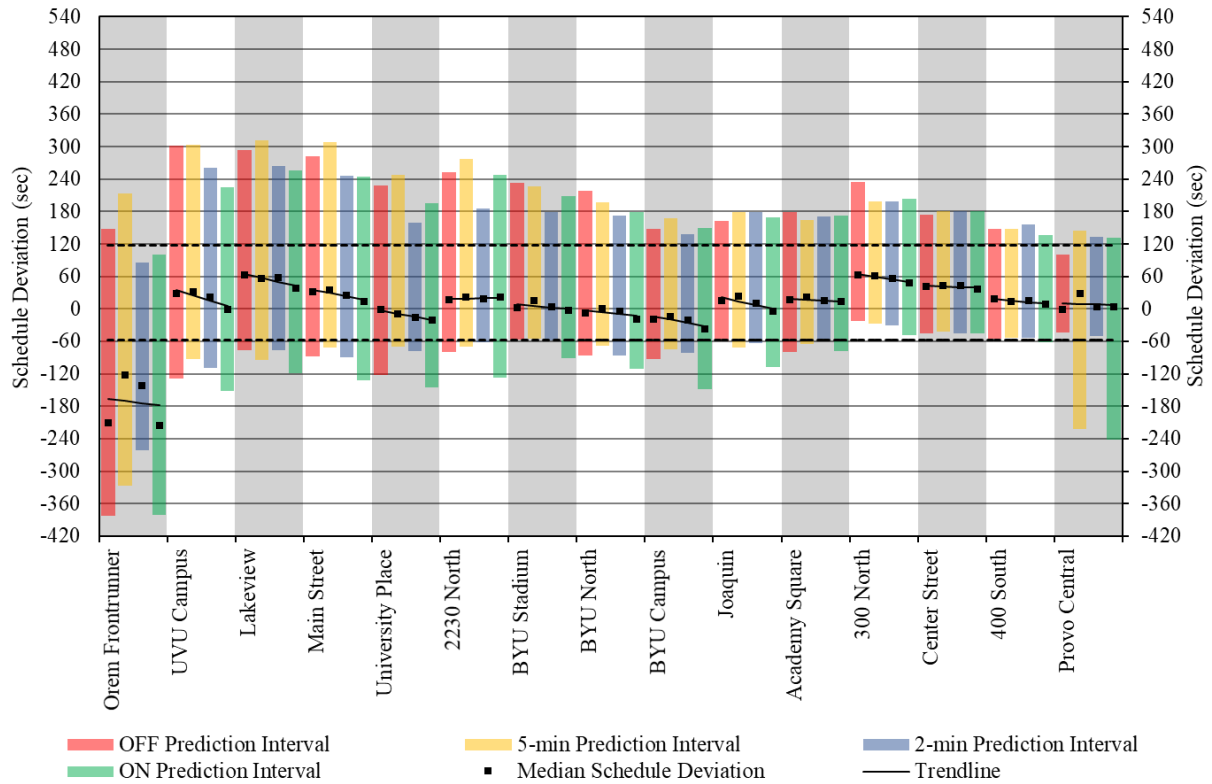


Figure 5-76: UVX AM NB schedule deviation prediction interval with all thresholds.

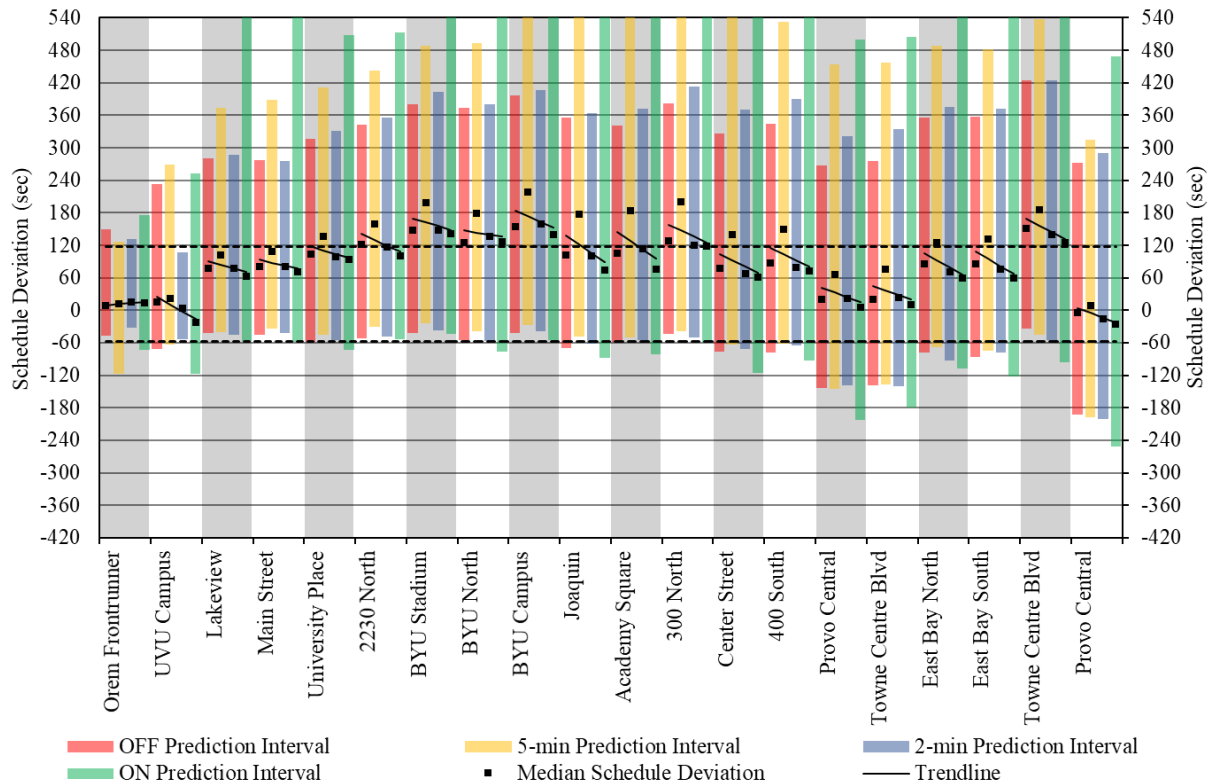


Figure 5-77: UVX PM SB schedule deviation prediction interval with all thresholds.

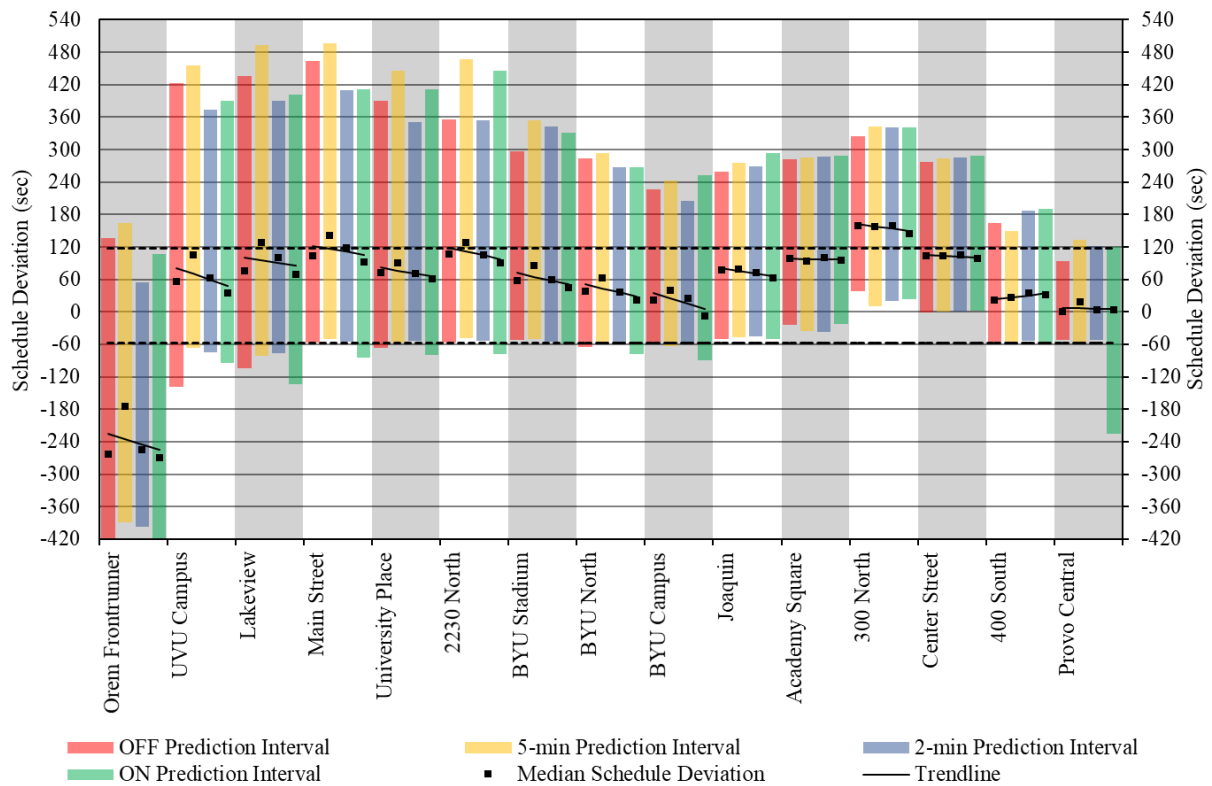


Figure 5-78: UVX PM NB schedule deviation prediction interval with all thresholds.

5.4.3 UVX – Travel Time

While OTP and schedule deviation are extremely dependent on the schedule, travel time is not and can be considered immune from a poorly created schedule. The travel-time values represent the elapsed time from departure of the previous timepoint to arrival at the current timepoint the bus had just left. In other words, for SB buses, travel time recorded at the UVU Campus timepoint represents the elapsed time since departing the Orem Frontrunner timepoint to arriving at the UVU Campus timepoint. Travel time was only analyzed at the timepoint-level through the 95 percent prediction interval, the results of which are summarized in this subsection and shown in Figure 5-79 (AM SB), Figure 5-80 (AM NB), Figure 5-81 (PM SB), and Figure 5-82 (PM NB).

The consistency and lack of variability for UVX data both generally and between requesting thresholds is remarkable. The small magnitudes of the 95 percent prediction interval show general lack of variability with many timepoints indicating that 95 percent of the data fall within a 60-second window. It is understandably difficult to perceive differences in the magnitude of the 95 percent prediction interval between requesting thresholds because the average is 102, 110, 106, and 105 seconds for the OFF, 5-minute, 2-minute, and ON requesting thresholds, respectively. Moreover, the median travel-time values are often so similar between requesting thresholds at a given timepoint that it is difficult to tell whether the slope of the trendline is positive or negative. Out of the 70 timepoints evaluated, the trendline (change in seconds per change in threshold) has a slope between -2 and 2 at 53 of the timepoints, or 76 percent. Nevertheless, 39 of the 70 timepoints, or 56 percent, do have a negative slope, which indicates that travel time decreases as the requesting threshold changes from OFF, to 5-minute, to 2-minute, to ON.

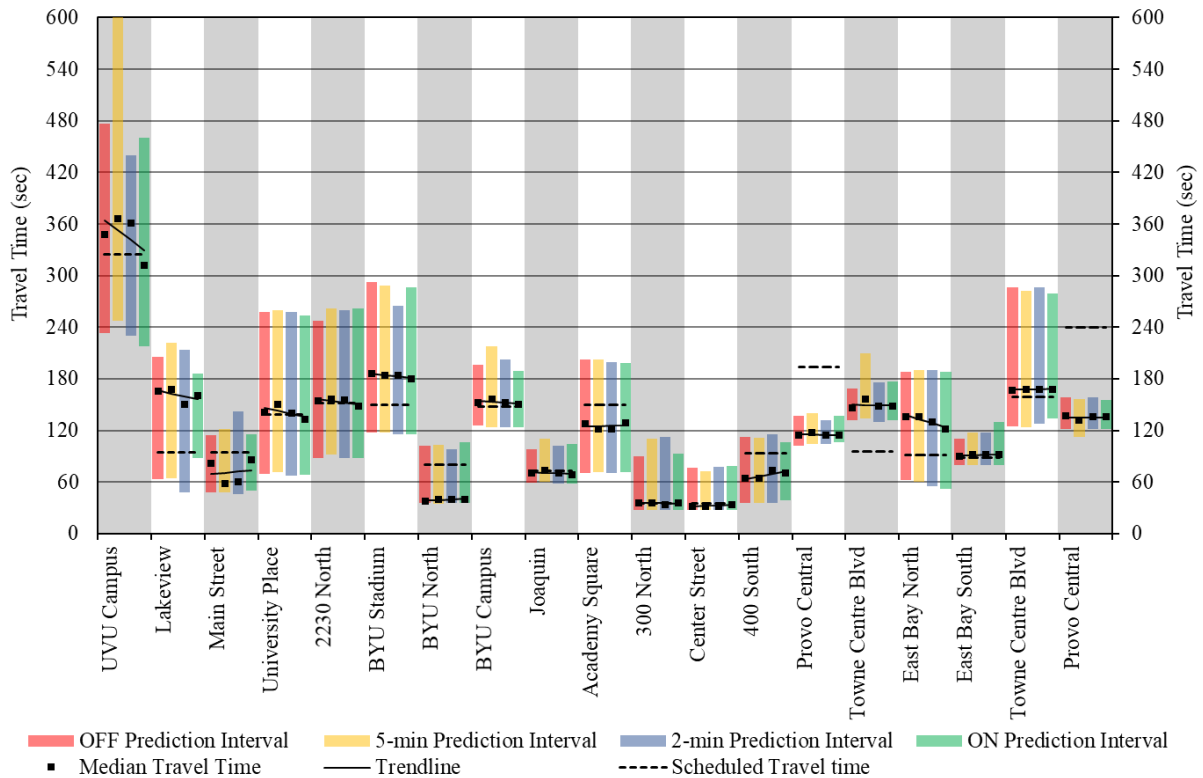


Figure 5-79: UVX AM SB travel time 95 percent prediction interval.

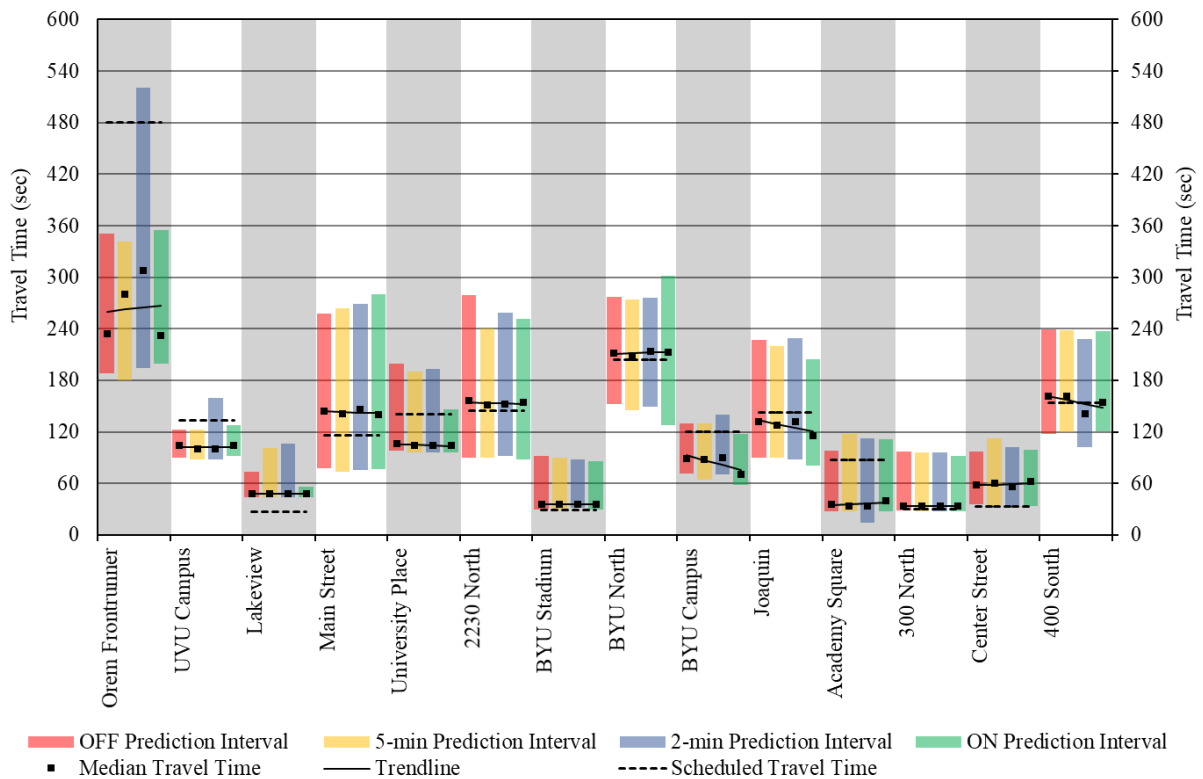


Figure 5-80: UVX AM NB travel time 95 percent prediction interval.

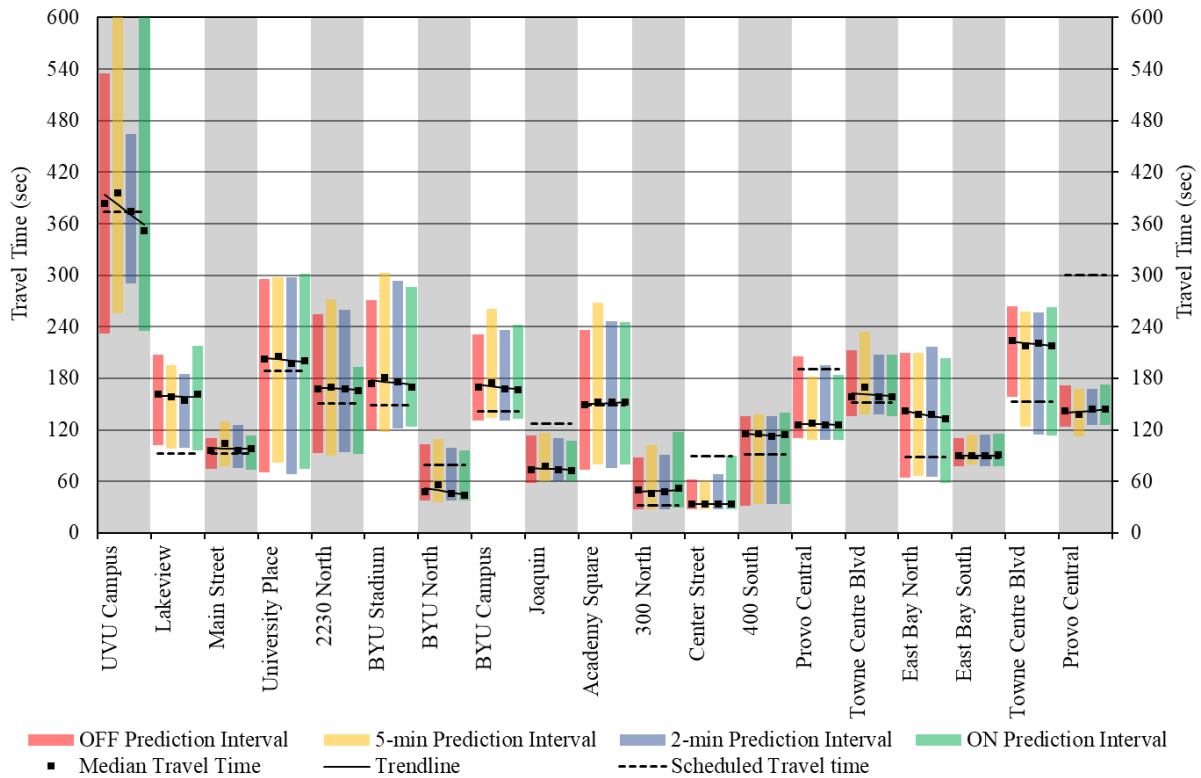


Figure 5-81: UVX PM SB travel time 95 percent prediction interval.

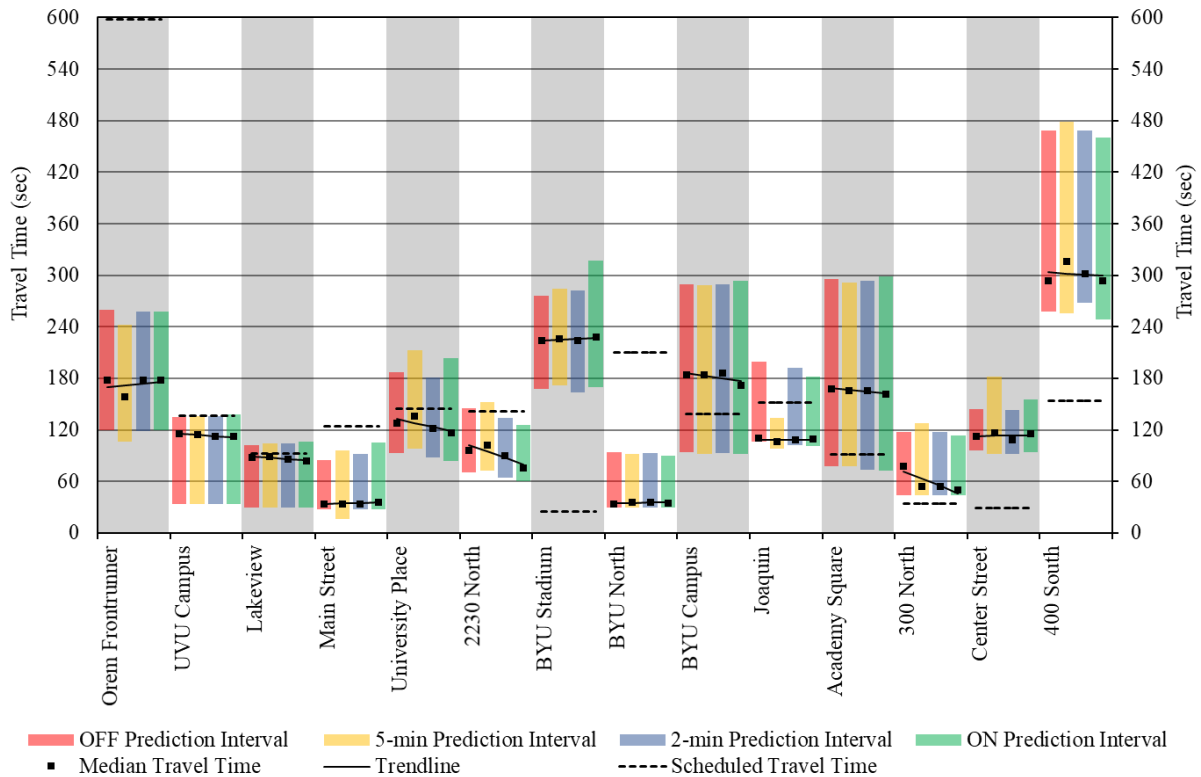


Figure 5-82: UVX PM NB travel time 95 percent prediction interval.

5.5 Chapter Summary

As the requesting threshold approaches zero, it was anticipated that OTP would increase and schedule deviation and travel time would decrease. With only a few exceptions, the data conclusively confirm these expectations.

For Route 217, the data are most appropriately compared between the 3-, 2-, and 0-minute requesting thresholds because the bus schedule was constant throughout the time during which these thresholds were operational. On average, as the requesting threshold changed from 3 minutes to 2 minutes OTP increased 2.0 percent, while a 2.5 percent increase was observed when the threshold changed from 2 minutes to 0 minutes. The largest OTP improvements were realized for the AM NB directional peak scenario, which experienced an average 4.6 percent improvement each time the requesting threshold changed. Likewise, the analysis of schedule deviation concluded that buses ran an average of 123.4 seconds behind schedule with the 3-minute requesting threshold, improved to 107.5 seconds behind schedule with the 2-minute threshold, and improved further to 86.6 seconds behind schedule with the 0-minute requesting threshold. The difference in means statistical analysis showed that these improvements were significant with p-values of 0.0005 and <0.0001, respectively. Statistically significant decreases in schedule deviation variability were achieved primarily during the AM peak but did not occur as uniformly as the other schedule adherence MOEs. Median travel time for Route 217 decreased as the requesting threshold approached zero at 26 of the 36 timepoints evaluated, or 72 percent of them, with nine timepoints evaluated for each of the four directional peak scenarios. The results of the travel-time variability analysis were inconsistent and no uniform trends could be determined. This was surprising provided that most TSP evaluations from the literature review reported large and meaningful reductions in travel time or travel-time variability.

For UVX, the data show that the ON requesting threshold resulted in the highest OTP and was followed in descending order by the 2-minute threshold, then OFF, and then the 5-minute threshold. The results of the mean schedule deviation align with the OTP findings by showing the ON threshold had the lowest schedule deviation (most on time) and was followed by the 2-minute threshold, OFF, and then 5-minute threshold in ascending order. The difference in means statistical analysis showed with convincing evidence that mean schedule deviation improves as

the requesting threshold changes from 5 minutes to 2 minutes ($p < 0.0001$) and from 2 minutes to ON ($p < 0.0001$). Although the ON requesting threshold resulted in the best bus performance for OTP and mean schedule deviation, it had the greatest magnitude for the 95 percent prediction interval for schedule deviation with the 2-minute threshold performing the best. Similar to Route 217, no consistent trends for travel time were recognized.

6.0 CONCLUSIONS

6.1 Overview

A DSRC-based TSP system was deployed in Utah along Route 217 in Salt Lake County in November 2017 and for UVX, a new BRT line in Utah County, in August 2018. The purpose of this research was to conduct a sensitivity analysis of the TSP requesting threshold on bus performance and impacts to general traffic for Route 217. A systematic evaluation of this element of the TSP system allows the identification of the requesting threshold at which TSP will be most efficient. Using these results, a similar experiment and analysis was conducted for UVX. The primary objective of this research regarded Route 217, so no traffic analysis was performed for UVX and this report does not evaluate UVX to the depth at which Route 217 is analyzed.

On Route 217, 5-, 3-, 2-, and 0-minute thresholds were evaluated. For UVX, 5- and 2-minute thresholds were evaluated, in addition to ON and OFF scenarios; ON meant the buses were always requesting TSP regardless of how late they were, while OFF meant that no requests were made and operations would be as if there were no TSP at all.

Only 10 equipped buses run on Route 217, so four PDUs were developed to accelerate data collection as each threshold was tested. A major part of this research was deploying the PDUs each day, which significantly increased the amount of data that was collected. Every UVX bus was equipped, so PDU deployment was not necessary to evaluate this route.

This chapter contains sections summarizing the results and recommendations and future research for Route 217 and UVX.

6.2 Route 217 – Summary of Results

The data show that as the requesting threshold approaches zero, OTP, schedule deviation, and travel time improve, while general traffic is only negligibly impacted. For Route 217 OTP, as the requesting threshold changed from 3 minutes to 2 minutes and from 2 minutes to 0 minutes, OTP improved 2.0 percent and 2.5 percent, respectively. For schedule deviation, as the

requesting threshold changed from 3 minutes to 2 minutes and from 2 minutes to 0 minutes, mean schedule deviation improved 15.9 seconds ($p = 0.0005$) and 20.9 seconds ($p < 0.0001$), respectively. Furthermore, statistically significant reductions in schedule deviation variability occurred, but it was mostly during the AM peak that this was detected. The improvements to Route 217 travel time were observational and showed that median travel time between timepoints decreased an average of 2.1 seconds each time the requesting threshold changed from 5, to 3, to 2, to 0 minutes.

The traffic analysis shows that negative impacts to general traffic rarely follow the serving of TSP. Even though serving TSP at the 0-minute threshold impacted general traffic three to four times as often as the 2-minute threshold, negative impacts were infrequent and were observed a maximum of once every 43 minutes.

6.3 Route 217 – Recommendations and Future Research

The limited recommendation for the Route 217 TSP system, as implemented, is to utilize the 0-minute requesting threshold. It is believed that the benefits achieved by changing from the 2-minute to the 0-minute requesting threshold outweigh the negative side-effects. However, if more aggressive TSP and controller logic settings are implemented, it is recommended that the 2-minute requesting threshold be considered, rather than the 0-minute threshold. Further investigation is needed to evaluate the impact of changing TSP or controller logic settings, such as lengthening the maximum allowable EG and GE at certain intersections, installing RSUs and enabling TSP at the unequipped intersections, and adjusting the size of the geofences.

Originally, this system was conservatively established due to concerns that the minor adjustments from TSP could cause major disruptions to general traffic. This does not appear to be the case, however, and although negative impacts are observed they do not last long nor are they frequent. Some of the busiest intersections do not have TSP capabilities, which coincide with the areas of the route where bus performance suffers the most. Thus, it is recommended that RSUs be installed and TSP implemented at all signalized intersections along Route 217. Buses receive the greatest benefit from GE priority treatments, yet there are many intersections where buses are able to receive more green time from the less effective EG treatment. Additional

research should be done to evaluate the size of the geofence of an intersection to maximize the extra amount of green time provided through GE treatments.

Further expansion of the traffic analysis can also be performed, in accordance with the current ATSPM data limitations, to incorporate additional metrics, such as vehicular delay, person delay, or percent arrivals on green. Collaboration with signal controller manufacturers may provide insight into the existing data limitations and how they can be overcome to enhance the understanding of the impact of providing TSP on signal and traffic operations. The solution provided by Econolite that addresses the TSP check-out issue addressed in Section 3.2 should be implemented and proven to appropriately handle this event.

6.4 UVX – Summary of Results

The data show that as the requesting threshold approaches zero, OTP and schedule deviation improved, while travel time achieved negligible improvements. For OTP, as the requesting threshold changed from 5 minutes to 2 minutes and from 2 minutes to ON, improvements of 7.6 percent and 4.7 percent, respectively, were realized. For schedule deviation, as the requesting threshold changed from 5 minutes to 2 minutes and from 2 minutes to ON, mean schedule deviation improved 24.3 seconds ($p < 0.0001$) and 15.0 seconds ($p < 0.0001$), respectively. However, it was the 2-minute requesting threshold that had the lowest average magnitude of the 95 percent prediction interval, a strong indication that this threshold led to the greatest reduction in variability.

6.5 UVX – Recommendations and Future Research

Although the data show that the greatest improvements are realized through the ON requesting threshold, the data also suggest that the 2-minute requesting threshold achieved the greatest reduction in schedule deviation variability. When the ON and 2-minute thresholds are compared, it is believed that the 15-second improvement in mean schedule is insufficient to overcome the 166-second increase in the magnitude of the 95 percent prediction interval for schedule deviation that is observed for the ON threshold. As such, it is recommended that UVX

utilize the 2-minute requesting threshold, which will also prevent early buses from receiving TSP and saving it for buses that are late and actually need it.

One of the most important areas of future research discovered by this research is the need for a headway-based method of requesting TSP to reflect the headway-based schedule on which UVX operates. There is a deficiency of understanding in the industry for this topic and headway adherence more appropriately reflects the “schedule” that is provided to the public.

Another topic of future research that relates to Route 217 but applies primarily to UVX, is a method to request TSP at an intersection prior to entering its geofence. The proximity of signalized intersections along UVX, coupled with the dedicated lanes, severely limit the amount of green time that can be allocated to the bus, even if the TSP logic permits more.

UVX should also be analyzed to evaluate the impact of the frequent schedule changes that have occurred. Signals along the UVX route require that two clean cycles occur before TSP can again be served. This makes the interaction between the requesting threshold and the ability of a bus to keep its schedule of paramount importance.

6.6 Concluding Remarks

The TSP deployments analyzed in this research uniquely operate through a live and fully functional DSRC system that is part of normal day-to-day operations for UTA Route 217 and UVX. It is clear that variations in the results exist between the directional peak scenarios (AM SB, AM NB, PM SB, and PM NB) and between timepoints, which are likely caused by external variables outside the control of this research, such as weather, construction, general traffic and transit ridership patterns and volumes, or bus operator behavior. Nevertheless, there is unmistakable evidence from the analyses performed that despite these variations, as the requesting threshold approaches zero, OTP, schedule deviation, and travel time improve, while general traffic is only negligibly impacted. These conclusions are drawn exclusively through data generated by live and deployed TSP operations with results produced completely outside of a simulated environment. It is imperative that TSP optimization follow deployment in order to maximize investment and attain a more efficient transportation network. While continuous

improvement should always be practiced, the results of the traffic analysis encourage a more aggressive TSP deployment aimed at further improving bus performance.

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APPENDIX A. ROUTE 217

Unless otherwise specified, all p-values contained in the appendix are the result of a two-sided t-test.

A.1 Route 217 Travel-Time Distributions

A.1.1 Route 217 SB Travel-Time Distributions

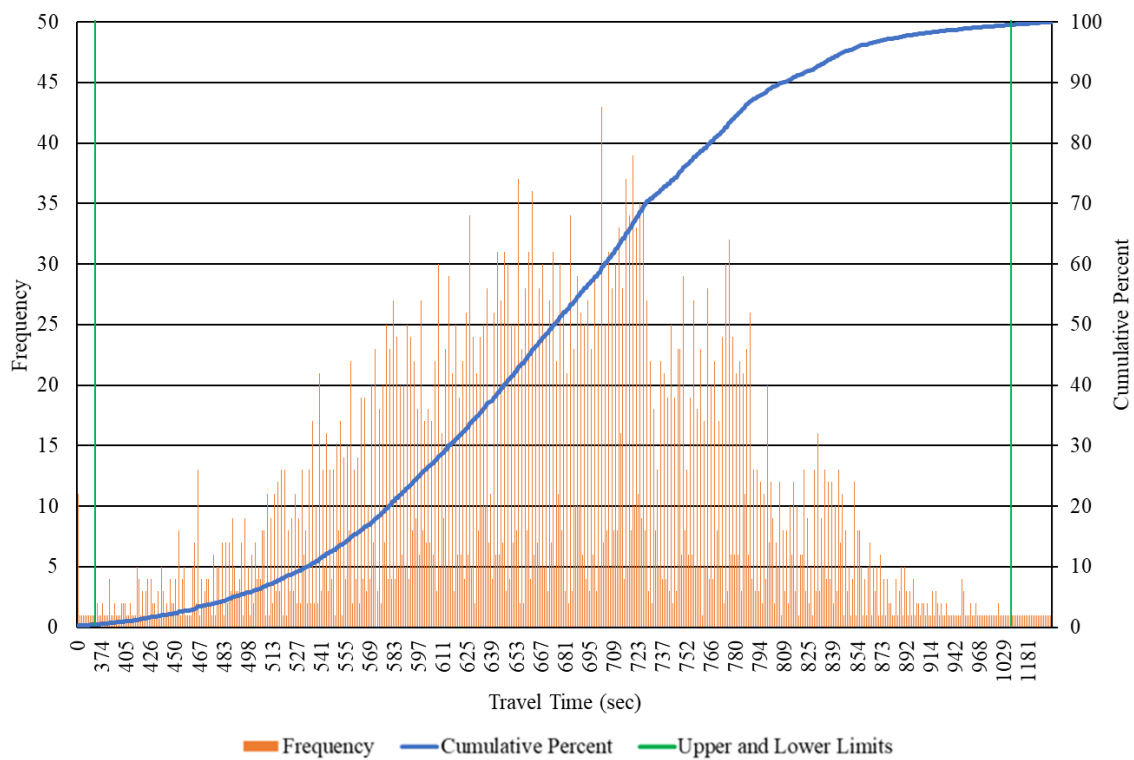


Figure A-1: Route 217 SB 1700 South travel-time distribution.

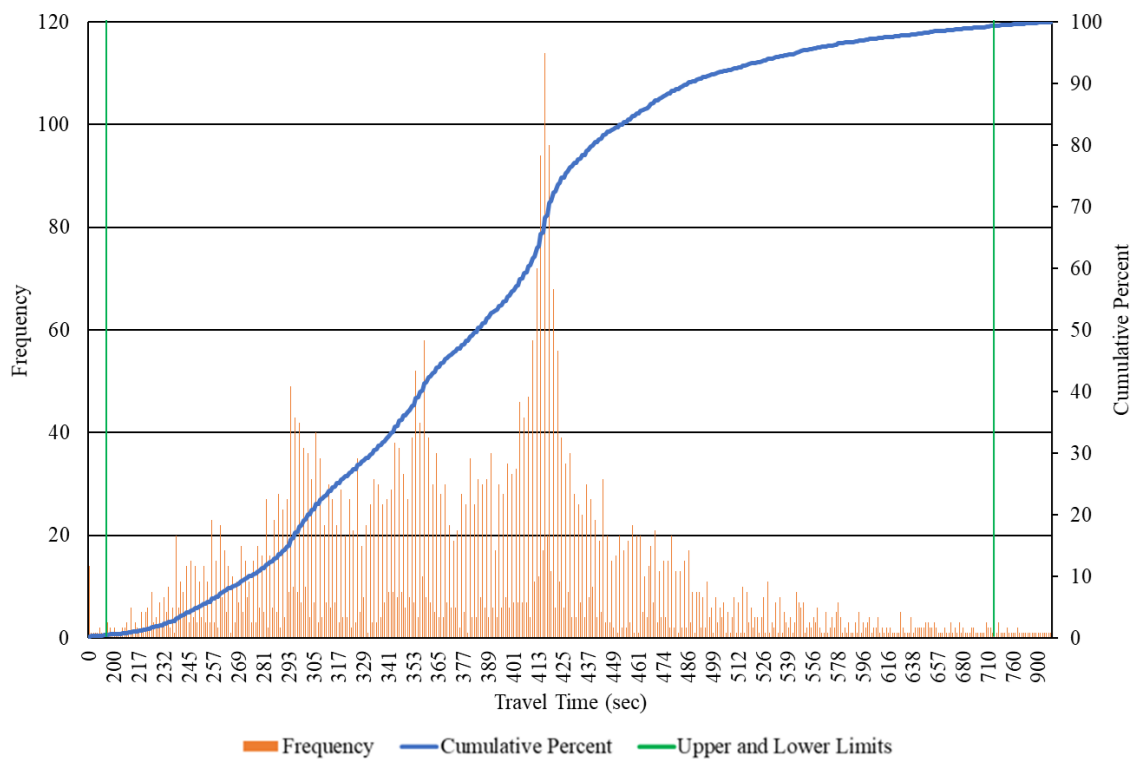


Figure A-2: Route 217 SB Redwood Junction travel-time distribution.

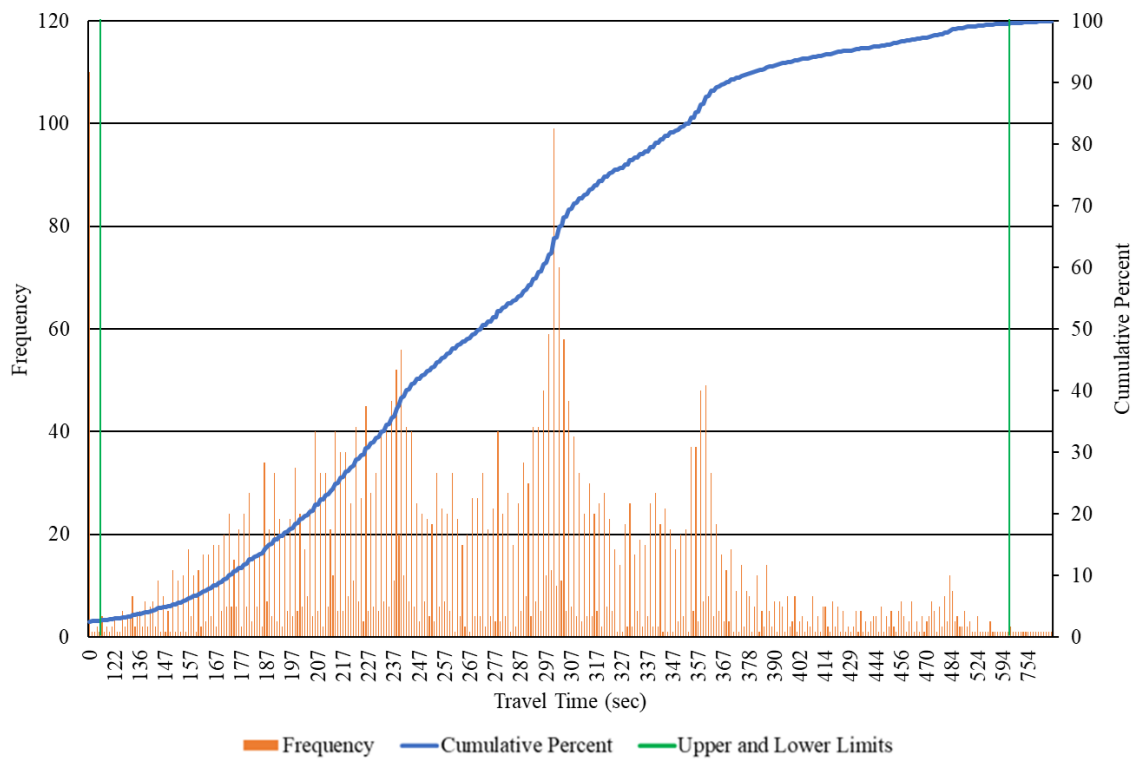


Figure A-3: Route 217 SB 3500 South travel-time distribution.

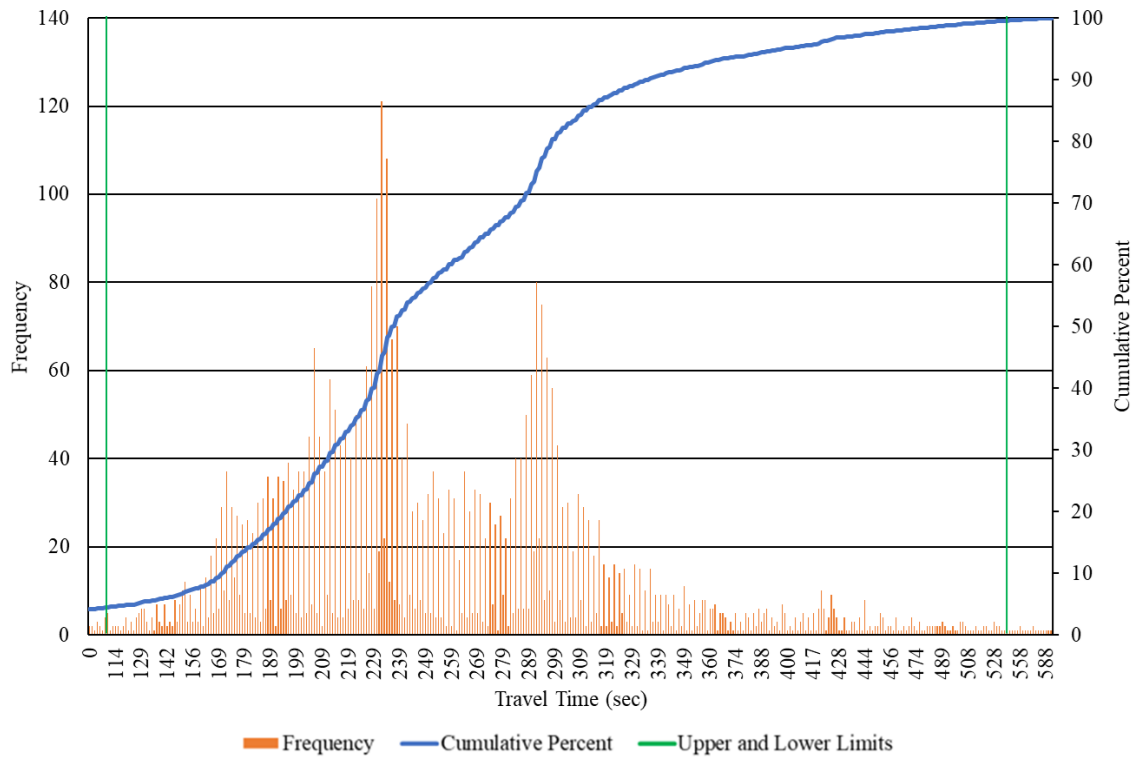


Figure A-4: Route 217 SB 4100 South travel-time distribution.

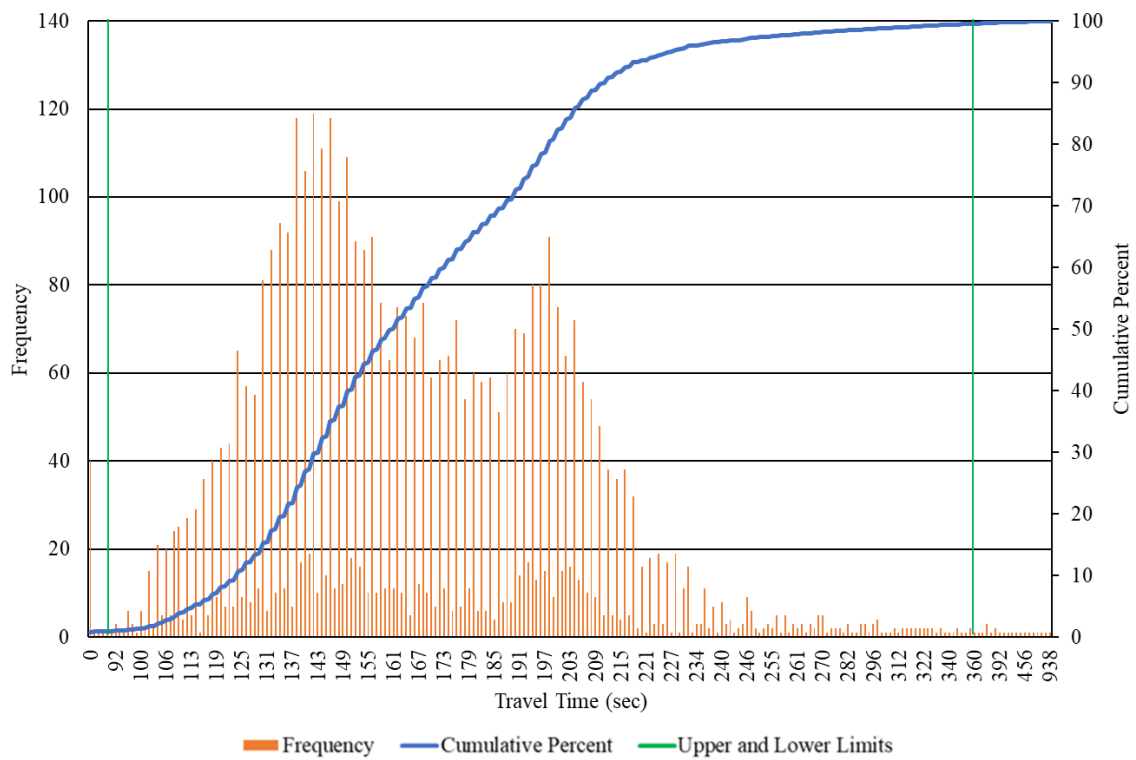


Figure A-5: Route 217 SB SLCC travel-time distribution.

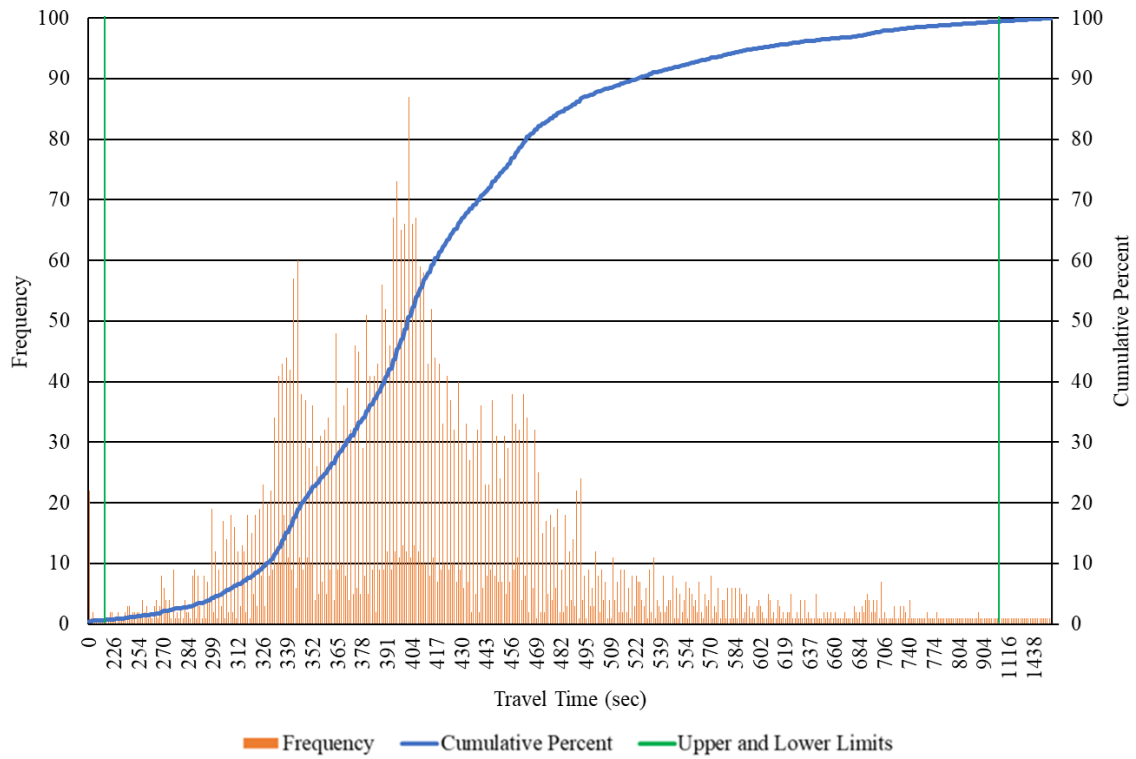


Figure A-6: Route 217 SB 5400 South travel-time distribution.

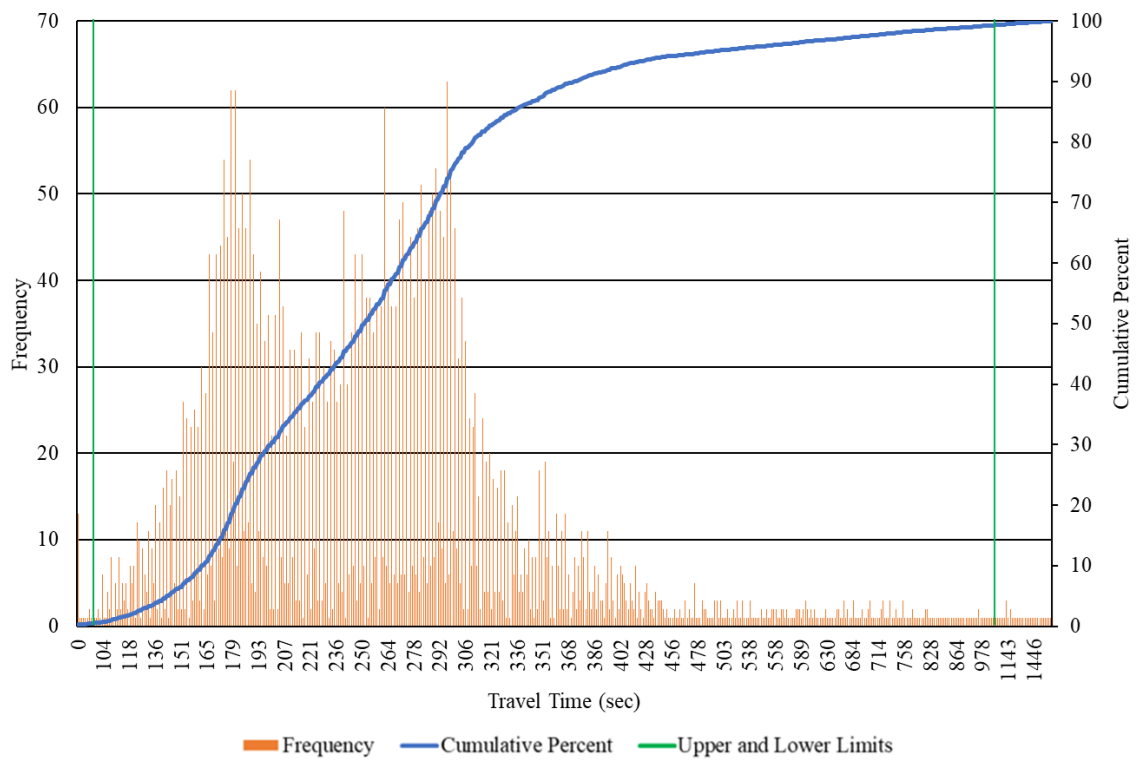


Figure A-7: Route 217 SB 6200 South travel-time distribution.

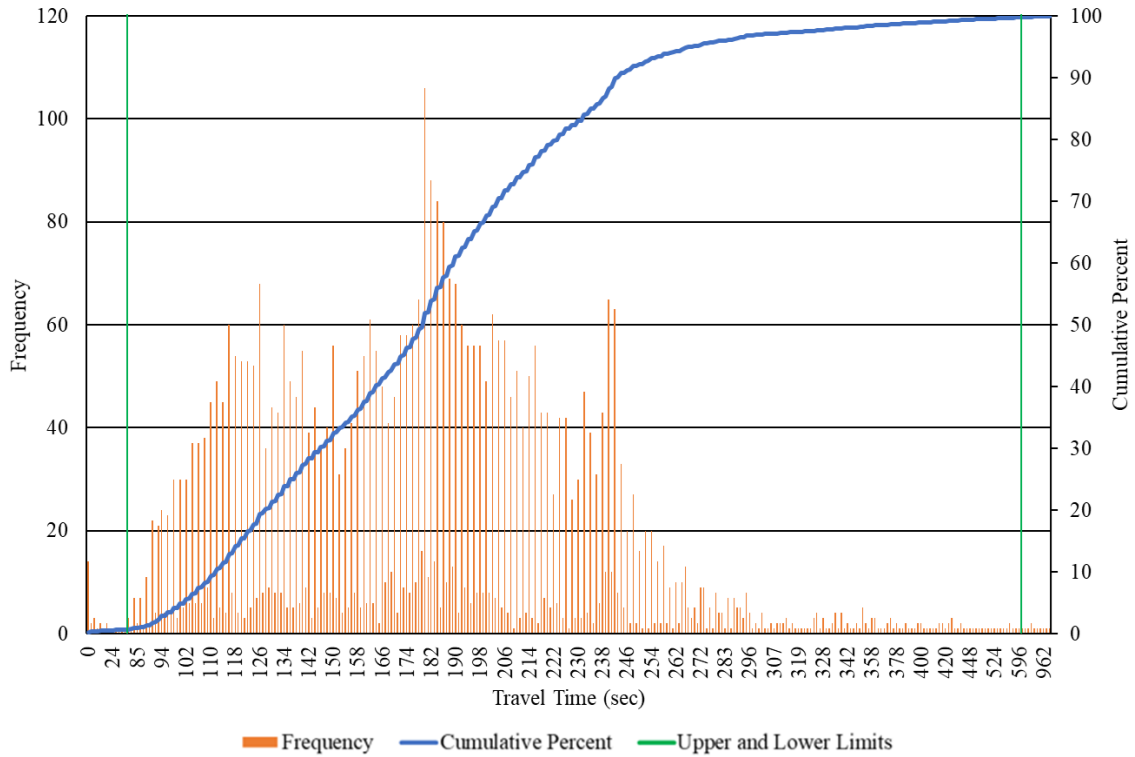


Figure A-8: Route 217 SB 7000 South travel-time distribution.

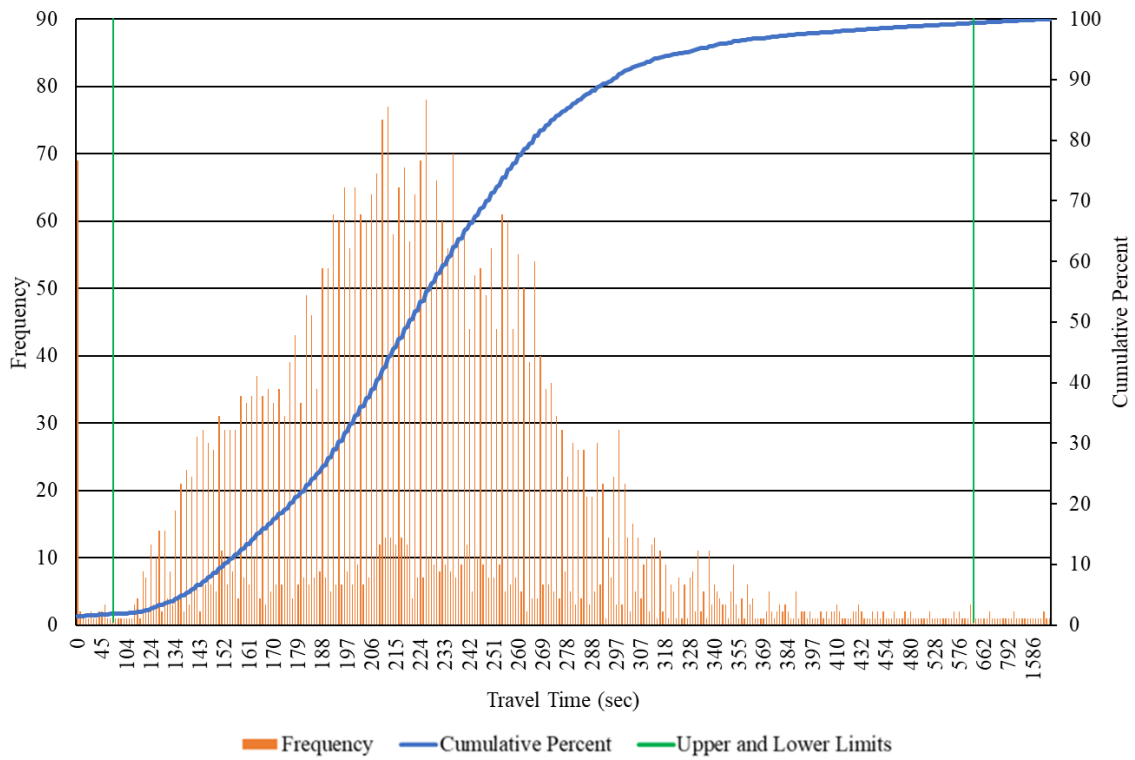


Figure A-9: Route 217 SB West Jordan City Center travel-time distribution.

A.1.2 Route 217 NB Travel-Time Distributions

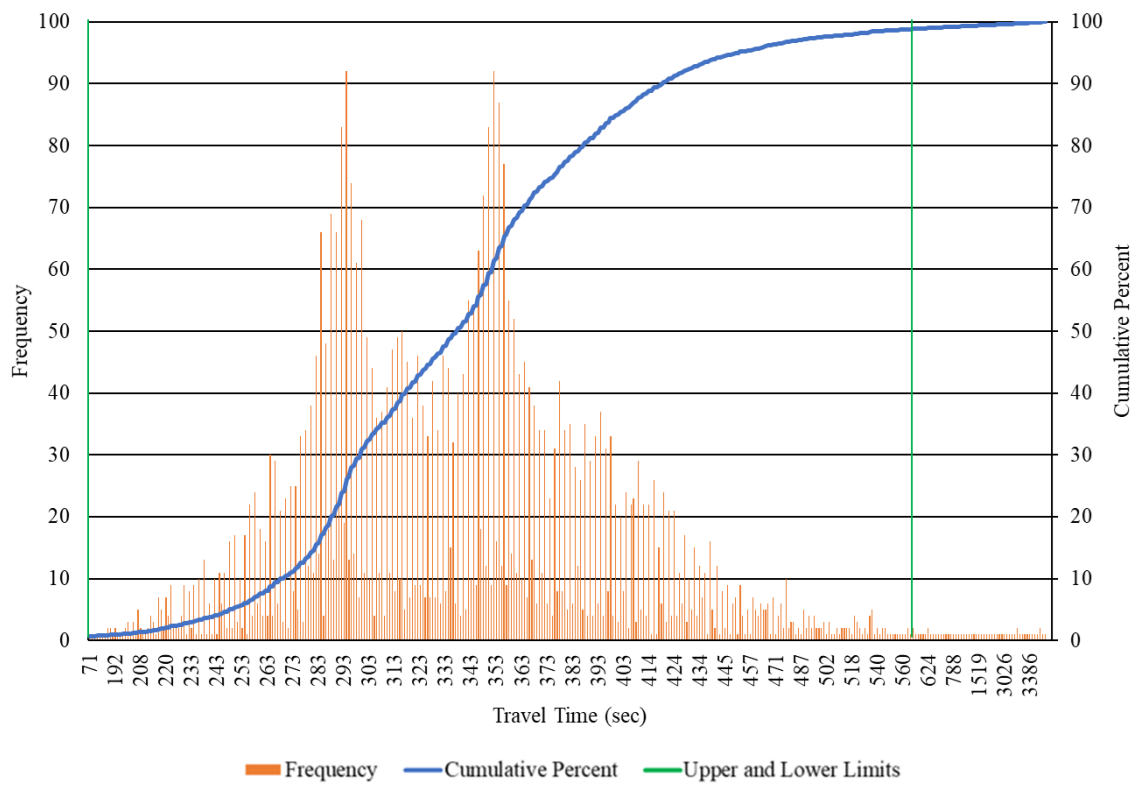


Figure A-10: Route 217 NB 7000 South travel-time distribution.

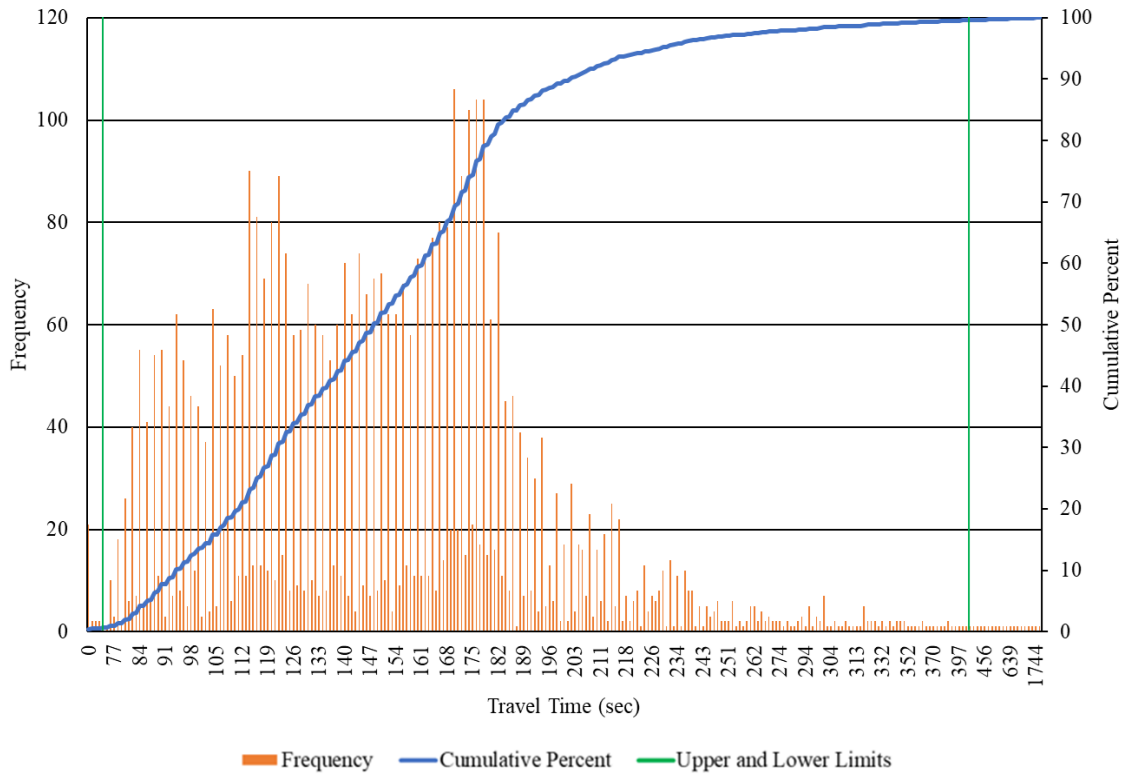


Figure A-11: Route 217 NB 6200 South travel-time distribution.

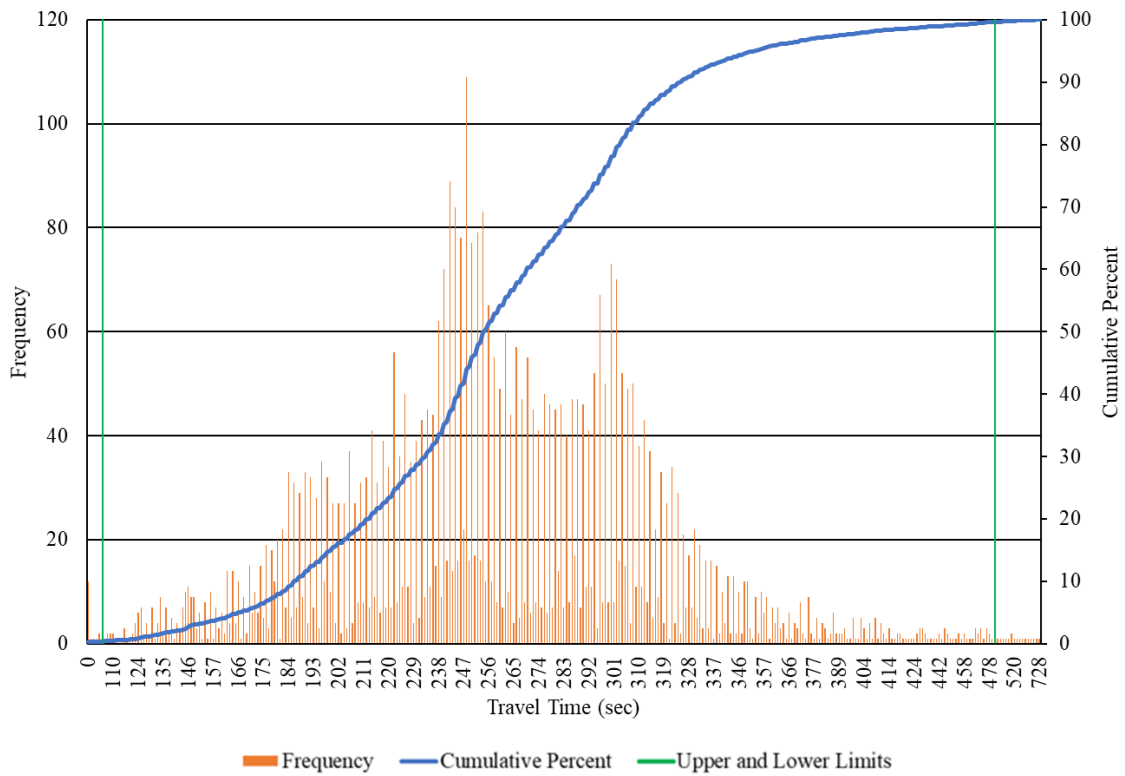


Figure A-12: Route 217 NB 5400 South travel-time distribution.

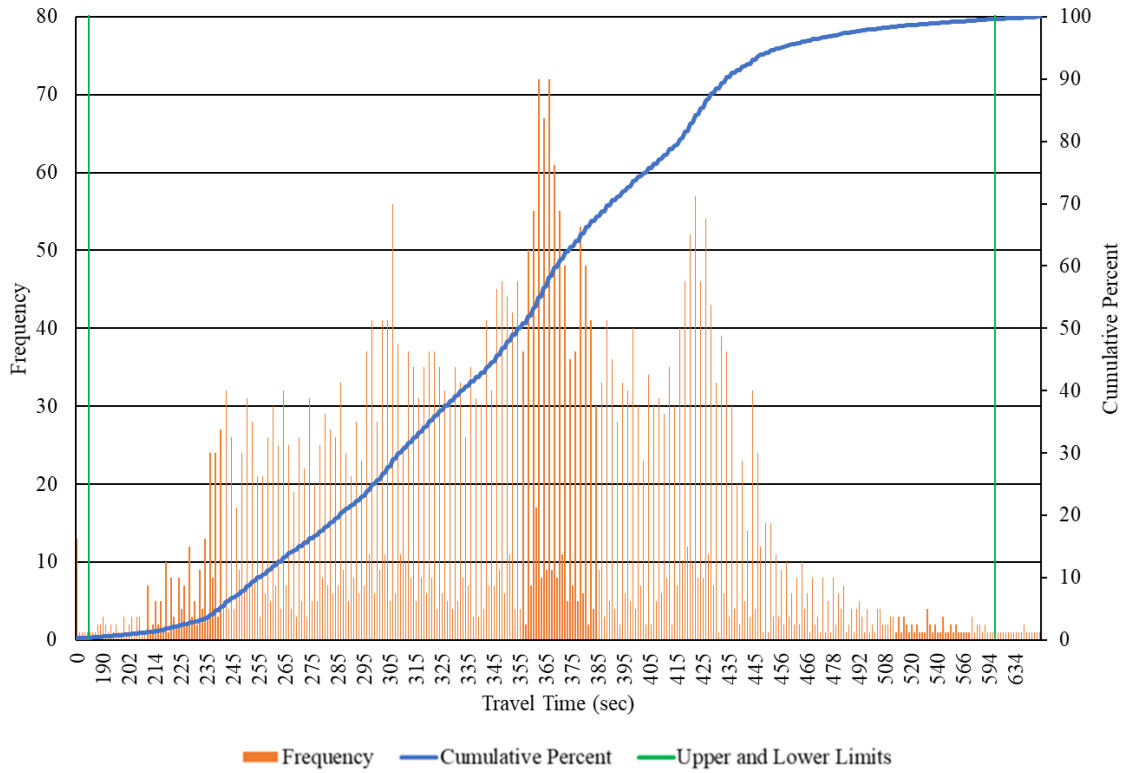


Figure A-13: Route 217 NB SLCC travel-time distribution.

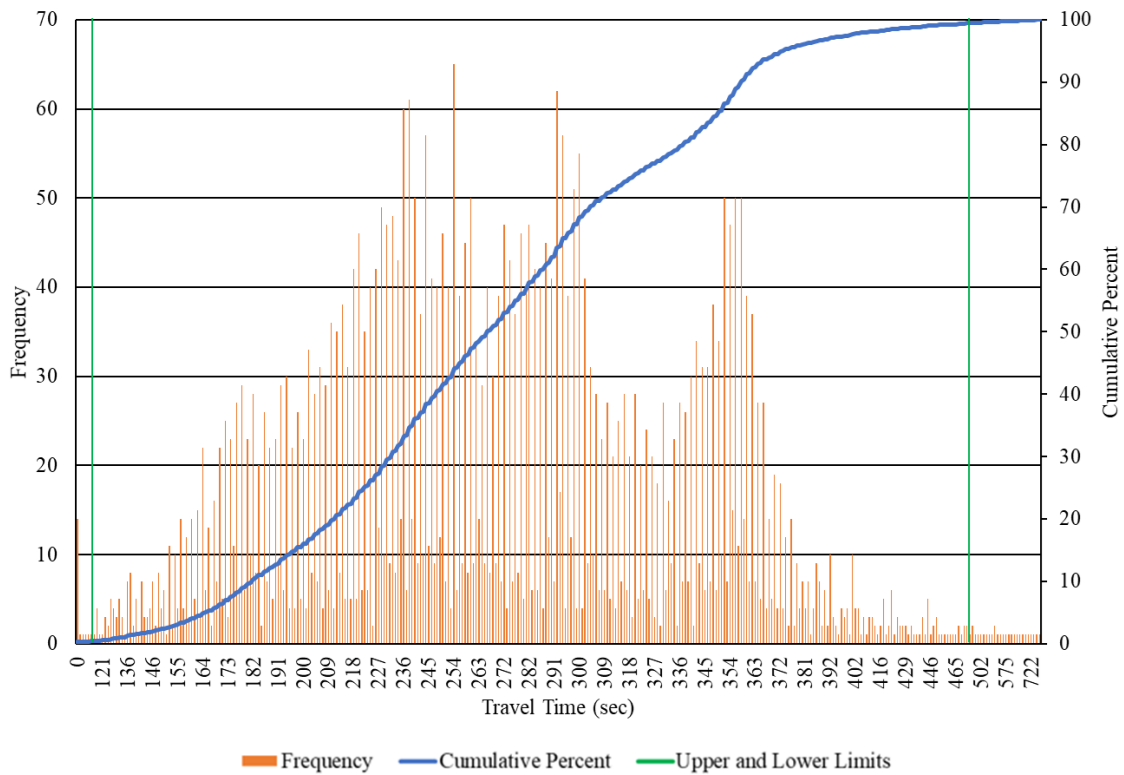


Figure A-14: Route 217 NB 4100 South travel-time distribution.

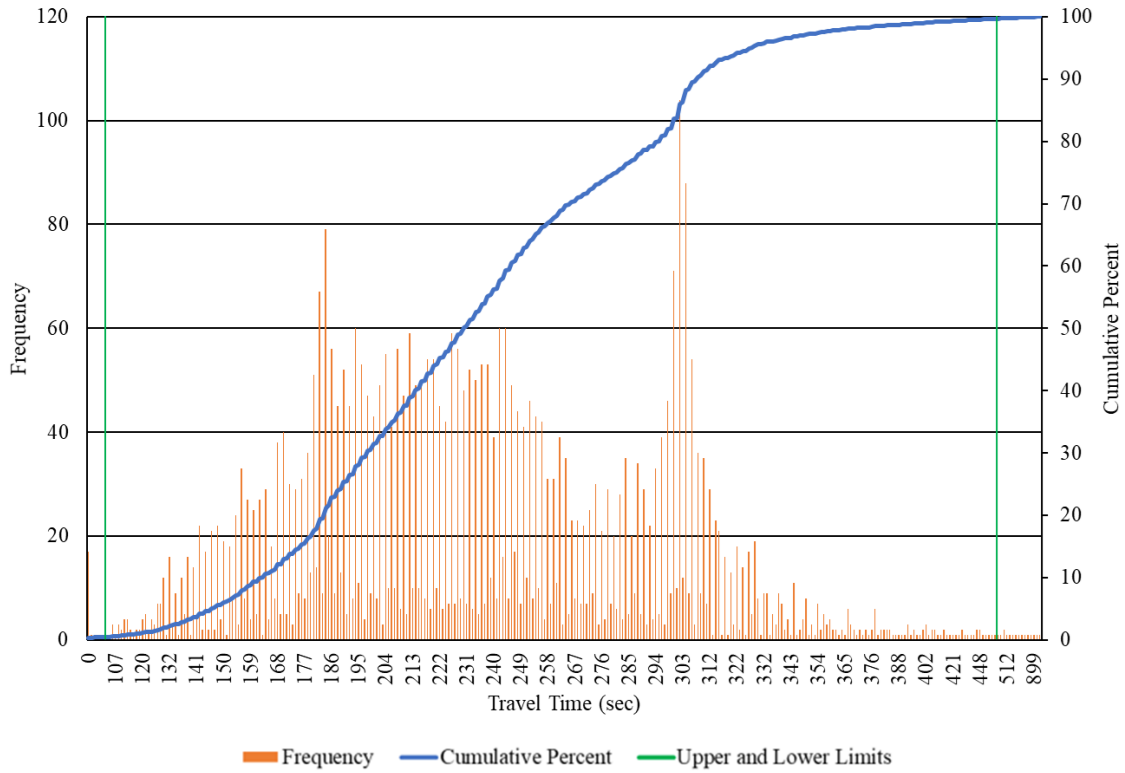


Figure A-15: Route 217 NB 3500 South travel-time distribution.

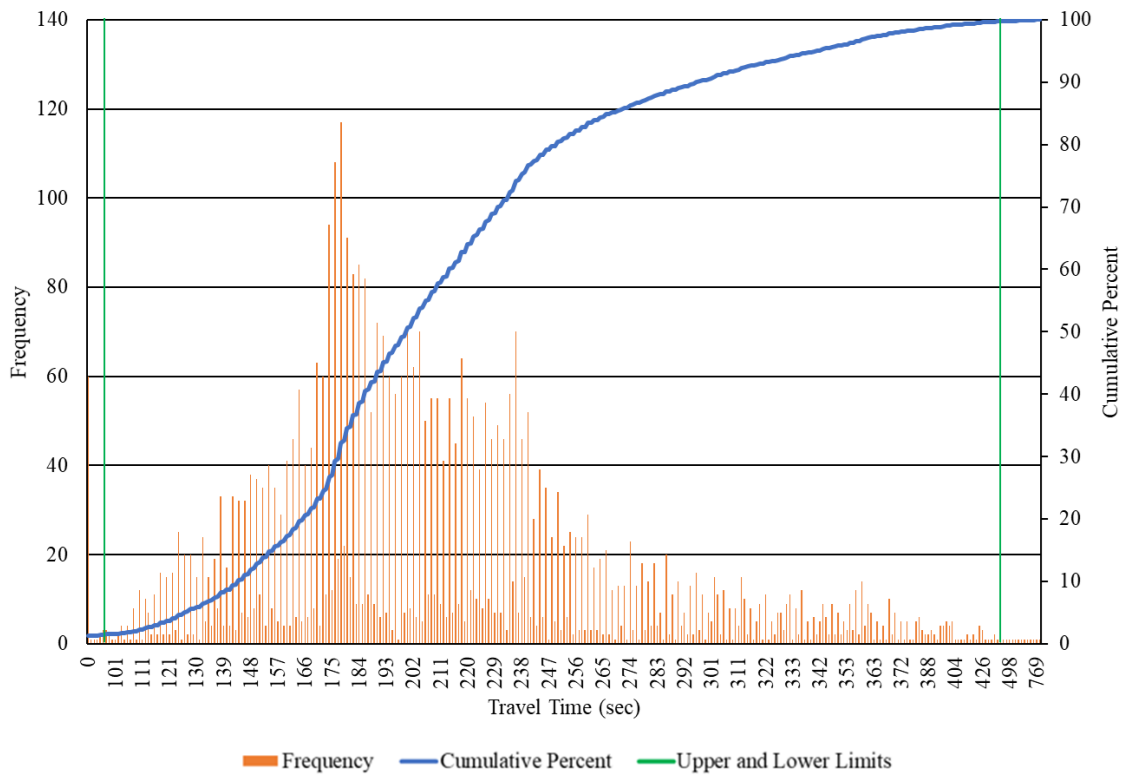


Figure A-16: Route 217 NB Redwood Junction travel-time distribution.

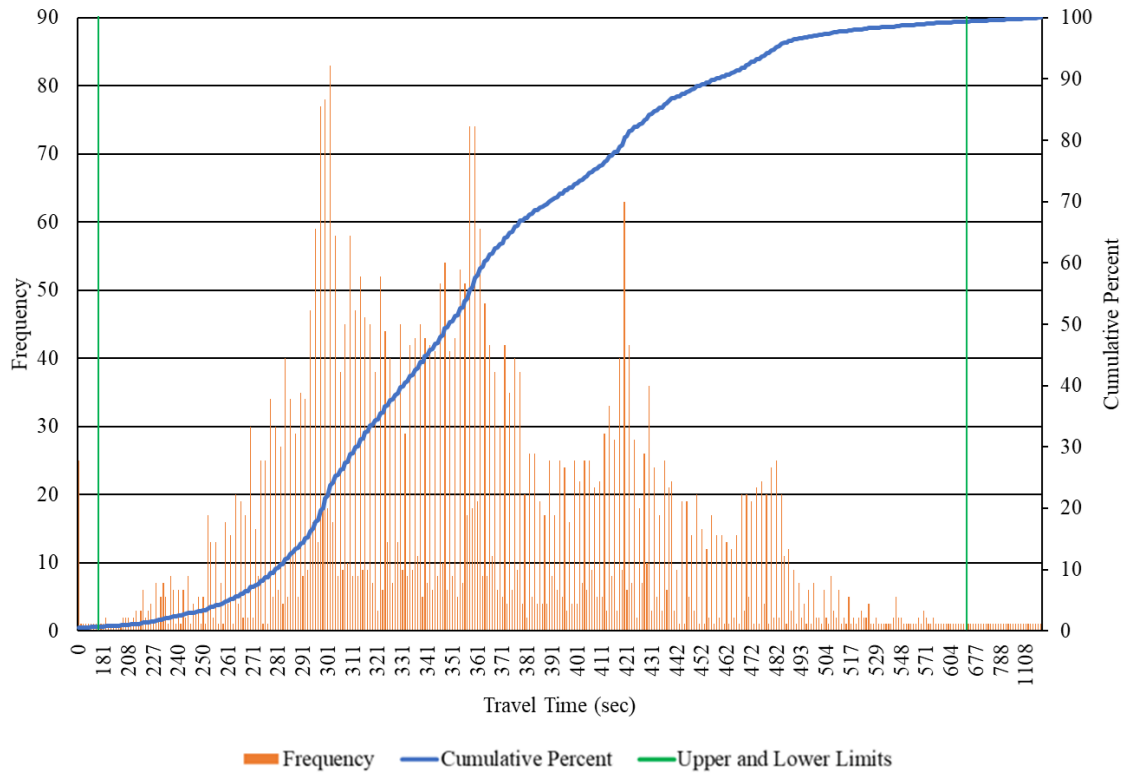


Figure A-17: Route 217 NB 1700 South travel-time distribution.

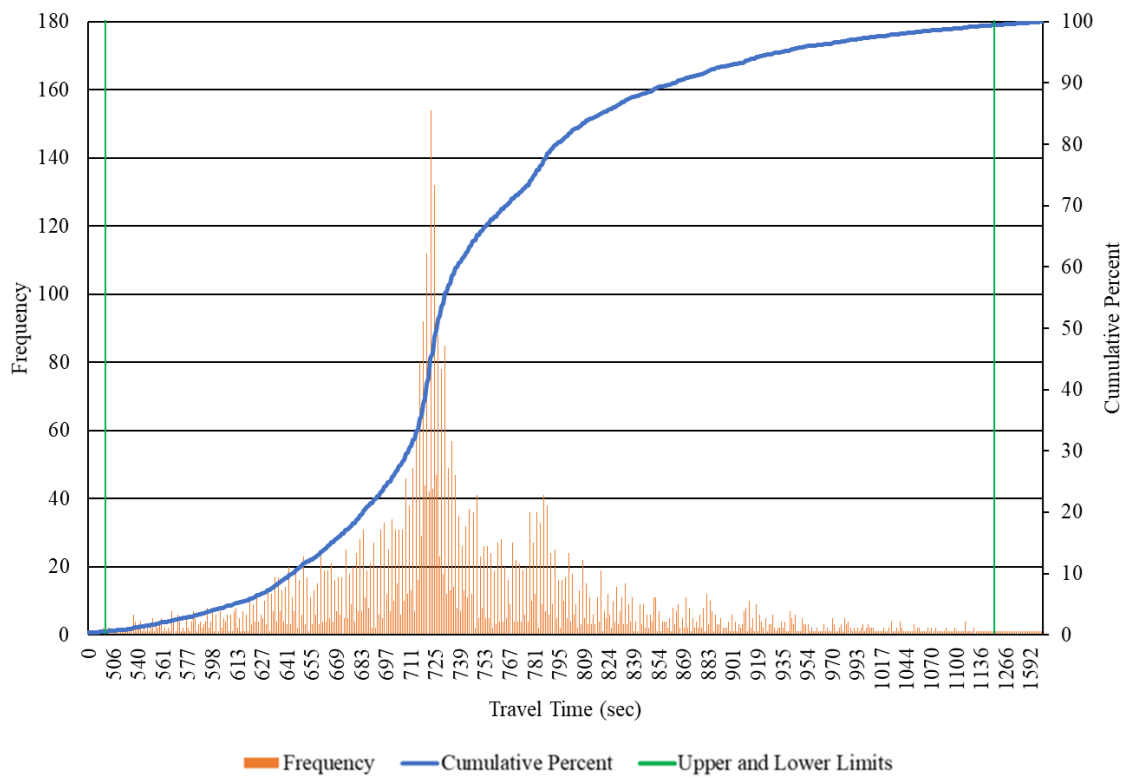


Figure A-18: Route 217 NB Power Station travel-time distribution.

A.2 Route 217 Schedule Deviation Difference in Means

A.2.1 Route 217 AM SB Schedule Deviation Statistical Output Difference in Means

Table A-1: Route 217 AM SB Schedule Deviation Statistical Output Difference in Means

Equipped Corridor	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	86.4328	12.891	11000	6.7	<.0001	
	2	93.2507	12.452	11000	7.49	<.0001	
	3	135.63	13.1974	11000	10.28	<.0001	
	5	85.4567	12.395	11000	6.89	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	0.9761	7.9117	11000	0.12	0.9018
	2	5	7.794	7.174	11000	1.09	0.2773
Power Station	3	5	50.1701	8.6078	11000	5.83	<.0001
	0	2	-6.818	7.9596	11000	-0.86	0.3917
	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	172.23	23.6428	1330	7.28	<.0001	
	2	156.49	22.4293	1330	6.98	<.0001	
	3	214.03	26.362	1330	8.12	<.0001	
	5	135.16	22.2687	1330	6.07	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
0	5	37.0648	21.6621	1330	1.71	0.0873	
2	5	21.328	20.3172	1330	1.05	0.294	
3	5	78.8662	24.6624	1330	3.2	0.0014	
0	2	15.7367	21.5645	1330	0.73	0.4657	

Table A-1 (continued)

1700 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	71.3153	20.2573	1381	3.52	0.0004	
	2	70.1855	18.1253	1381	3.87	0.0001	
	3	106.86	23.6056	1381	4.53	<.0001	
	5	49.1348	18.2594	1381	2.69	0.0072	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	22.1805	25.3853	1381	0.87	0.3824
	2	5	21.0507	23.7041	1381	0.89	0.3747
	3	5	57.7291	28.2693	1381	2.04	0.0413
	0	2	1.1298	25.2545	1381	0.04	0.9643
Redwood Junction	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	107.2	23.4121	1328	4.58	<.0001	
	2	115.79	21.5224	1328	5.38	<.0001	
	3	162.25	26.7306	1328	6.07	<.0001	
	5	97.997	21.5988	1328	4.54	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	9.2044	27.4558	1328	0.34	0.7375
	2	5	17.7966	25.85	1328	0.69	0.4913
	3	5	64.2513	30.5346	1328	2.1	0.0355
	0	2	-8.5922	27.4001	1328	-0.31	0.7539
3500 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	64.763	25.9934	1241	2.49	0.0128	
	2	79.3071	24.0905	1241	3.29	0.001	
	3	132.52	27.964	1241	4.74	<.0001	
	5	66.9335	24.4277	1241	2.74	0.0062	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-2.1705	26.9541	1241	-0.08	0.9358
	2	5	12.3737	25.1482	1241	0.49	0.6228
	3	5	65.5903	28.9949	1241	2.26	0.0239
	0	2	-14.5441	26.6838	1241	-0.55	0.5858

Table A-1 (continued)

4100 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	75.9784	20.873	1244	3.64	0.0003	
	2	80.3602	18.3098	1244	4.39	<.0001	
	3	130.92	22.2424	1244	5.89	<.0001	
	5	92.7969	17.9174	1244	5.18	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-16.8185	26.1237	1244	-0.64	0.5198
	2	5	-12.4367	24.079	1244	-0.52	0.6056
	3	5	38.1207	27.837	1244	1.37	0.1711
	0	2	-4.3819	26.3793	1244	-0.17	0.8681
SLCC	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	64.3838	19.2316	1233	3.35	0.0008	
	2	65.7402	17.1737	1233	3.83	0.0001	
	3	106.47	20.8479	1233	5.11	<.0001	
	5	78.7066	16.6879	1233	4.72	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-14.3229	21.0323	1233	-0.68	0.496
	2	5	-12.9664	19.2012	1233	-0.68	0.4996
	3	5	27.759	22.7704	1233	1.22	0.223
	0	2	-1.3565	21.3605	1233	-0.06	0.9494
5400 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	68.774	21.6716	1167	3.17	0.0015	
	2	73.1548	18.2296	1167	4.01	<.0001	
	3	105.3	21.9747	1167	4.79	<.0001	
	5	80.4732	17.1651	1167	4.69	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-11.6992	24.6944	1167	-0.47	0.6358
	2	5	-7.3184	21.7596	1167	-0.34	0.7367
	3	5	24.8262	25.3367	1167	0.98	0.3274
	0	2	-4.3808	25.2028	1167	-0.17	0.862

Table A-1 (continued)

6200 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	105.91	24.1872	1206	4.38	<.0001	
	2	117.91	21.1026	1206	5.59	<.0001	
	3	141.65	24.0253	1206	5.9	<.0001	
	5	105.89	20.3737	1206	5.2	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	0.02138	24.3363	1206	0	0.9993
	2	5	12.0248	21.2814	1206	0.57	0.5722
	3	5	35.7643	24.8035	1206	1.44	0.1496
	0	2	-12.0034	24.6615	1206	-0.49	0.6265
7000 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	69.8606	30.1154	1249	2.32	0.0205	
	2	95.9482	27.4193	1249	3.5	0.0005	
	3	119.03	28.9642	1249	4.11	<.0001	
	5	73.6621	26.274	1249	2.8	0.0051	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-3.8015	28.1407	1249	-0.14	0.8926
	2	5	22.2861	25.2726	1249	0.88	0.378
	3	5	45.3679	27.3353	1249	1.66	0.0972
	0	2	-26.0876	28.919	1249	-0.9	0.3672

A.2.2 Route 217 AM NB Schedule Deviation Statistical Output Difference in Means

Table A-2: Route 217 AM NB Schedule Deviation Statistical Output Difference in Means

Equipped Corridor	Least Squares Means							
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t		
	0	67.1466	15.4349	11000	4.35	<.0001		
	2	81.8742	15.2413	11000	5.37	<.0001		
	3	128.93	16.1762	11000	7.97	<.0001		
	5	118.45	15.2231	11000	7.78	<.0001		
	Differences of Least Squares Means							
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	5	-51.3022	5.8586	11000	-8.76	<.0001	
	2	5	-36.5746	5.3271	11000	-6.87	<.0001	
Power Station	3	5	10.4812	7.5886	11000	1.38	0.1673	
	0	2	-14.7276	5.8472	11000	-2.52	0.0118	
	Least Squares Means							
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t		
	0	73.2056	23.1755	1133	3.16	0.0016		
	2	77.9092	21.4558	1133	3.63	0.0003		
	3	130.48	32.6864	1133	3.99	<.0001		
	5	120.99	20.95	1133	5.77	<.0001		
	Differences of Least Squares Means							
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
1700 South	0	5	-47.7807	28.4083	1133	-1.68	0.0929	
	2	5	-43.0771	27.0189	1133	-1.59	0.1111	
	3	5	9.4942	36.5596	1133	0.26	0.7951	
	0	2	-4.7036	28.7561	1133	-0.16	0.8701	
	Least Squares Means							
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t		
	0	76.3449	19.3733	1210	3.94	<.0001		
	2	92.457	17.6428	1210	5.24	<.0001		
	3	147.77	26.9054	1210	5.49	<.0001		
	5	147.1	17.4669	1210	8.42	<.0001		
Differences of Least Squares Means								
Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t		
0	5	-70.7599	22.8572	1210	-3.1	0.002		
2	5	-54.6479	21.3911	1210	-2.55	0.0107		
3	5	0.6609	29.4268	1210	0.02	0.9821		
0	2	-16.112	22.871	1210	-0.7	0.4813		

Table A-2 (continued)

Redwood Junction	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	96.0453	20.4688	1250	4.69	<.0001	
	2	108.14	19.1043	1250	5.66	<.0001	
	3	139.34	27.2482	1250	5.11	<.0001	
	5	149.67	18.944	1250	7.9	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-53.6251	22.9662	1250	-2.33	0.0197
	2	5	-41.534	21.7507	1250	-1.91	0.0564
	3	5	-10.3257	29.0777	1250	-0.36	0.7226
	0	2	-12.091	22.98	1250	-0.53	0.5989
3500 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	90.3148	18.0393	1254	5.01	<.0001	
	2	109.65	16.6342	1254	6.59	<.0001	
	3	166.73	24.2171	1254	6.88	<.0001	
	5	161.66	16.5344	1254	9.78	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-71.3412	18.1228	1254	-3.94	<.0001
	2	5	-52.0107	16.7149	1254	-3.11	0.0019
	3	5	5.0722	24.1968	1254	0.21	0.834
	0	2	-19.3305	18.0593	1254	-1.07	0.2847
4100 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	77.0265	13.6317	1271	5.65	<.0001	
	2	105.17	11.6049	1271	9.06	<.0001	
	3	149.75	20.5079	1271	7.3	<.0001	
	5	152.18	11.6231	1271	13.09	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-75.1505	17.0579	1271	-4.41	<.0001
	2	5	-47.0048	15.4887	1271	-3.03	0.0025
	3	5	-2.4261	22.8819	1271	-0.11	0.9156
	0	2	-28.1457	16.9939	1271	-1.66	0.0979

Table A-2 (continued)

SLCC	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	84.7047	19.4431	1304	4.36	<.0001	
	2	91.6623	17.819	1304	5.14	<.0001	
	3	130.84	24.5071	1304	5.34	<.0001	
	5	130.49	17.775	1304	7.34	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-45.7863	19.4979	1304	-2.35	0.019
	2	5	-38.8288	17.8922	1304	-2.17	0.0302
	3	5	0.3444	24.5137	1304	0.01	0.9888
0	2	-6.9576	19.4512	1304	-0.36	0.7206	
5400 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	48.8224	12.7283	1292	3.84	0.0001	
	2	60.7703	10.8494	1292	5.6	<.0001	
	3	104.68	16.3911	1292	6.39	<.0001	
	5	80.2683	10.8903	1292	7.37	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-31.4459	13.0529	1292	-2.41	0.0161
	2	5	-19.498	11.2299	1292	-1.74	0.0828
	3	5	24.4129	16.6619	1292	1.47	0.1431
0	2	-11.9479	12.9156	1292	-0.93	0.3551	
6200 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	59.3766	12.5305	1280	4.74	<.0001	
	2	77.1616	10.8019	1280	7.14	<.0001	
	3	122.02	15.5096	1280	7.87	<.0001	
	5	83.6781	10.772	1280	7.77	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-24.3015	12.8059	1280	-1.9	0.058
	2	5	-6.5165	11.1237	1280	-0.59	0.5581
	3	5	38.3392	15.7451	1280	2.43	0.015
0	2	-17.785	12.7117	1280	-1.4	0.162	

Table A-2 (continued)

7000 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	46.723	14.3823	1276	3.25	0.0012	
	2	59.3314	13.395	1276	4.43	<.0001	
	3	87.8087	16.3927	1276	5.36	<.0001	
	5	74.251	13.3262	1276	5.57	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-27.528	10.404	1276	-2.65	0.0082
	2	5	-14.9196	8.988	1276	-1.66	0.0972
	3	5	13.5577	13.0696	1276	1.04	0.2998
	0	2	-12.6084	10.2859	1276	-1.23	0.2205

A.2.3 Route 217 PM SB Schedule Deviation Statistical Output Difference in Means

Table A-3: Route 217 PM SB Schedule Deviation Statistical Output Difference in Means

Equipped Corridor	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	112.14	17.0967	11000	6.56	<.0001	
	2	138.88	16.8535	11000	8.24	<.0001	
	3	140.66	17.429	11000	8.07	<.0001	
	5	102.15	16.9173	11000	6.04	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	9.9868	11.6808	11000	0.85	0.3926
	2	5	36.7282	11.3198	11000	3.24	0.0012
	3	5	38.5073	12.1734	11000	3.16	0.0016
	0	2	-26.7414	11.573	11000	-2.31	0.0209

Table A-3 (continued)

Power Station	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	184.33	35.9789	1330	5.12	<.0001	
	2	164.13	35.3539	1330	4.64	<.0001	
	3	166.28	36.8414	1330	4.51	<.0001	
	5	186.21	35.7651	1330	5.21	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-1.8847	35.0846	1330	-0.05	0.9572
	2	5	-22.0815	34.4357	1330	-0.64	0.5215
	3	5	-19.9344	35.9758	1330	-0.55	0.5796
	0	2	20.1969	34.6366	1330	0.58	0.5599
1700 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	107.92	34.9857	1365	3.08	0.0021	
	2	111.38	34.072	1365	3.27	0.0011	
	3	100.85	36.0055	1365	2.8	0.0052	
	5	106.31	35.0259	1365	3.04	0.0024	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	1.6094	25.2157	1365	0.06	0.9491
	2	5	5.0698	23.9119	1365	0.21	0.8321
	3	5	-5.463	26.6252	1365	-0.21	0.8375
	0	2	-3.4603	23.8039	1365	-0.15	0.8844
Redwood Junction	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	112.14	19.32	1372	5.8	<.0001	
	2	112.97	17.7344	1372	6.37	<.0001	
	3	117.01	21.1908	1372	5.52	<.0001	
	5	98.3589	18.4051	1372	5.34	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	13.7791	23.4748	1372	0.59	0.5573
	2	5	14.6082	22.1827	1372	0.66	0.5103
	3	5	18.6541	25.0679	1372	0.74	0.4569
	0	2	-0.8291	22.887	1372	-0.04	0.9711

Table A-3 (continued)

3500 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	80.1175	20.5986	1129	3.89	0.0001	
	2	90.585	18.7207	1129	4.84	<.0001	
	3	89.6218	21.8594	1129	4.1	<.0001	
	5	91.4338	19.0074	1129	4.81	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-11.3163	24.654	1129	-0.46	0.6463
	2	5	-0.8488	23.1021	1129	-0.04	0.9707
4100 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	93.0705	29.5867	1177	3.15	0.0017	
	2	127.69	28.4031	1177	4.5	<.0001	
	3	103.58	30.6909	1177	3.38	0.0008	
	5	109.17	28.8732	1177	3.78	0.0002	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-16.1005	23.686	1177	-0.68	0.4968
	2	5	18.5168	22.1935	1177	0.83	0.4043
SLCC	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	108.1	25.8864	1288	4.18	<.0001	
	2	140.88	24.7816	1288	5.68	<.0001	
	3	112.35	27.5102	1288	4.08	<.0001	
	5	130.32	25.269	1288	5.16	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-22.219	20.3548	1288	-1.09	0.2752
	2	5	10.5587	18.953	1288	0.56	0.5776

Table A-3 (continued)

5400 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	87.0888	27.1601	1301	3.21	0.0014	
	2	154.23	26.1607	1301	5.9	<.0001	
	3	125.96	29.4596	1301	4.28	<.0001	
	5	107.7	26.3434	1301	4.09	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-20.6161	30.2045	1301	-0.68	0.495
	2	5	46.5263	29.3381	1301	1.59	0.113
	3	5	18.2599	32.4479	1301	0.56	0.5737
	0	2	-67.1424	30.0754	1301	-2.23	0.0258
6200 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	159.24	40.1488	1078	3.97	<.0001	
	2	206.66	38.8581	1078	5.32	<.0001	
	3	265.59	43.7541	1078	6.07	<.0001	
	5	96.0245	37.9938	1078	2.53	0.0116	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	63.2196	49.7941	1078	1.27	0.2045
	2	5	110.64	48.7593	1078	2.27	0.0235
	3	5	169.57	52.7821	1078	3.21	0.0014
	0	2	-47.4166	50.3539	1078	-0.94	0.3466
7000 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	126.87	38.2331	1127	3.32	0.0009	
	2	188.48	36.134	1127	5.22	<.0001	
	3	249.84	40.922	1127	6.11	<.0001	
	5	22.5892	35.8256	1127	0.63	0.5285	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	104.28	43.4943	1127	2.4	0.0167
	2	5	165.89	41.6687	1127	3.98	<.0001
	3	5	227.26	45.8876	1127	4.95	<.0001
	0	2	-61.6183	43.6865	1127	-1.41	0.1587

A.2.4 Route 217 PM SB Schedule Deviation Difference in Means Figures

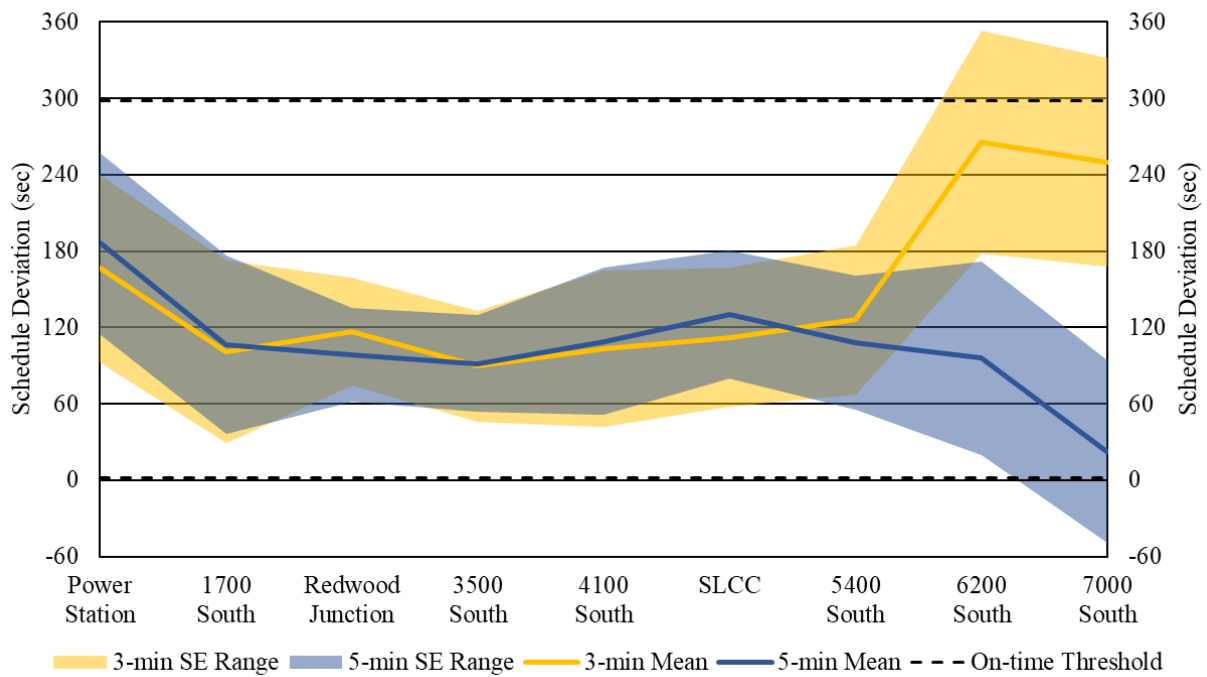


Figure A-19: Route 217 PM SB schedule deviation SE range 5-min vs 3-min (p-value=0.0016).

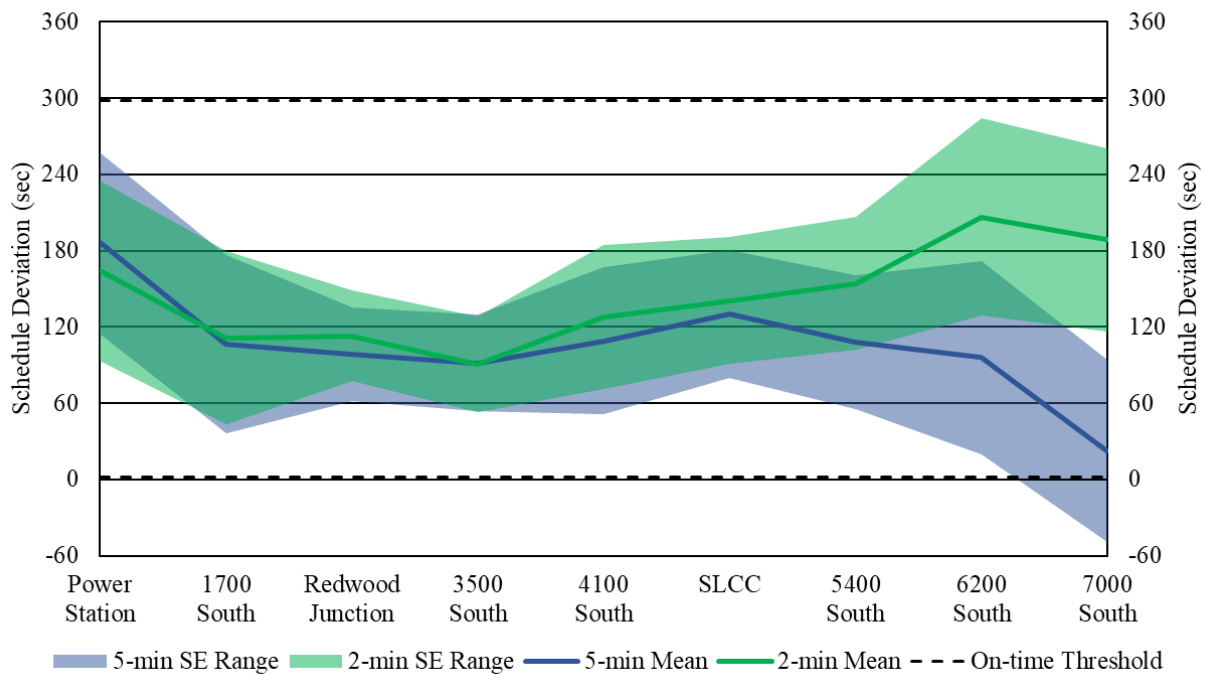


Figure A-20: Route 217 PM SB schedule deviation SE range 5-min vs 2-min (p-value=0.0012).

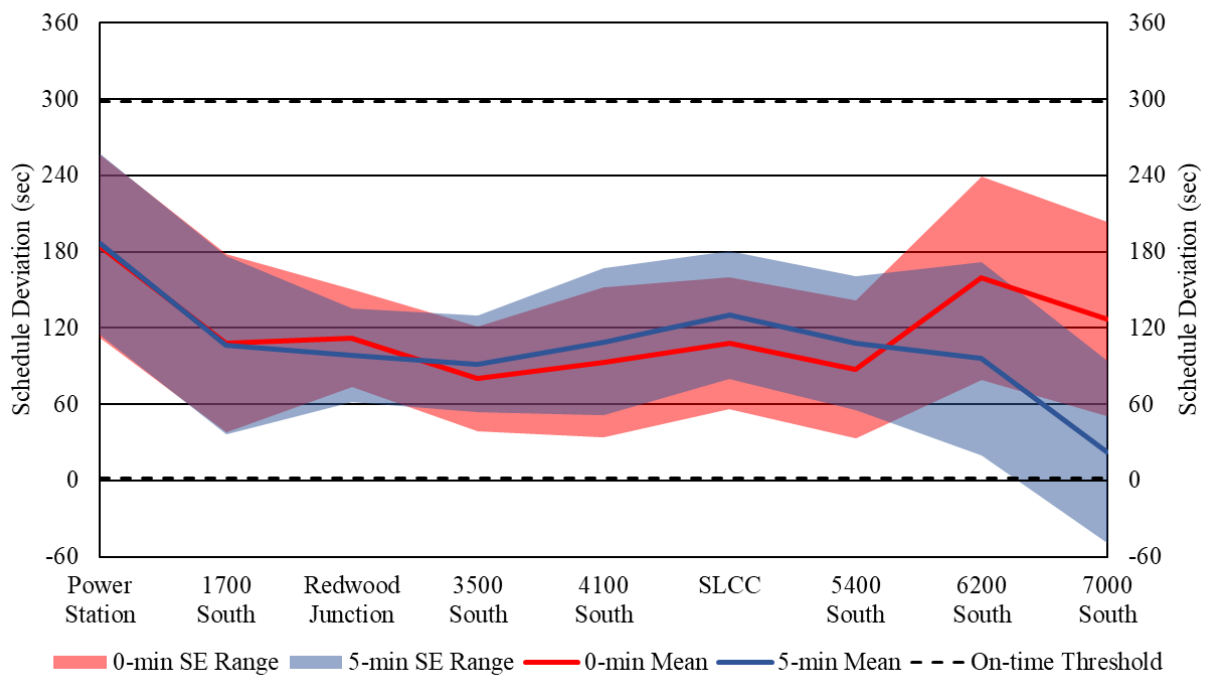


Figure A-21: Route 217 PM SB schedule deviation SE range 5-min vs 0-min (p-value=0.3926).

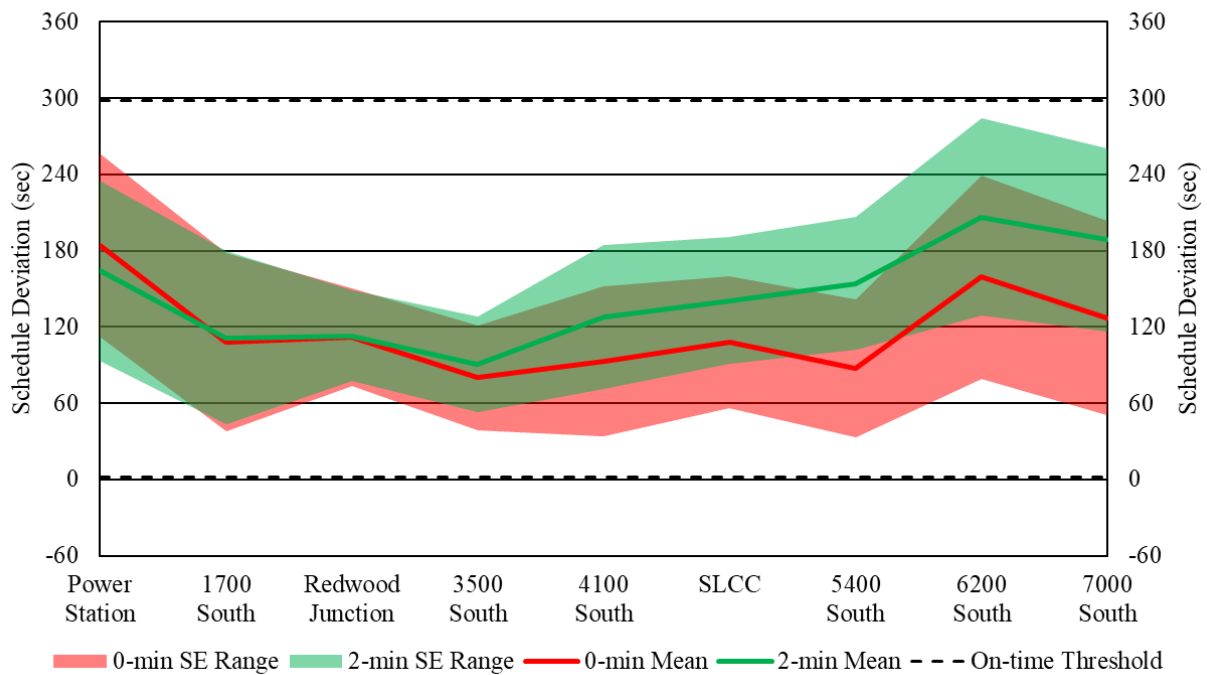


Figure A-22: Route 217 PM SB schedule deviation SE range 2-min vs 0-min (p-value=0.0209).

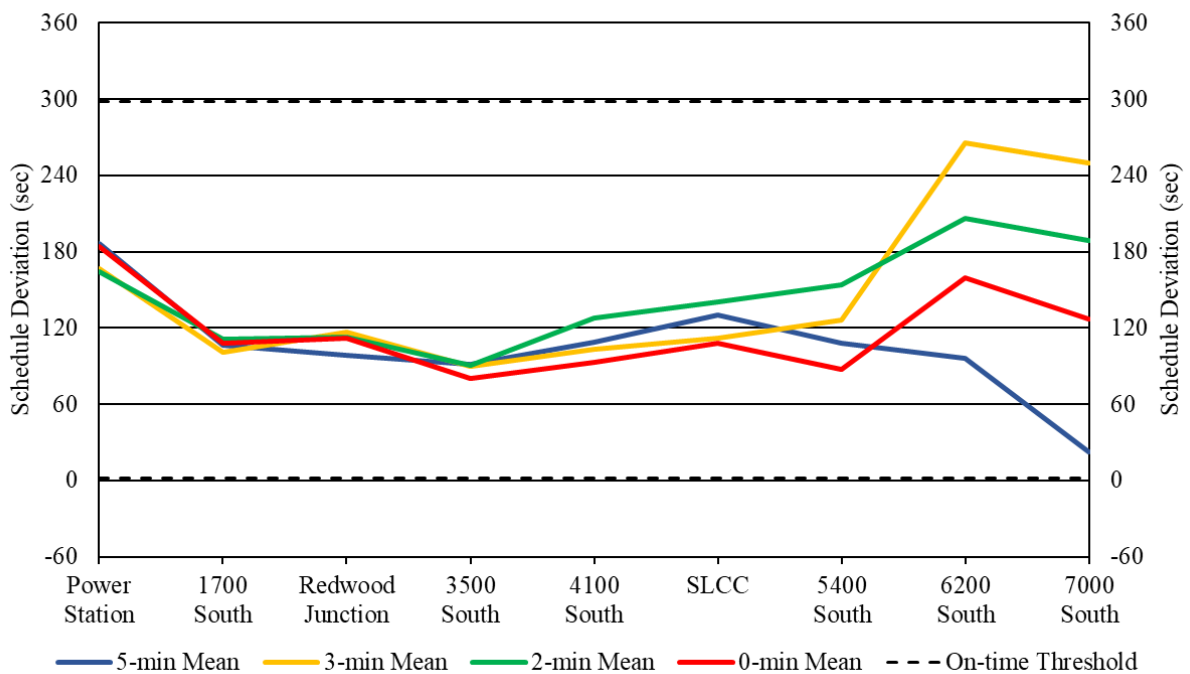


Figure A-23: Route 217 PM SB mean schedule deviation.

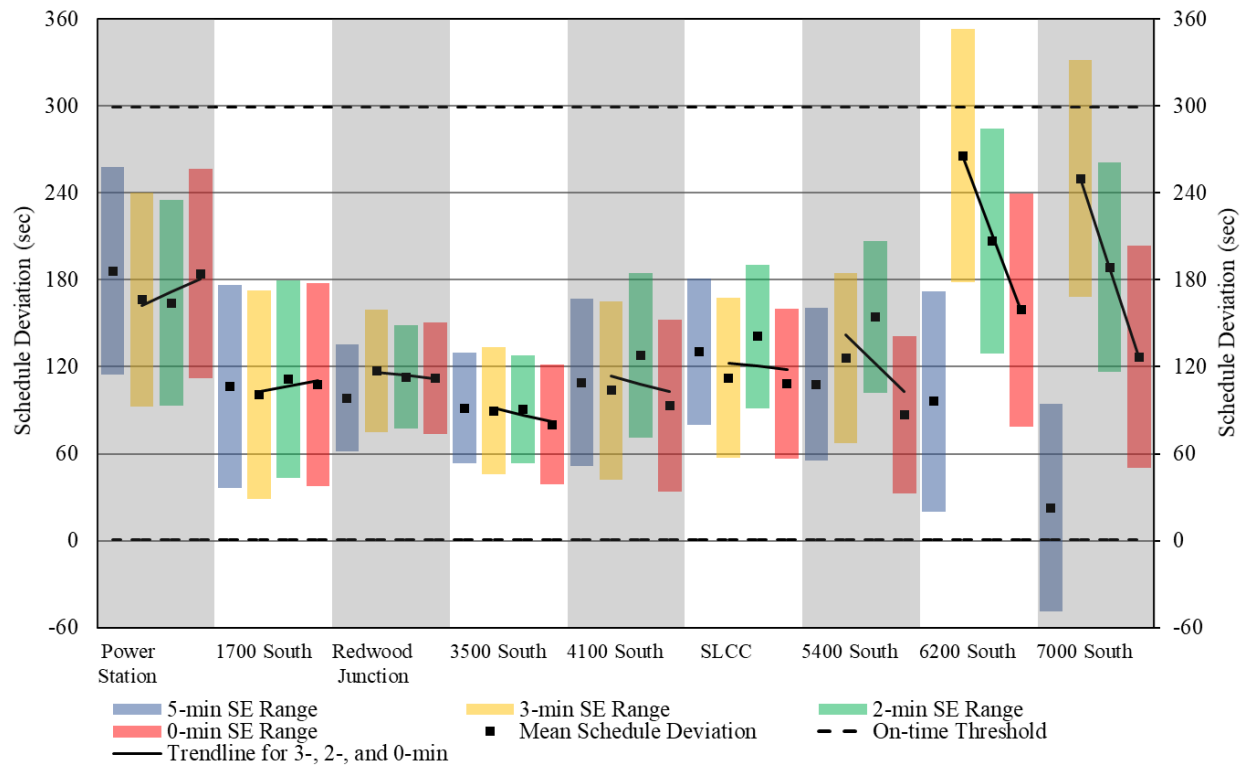


Figure A-24: Route 217 PM SB schedule deviation SE range with all thresholds.

A.2.5 Route 217 PM NB Schedule Deviation Statistical Output Difference in Means

Table A-4: Route 217 PM NB Schedule Deviation Statistical Output Difference in Means

Equipped Corridor	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	80.7267	17.507	12000	4.61	<.0001	
	2	106.99	17.4161	12000	6.14	<.0001	
	3	84.922	17.6596	12000	4.81	<.0001	
	5	87.603	17.477	12000	5.01	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-6.8763	4.5723	12000	-1.5	0.1326
	2	5	19.3837	4.2102	12000	4.6	<.0001
	3	5	-2.681	5.1257	12000	-0.52	0.6009
	0	2	-26.26	4.3182	12000	-6.08	<.0001

Table A-4 (continued)

Power Station	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	126.84	45.5015	1306	2.79	0.0054	
	2	170.72	44.9747	1306	3.8	0.0002	
	3	142.34	46.2715	1306	3.08	0.0021	
	5	131.25	45.3983	1306	2.89	0.0039	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-4.4118	18.9466	1306	-0.23	0.8159
	2	5	39.4709	17.6347	1306	2.24	0.0254
	3	5	11.0845	20.7533	1306	0.53	0.5934
	0	2	-43.8827	17.8625	1306	-2.46	0.0142
1700 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	73.4747	36.2318	1303	2.03	0.0428	
	2	88.7293	35.8022	1303	2.48	0.0133	
	3	54.6808	36.9136	1303	1.48	0.1388	
	5	72.2106	36.0879	1303	2	0.0456	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	1.2641	14.8824	1303	0.08	0.9323
	2	5	16.5187	13.806	1303	1.2	0.2317
	3	5	-17.5297	16.4477	1303	-1.07	0.2867
	0	2	-15.2546	14.1499	1303	-1.08	0.2812
Redwood Junction	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	82.4488	10.3898	1321	7.94	<.0001	
	2	88.7492	9.0147	1321	9.84	<.0001	
	3	55.862	12.488	1321	4.47	<.0001	
	5	73.8066	9.8688	1321	7.48	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	8.6423	14.1876	1321	0.61	0.5425
	2	5	14.9426	13.2173	1321	1.13	0.2585
	3	5	-17.9446	15.775	1321	-1.14	0.2555
	0	2	-6.3003	13.6019	1321	-0.46	0.6433

Table A-4 (continued)

3500 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	42.5309	8.0441	1301	5.29	<.0001	
	2	56.5965	6.6268	1301	8.54	<.0001	
	3	31.9773	10.1227	1301	3.16	0.0016	
	5	43.4327	7.6134	1301	5.7	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-0.9018	10.1986	1301	-0.09	0.9296
	2	5	13.1638	9.1188	1301	1.44	0.1491
	3	5	-11.4554	11.8967	1301	-0.96	0.3358
	0	2	-14.0656	9.4625	1301	-1.49	0.1374
4100 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	49.0486	9.4691	1283	5.18	<.0001	
	2	67.7016	7.9912	1283	8.47	<.0001	
	3	51.4405	12.0243	1283	4.28	<.0001	
	5	65.9008	9.5479	1283	6.9	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-16.8523	12.1415	1283	-1.39	0.1654
	2	5	1.8008	11.0443	1283	0.16	0.8705
	3	5	-14.4603	14.2021	1283	-1.02	0.3088
	0	2	-18.653	10.9623	1283	-1.7	0.0891
SLCC	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	82.7454	21.6433	1356	3.82	0.0001	
	2	107.04	20.9836	1356	5.1	<.0001	
	3	99.1683	22.7105	1356	4.37	<.0001	
	5	83.135	21.4073	1356	3.88	0.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-0.3896	13.6794	1356	-0.03	0.9773
	2	5	23.9083	12.6104	1356	1.9	0.0582
	3	5	16.0333	15.2841	1356	1.05	0.2944
	0	2	-24.2979	12.9621	1356	-1.87	0.0611

Table A-4 (continued)

5400 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	84.0009	14.9524	1366	5.62	<.0001	
	2	121.6	13.9686	1366	8.71	<.0001	
	3	105.95	16.4124	1366	6.46	<.0001	
	5	94.3131	14.5758	1366	6.47	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-10.3122	13.0594	1366	-0.79	0.4299
	2	5	27.289	11.9127	1366	2.29	0.0221
3	5	11.6346	14.6754	1366	0.79	0.428	
0	2	-37.6011	12.3177	1366	-3.05	0.0023	
6200 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	99.2958	14.037	1281	7.07	<.0001	
	2	144.6	13.192	1281	10.96	<.0001	
	3	119.01	15.2569	1281	7.8	<.0001	
	5	129.81	13.6992	1281	9.48	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-30.5136	11.12	1281	-2.74	0.0062
	2	5	14.7869	10.0276	1281	1.47	0.1406
3	5	-10.795	12.6138	1281	-0.86	0.3923	
0	2	-45.3005	10.3821	1281	-4.36	<.0001	
7000 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	0	81.3525	18.2484	1341	4.46	<.0001	
	2	128.41	17.6967	1341	7.26	<.0001	
	3	94.0414	18.8533	1341	4.99	<.0001	
	5	108.18	17.9062	1341	6.04	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	0	5	-26.8302	17.7407	1341	-1.51	0.1307
	2	5	20.2266	17.1685	1341	1.18	0.239
3	5	-14.1414	18.4085	1341	-0.77	0.4425	
0	2	-47.0569	17.5063	1341	-2.69	0.0073	

A.2.6 Route 217 PM NB Schedule Deviation Difference in Means Figures

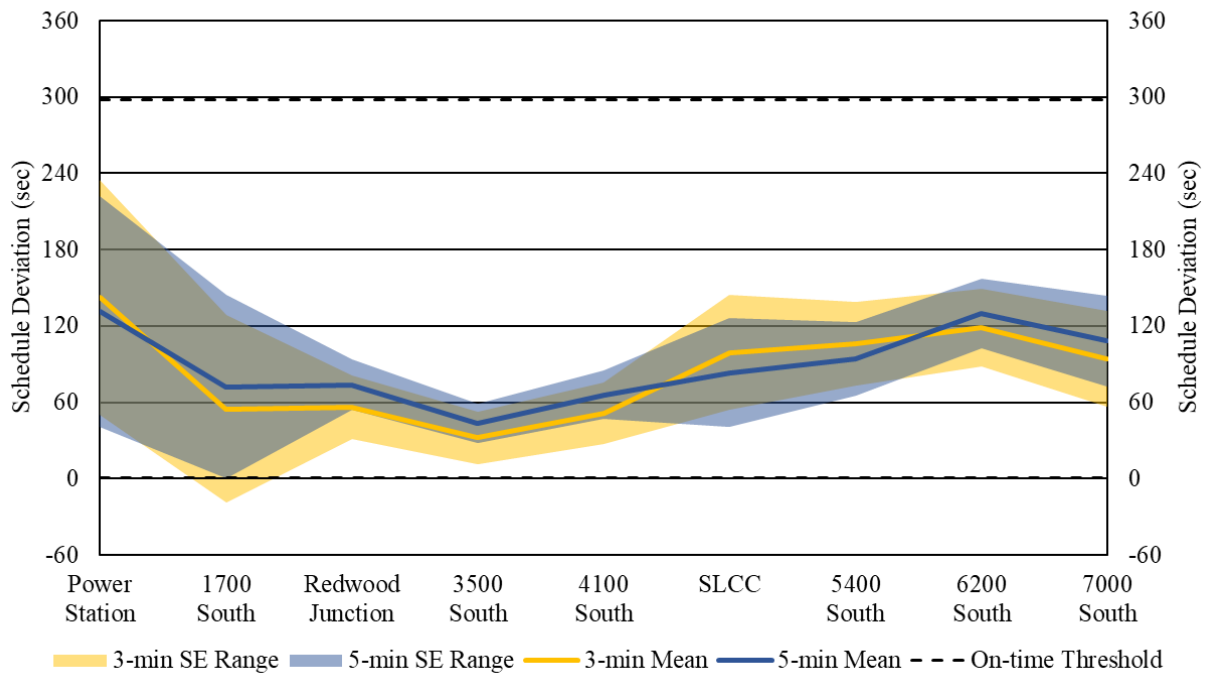


Figure A-25: Route 217 PM NB schedule deviation SE range 5-min vs 3-min (p-value=0.6009).

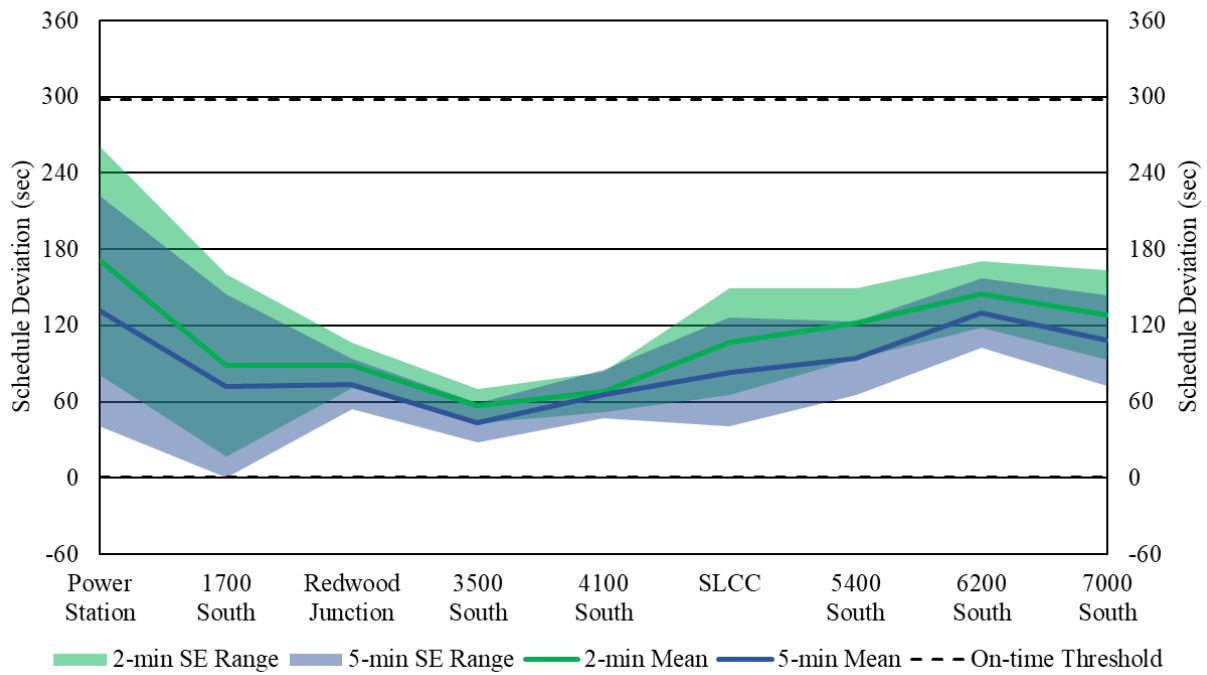


Figure A-26: Route 217 PM NB schedule deviation SE range 5-min vs 2-min (p-value=<0.0001).

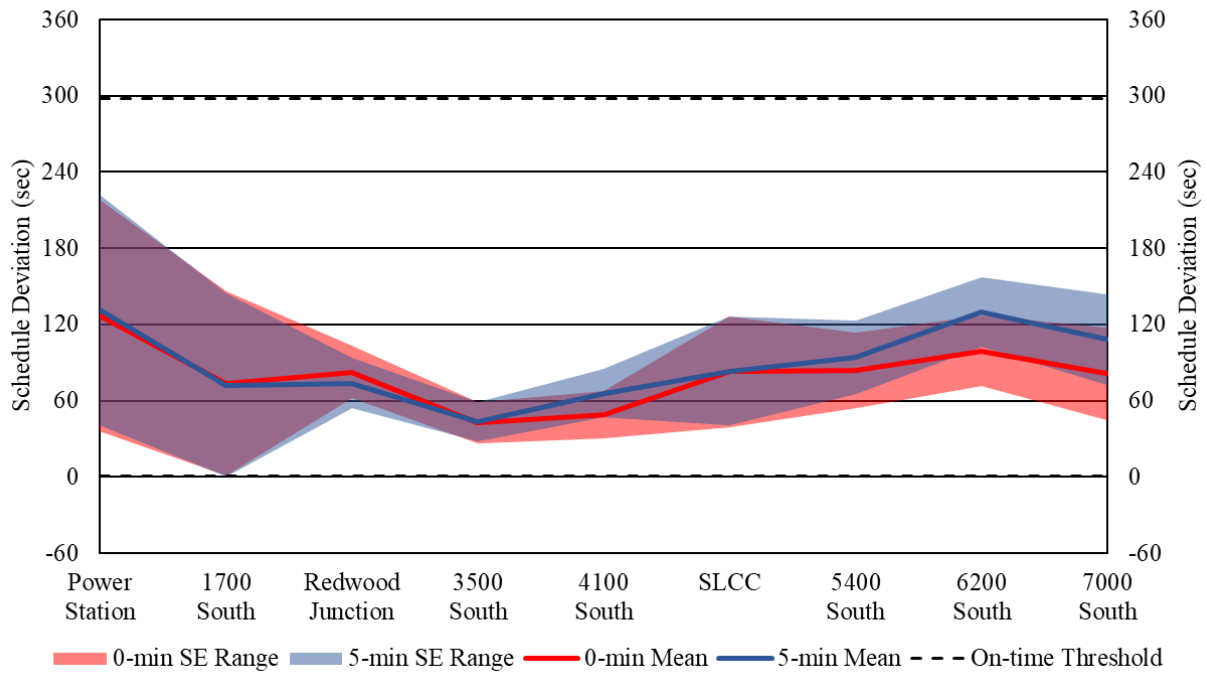


Figure A-27: Route 217 PM NB schedule deviation SE range 5-min vs 0-min (p-value=0.1326).

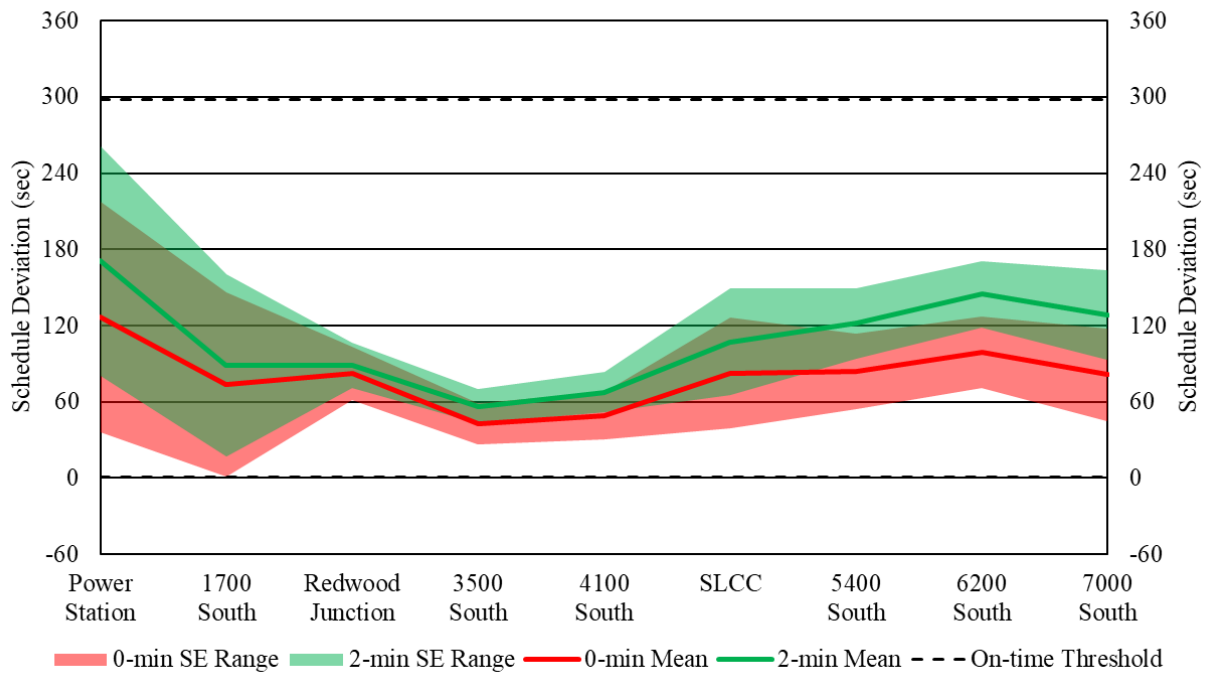


Figure A-28: Route 217 PM NB schedule deviation SE range 2-min vs 0-min (p-value=<0.0001).

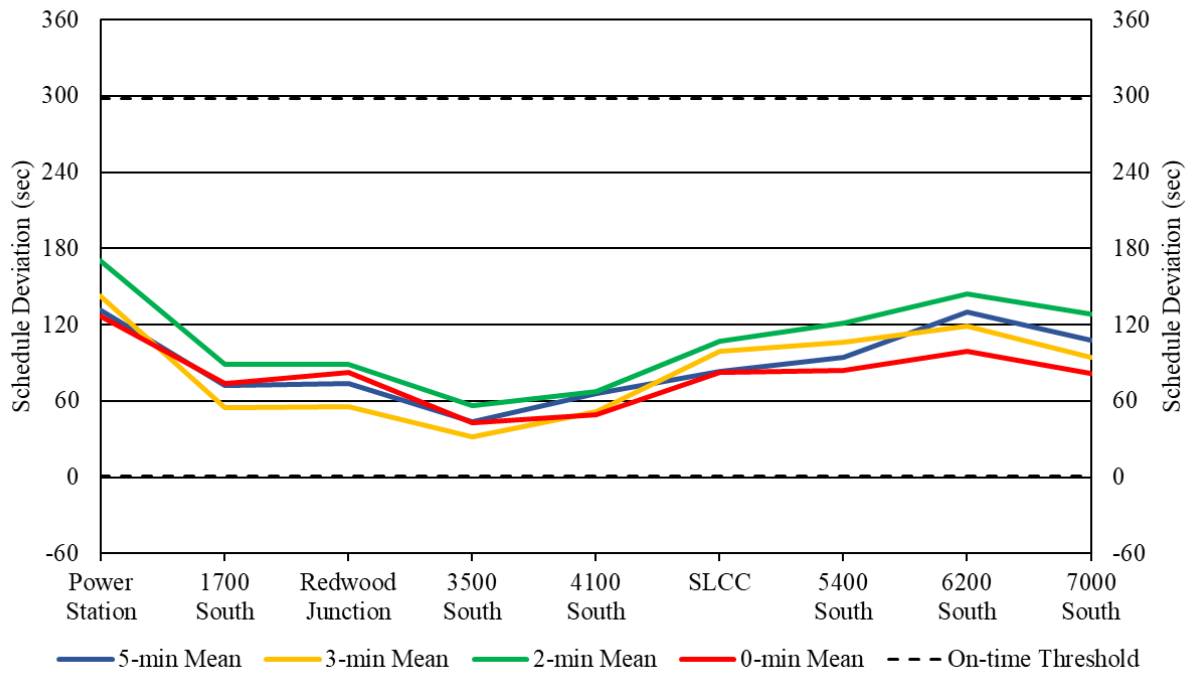


Figure A-29: Route 217 PM NB mean schedule deviation.

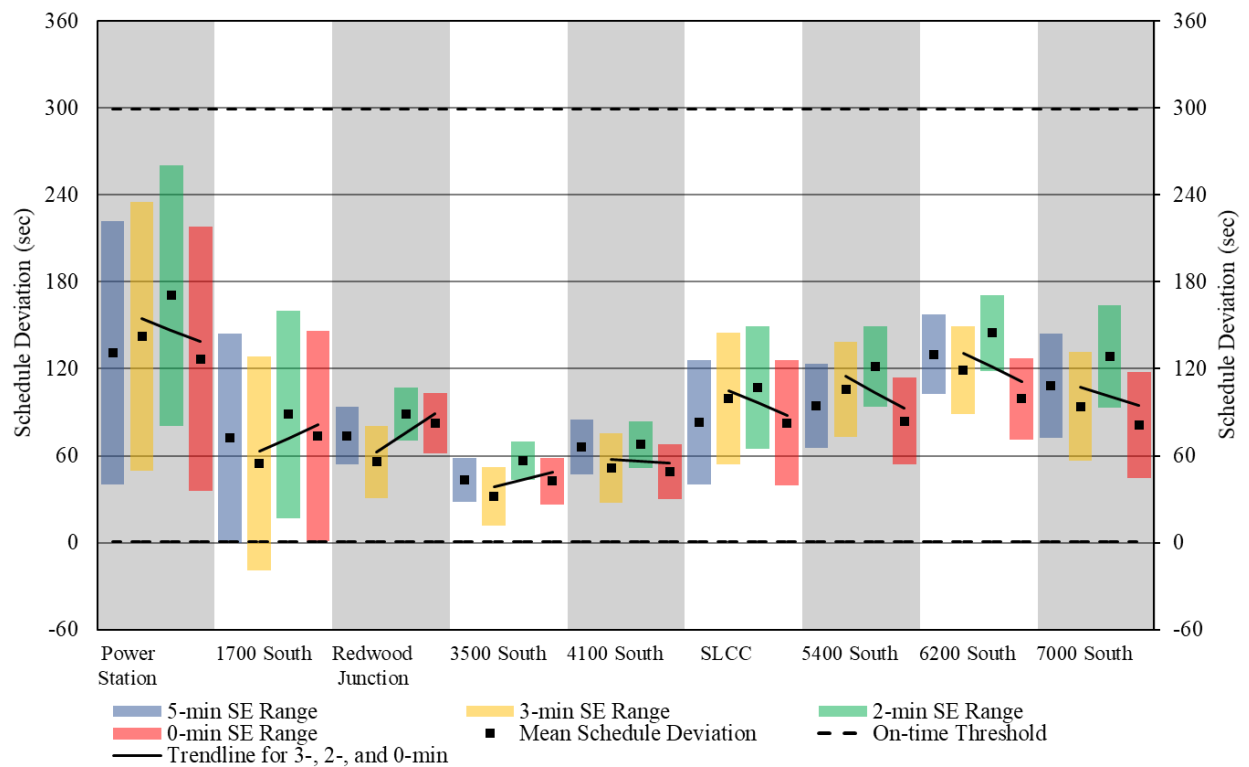


Figure A-30: Route 217 PM NB schedule deviation SE range with all thresholds.

A.3 Route 217 PM Schedule Deviation 95 Percent Prediction Interval

A.3.1 Route 217 PM SB Schedule Deviation 95 Percent Prediction Interval

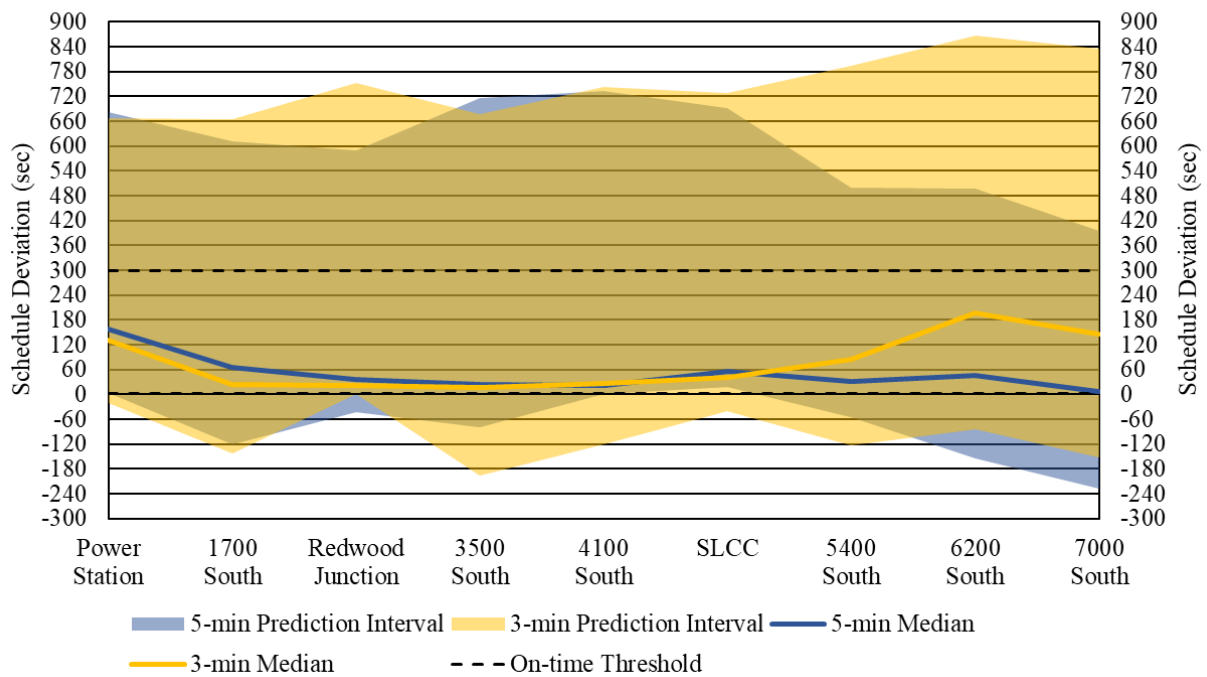


Figure A-31: Route 217 PM SB schedule deviation prediction interval 5-min vs. 3-min.

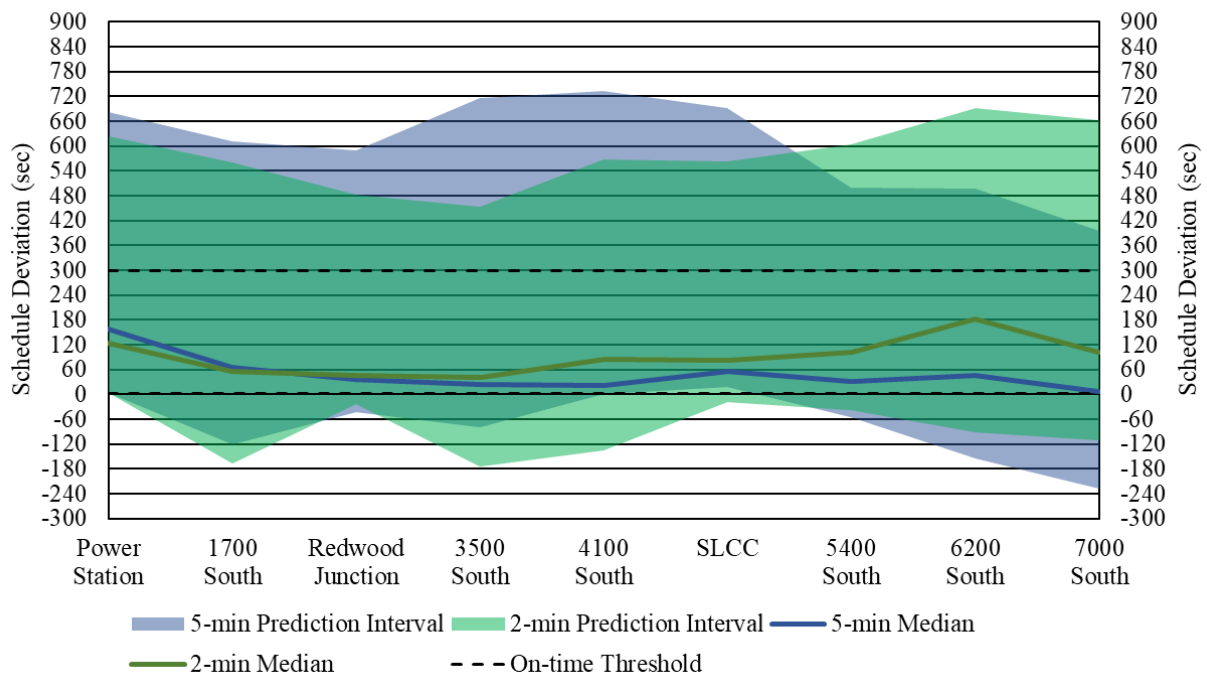


Figure A-32: Route 217 PM SB schedule deviation prediction interval 5-min vs. 2-min.

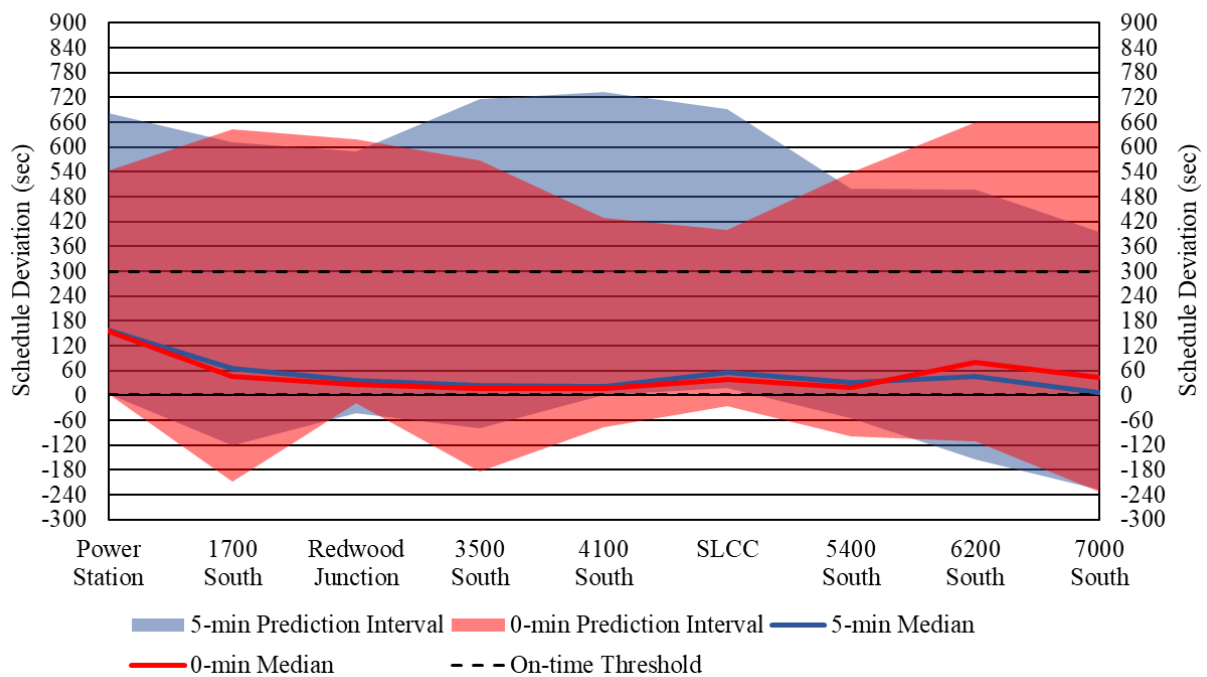


Figure A-33: Route 217 PM SB schedule deviation prediction interval 5-min vs. 0-min.

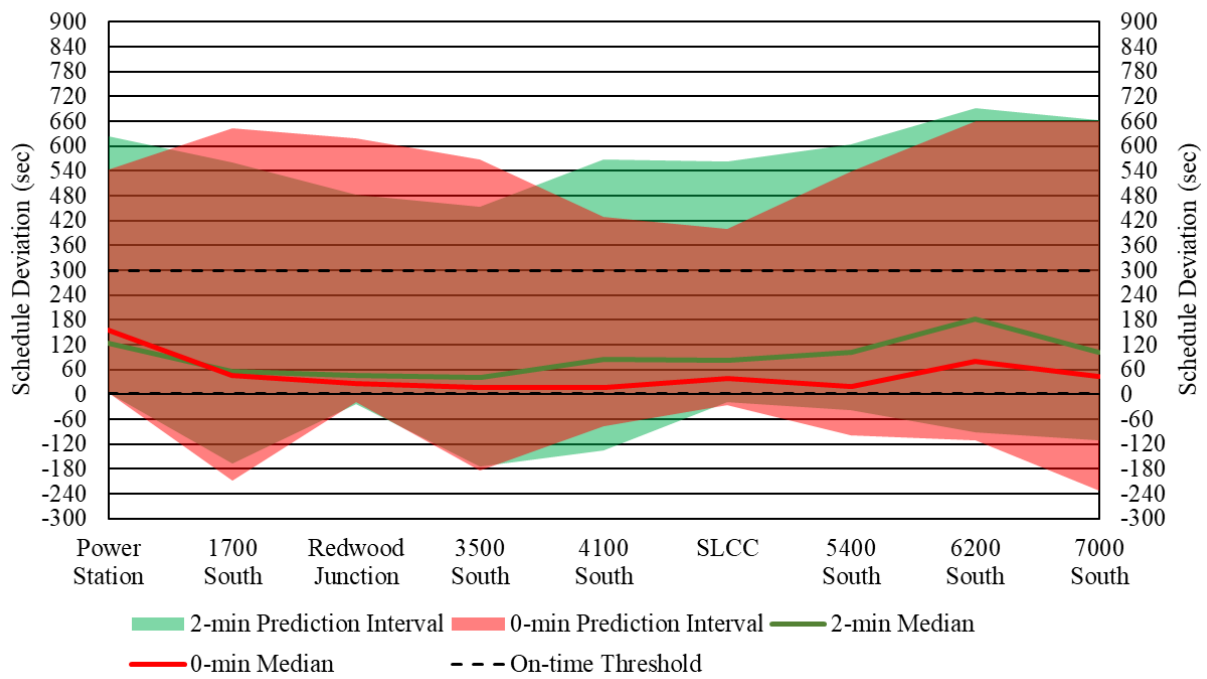


Figure A-34: Route 217 PM SB schedule deviation prediction interval 0-min vs. 2-min.

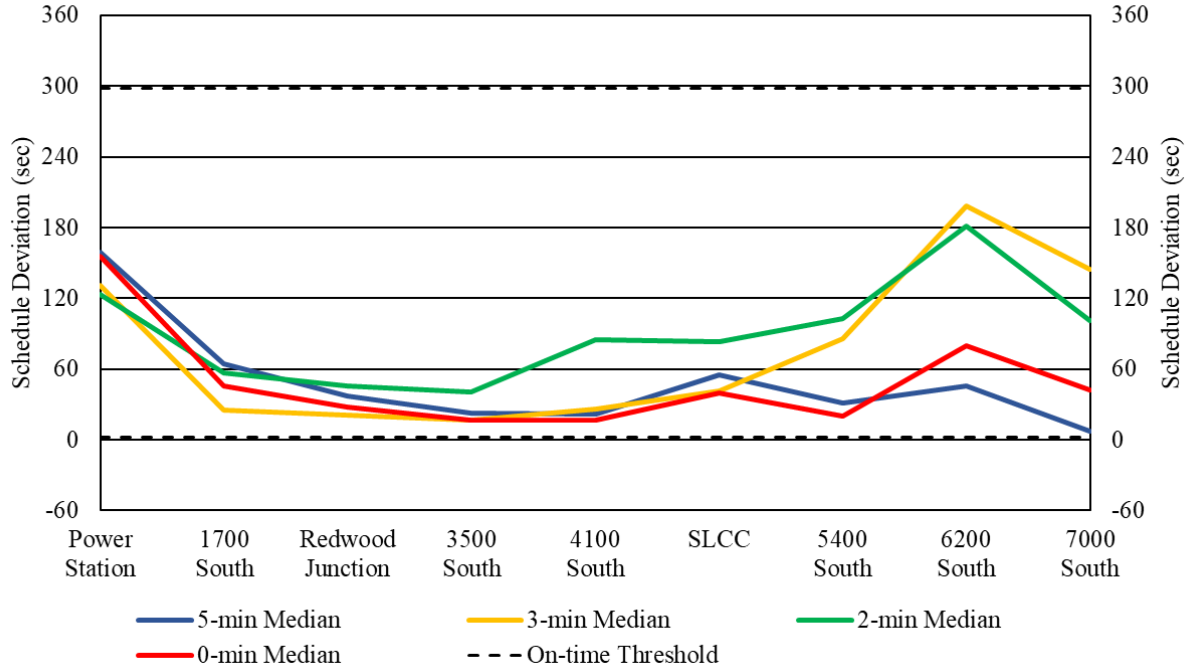


Figure A-35: Route 217 PM SB median schedule deviation.

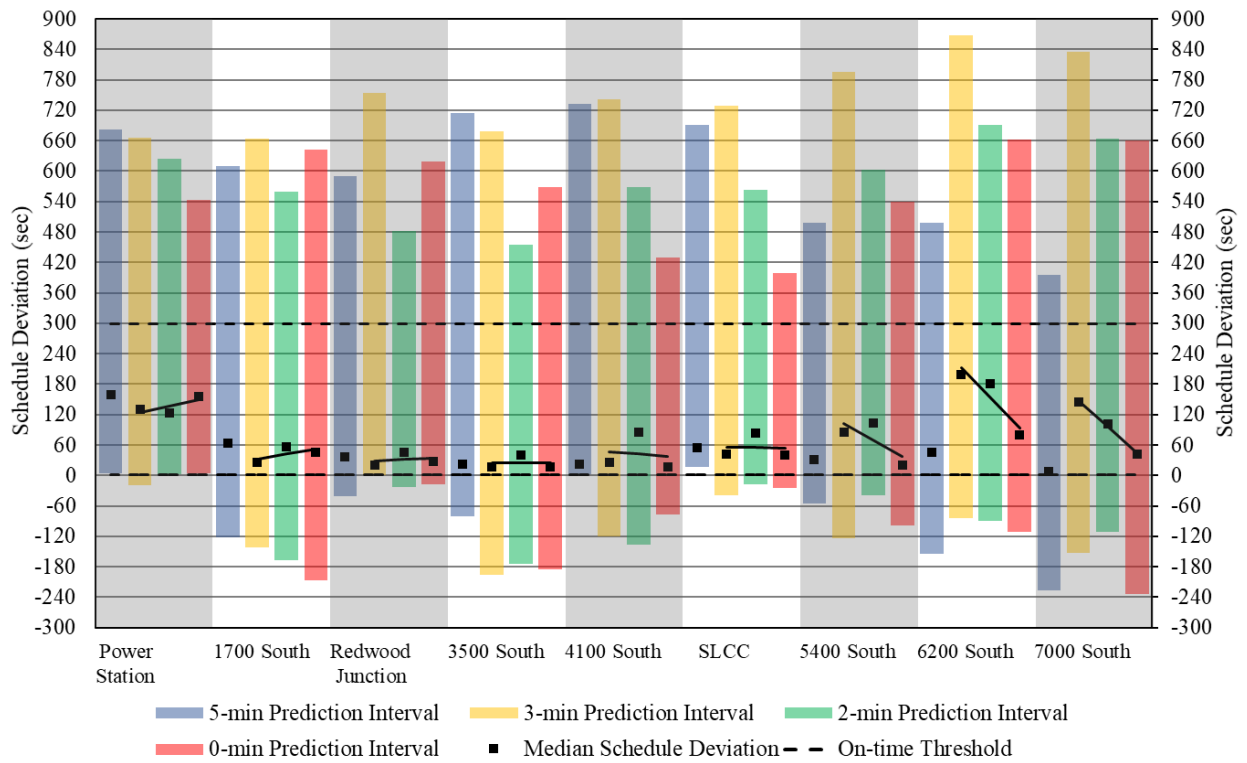


Figure A-36: Route 217 PM SB schedule deviation prediction interval with all thresholds.

A.3.2 Route 217 PM NB Schedule Deviation 95 Percent Prediction Interval

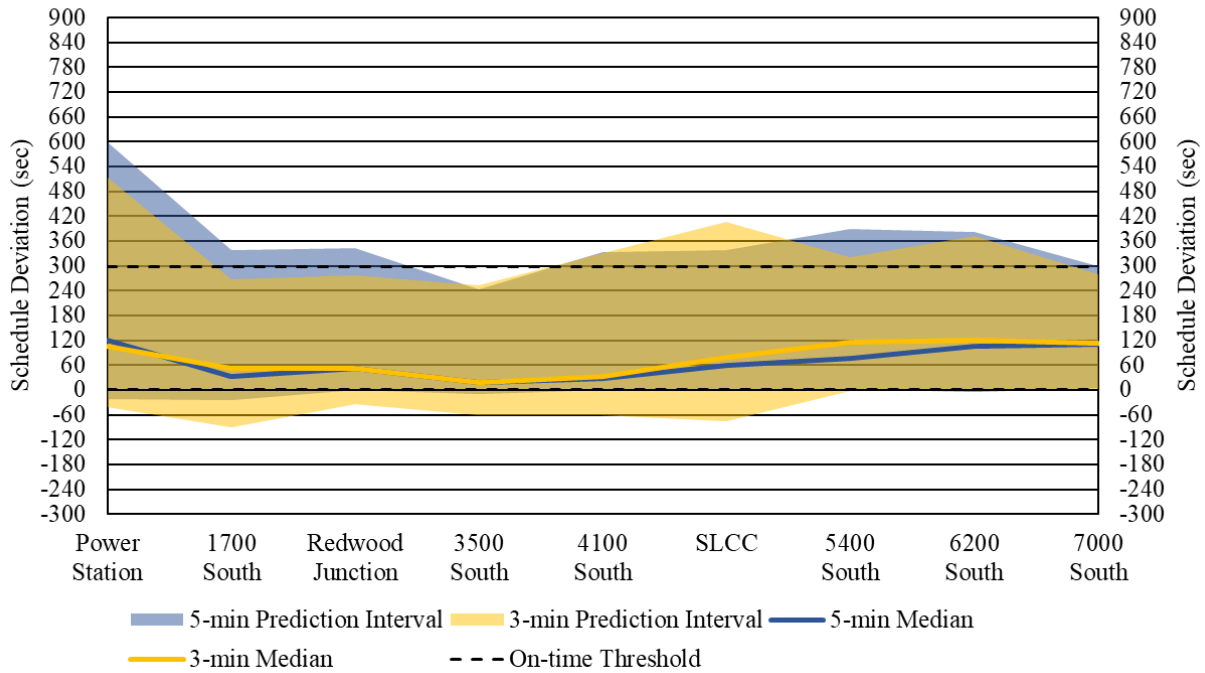


Figure A-37: Route 217 PM NB schedule deviation prediction interval 5-min vs. 3-min.

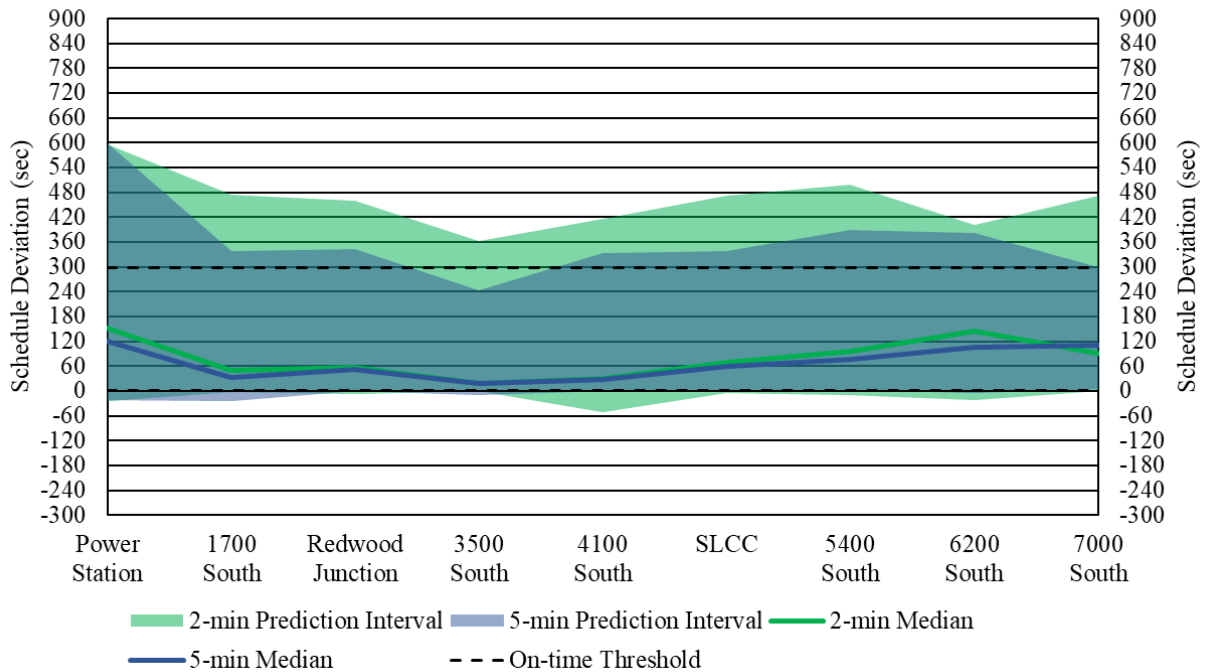


Figure A-38: Route 217 PM NB schedule deviation prediction interval 5-min vs. 2-min.

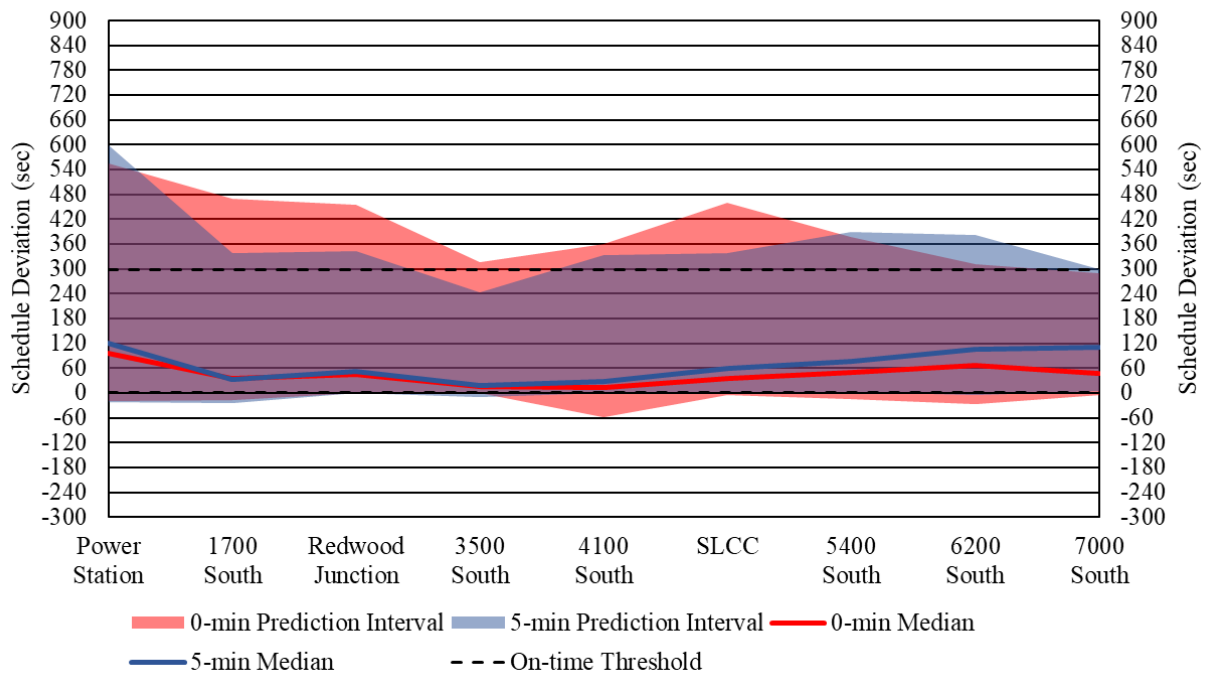


Figure A-39: Route 217 PM NB schedule deviation prediction interval 5-min vs. 0-min.

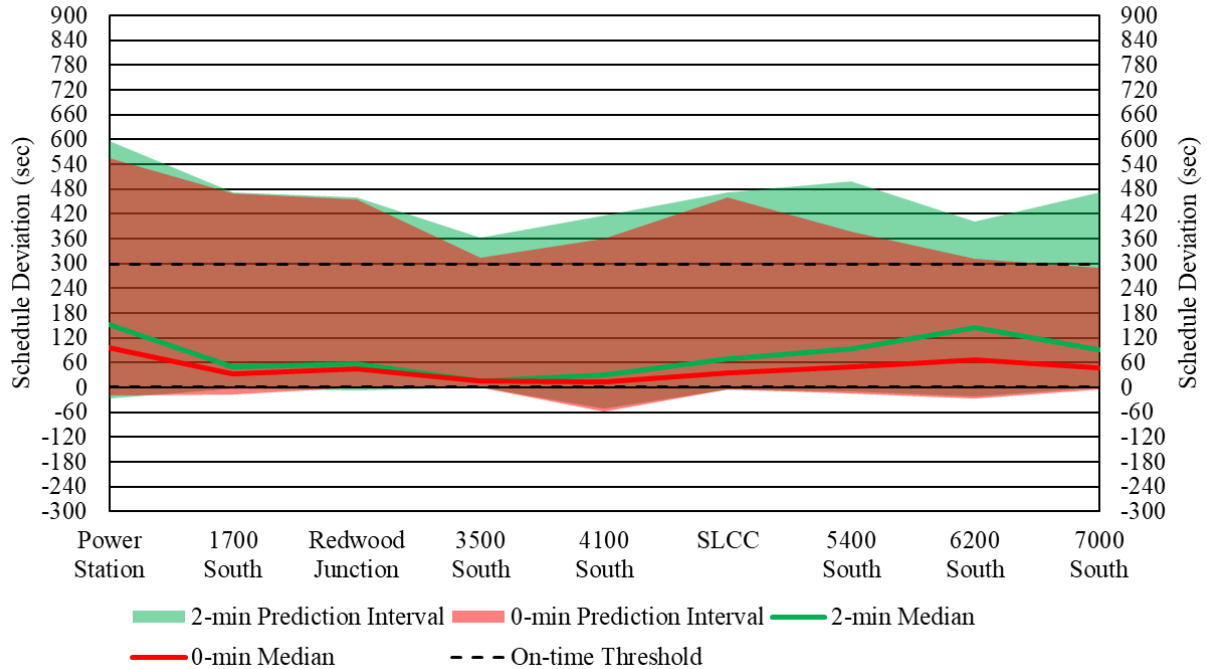


Figure A-40: Route 217 PM NB schedule deviation prediction interval 2-min vs. 0-min.

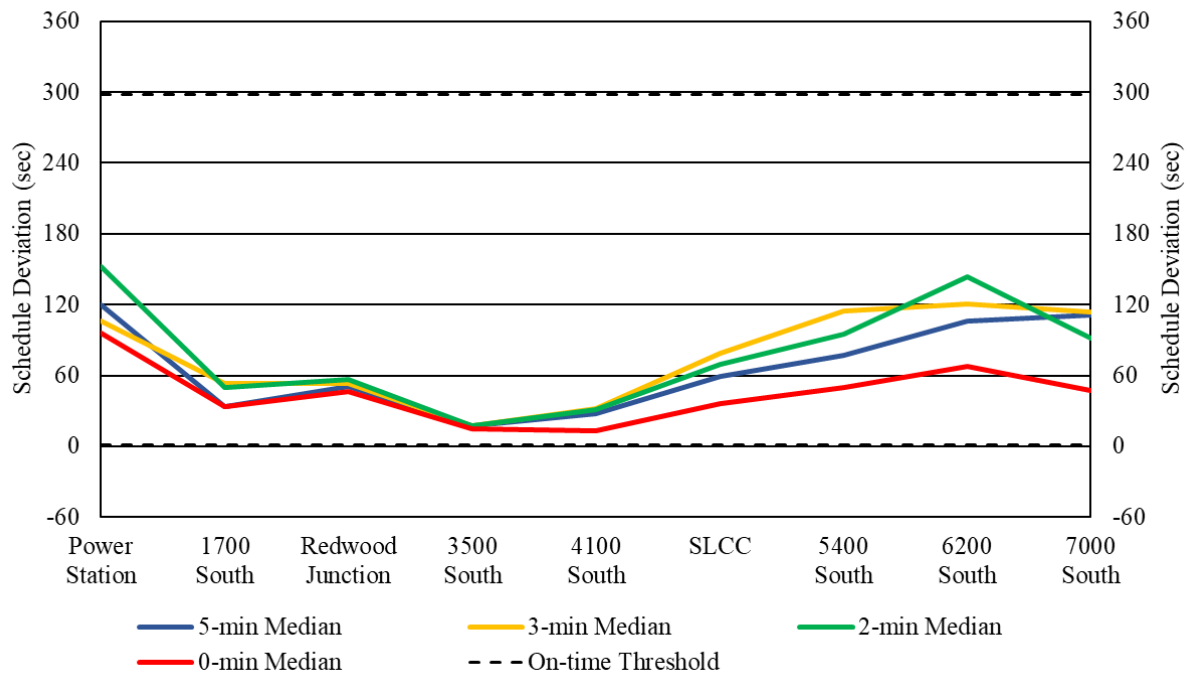


Figure A-41: Route 217 PM NB median schedule deviation.

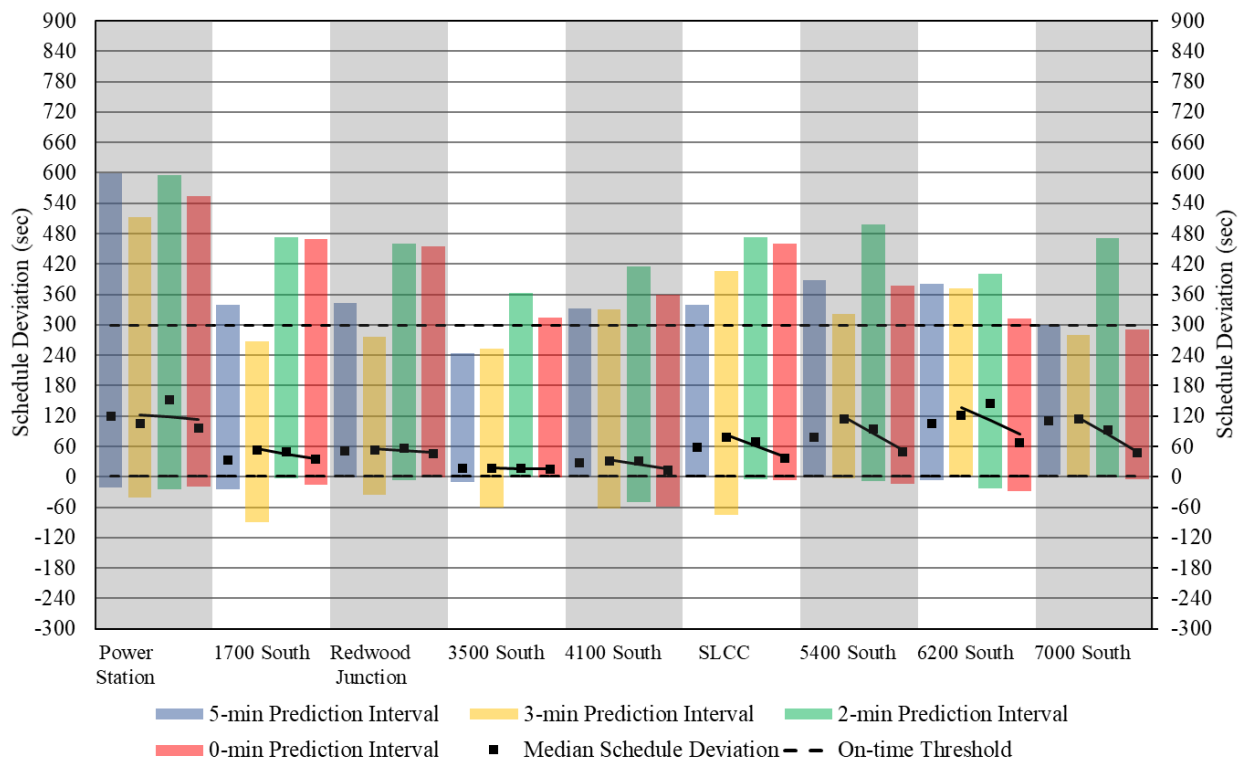


Figure A-42: Route 217 PM NB schedule deviation prediction interval with all thresholds.

A.4 Route 217 PM Schedule Deviation Variability

A.4.1 Route 217 PM SB Schedule Deviation Variability

Table A-5: Route 217 PM SB Schedule Deviation Variability

Timepoint	Mean Residual SD (sec)				% Change in Variability (p-value)		
	5 min	3 min	2 min	0 min	3 min vs 5 min	2 min vs 5 min	0 min vs 5 min
Power Station	106.9	139.0	133.8	111.8	30.1% (0.0990)	25.2% (0.1528)	4.6% (0.7146)
1700 South	130.8	161.2	152.3	152.7	23.2% (0.2617)	16.4% (0.2807)	16.7% (0.297)
Redwood Junction	126.3	169.8	148.7	152.8	34.5% (0.0887)	17.7% (0.2595)	21.0% (0.1983)
3500 South	161.3	171.1	140.1	171.0	6.1% (0.7968)	-13.1% (0.4584)	6.0% (0.7709)
4100 South	156.5	155.0	129.7	118.5	-1.0% (0.9554)	-17.1% (0.3260)	-24.3% (0.2101)
SLCC	151.9	150.2	140.9	103.2	-1.1% (0.9435)	-7.2% (0.6482)	-32.1% (0.0644)
5400 South	128.3	175.8	177.9	133.0	37.1% (0.0608)	38.7% (0.0149)	3.7% (0.8372)
6200 South	129.5	242.5	195.5	178.6	87.3% (<0.0001)	51.0% (0.0006)	37.9% (0.0087)
7000 South	123.6	250.3	210.8	190.8	102.5% (<0.0001)	70.5% (<0.0001)	54.3% (0.0007)
Corridor	138.1	180.7	159.8	147.3	30.8% (<0.0001)	15.7% (0.0031)	6.6% (0.2399)

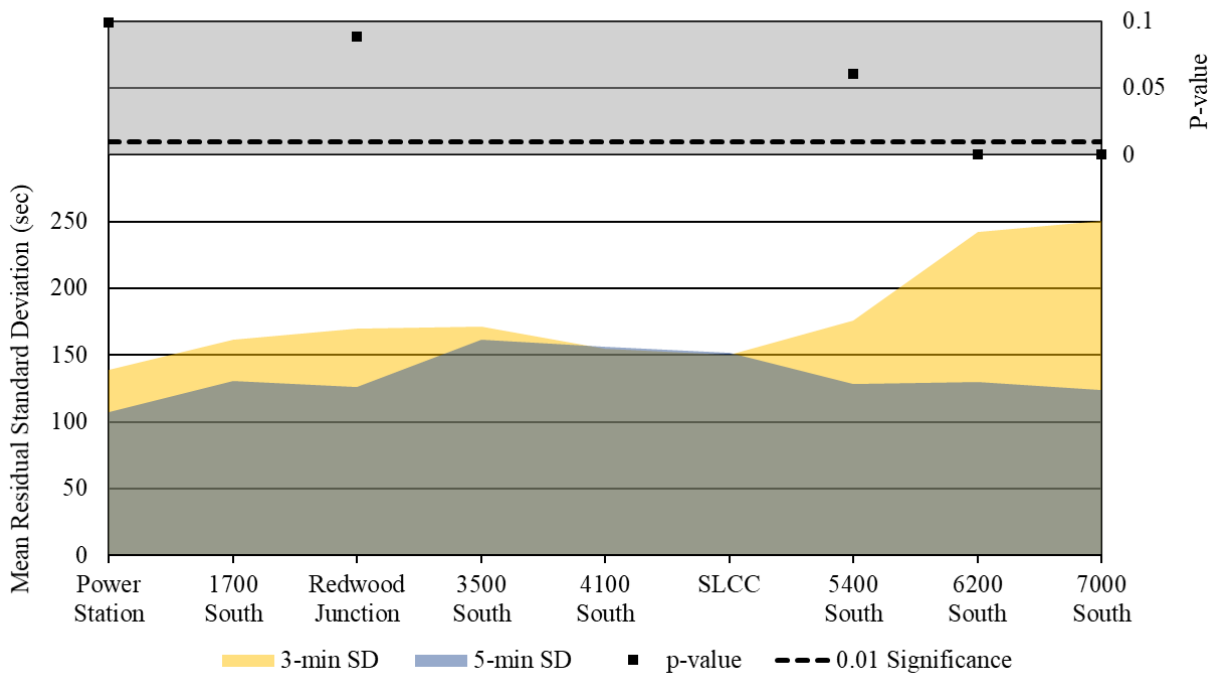


Figure A-43: Route 217 PM SB schedule deviation variability 5-min vs. 3-min (p-value= <0.0001).

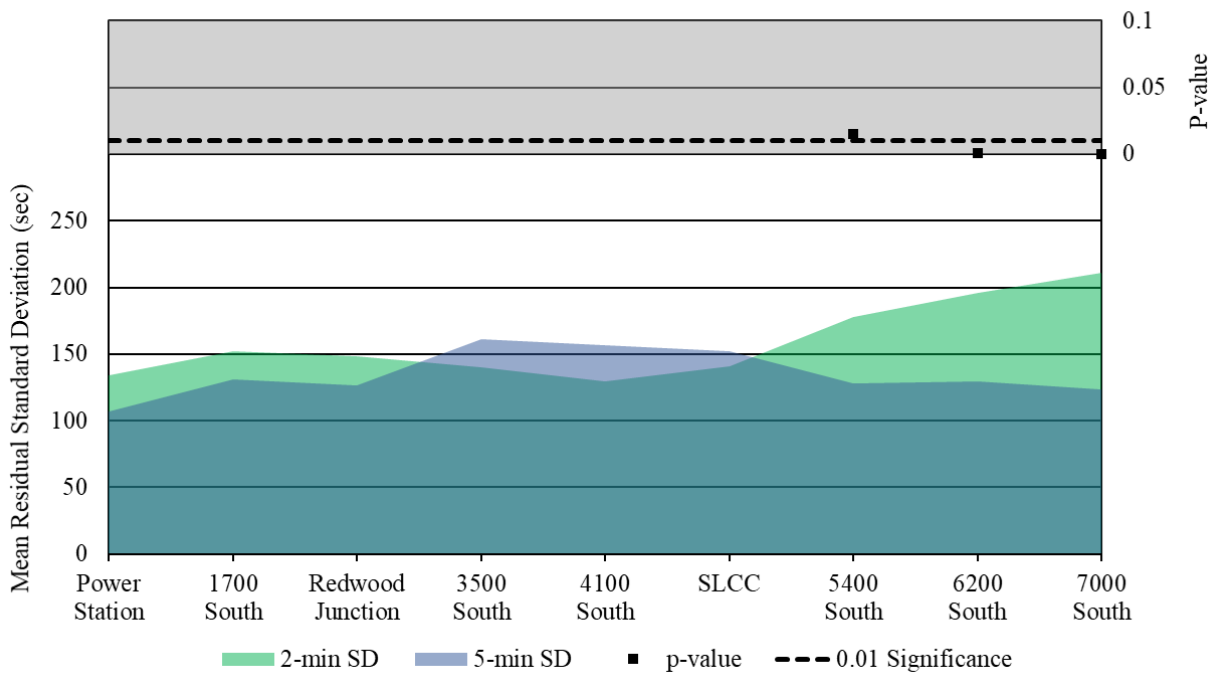


Figure A-44: Route 217 PM SB schedule deviation variability 5-min vs. 2-min (p-value=0.0031).

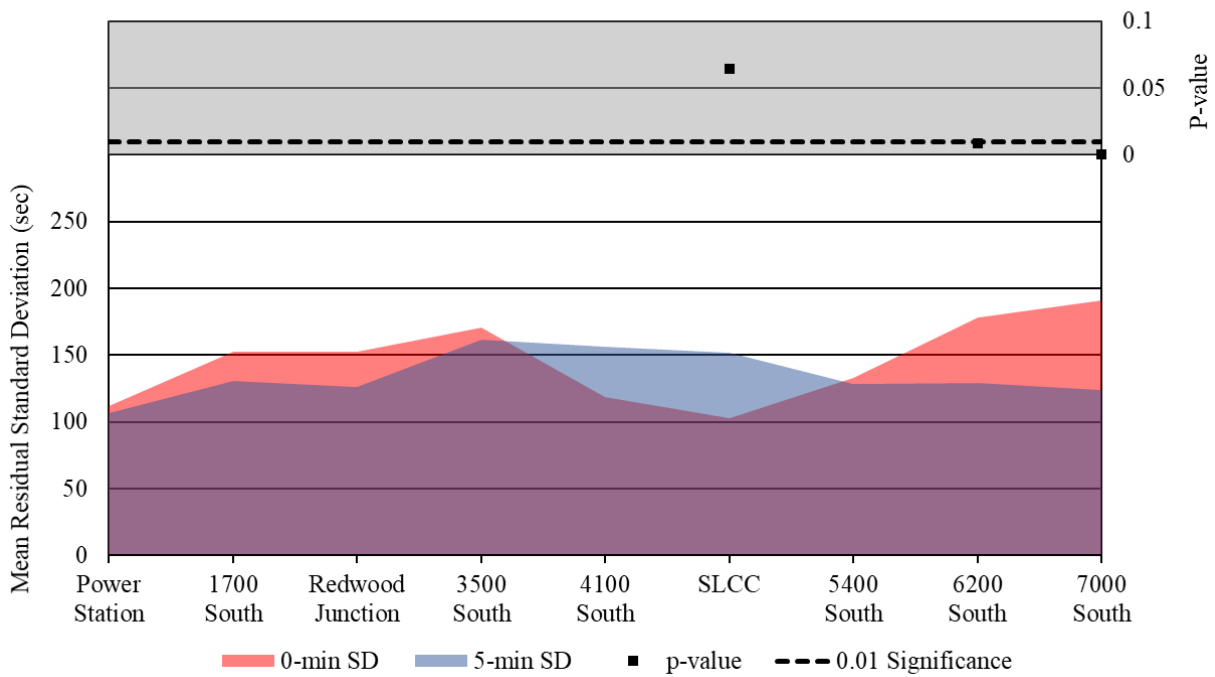


Figure A-45: Route 217 PM SB schedule deviation variability 5-min vs. 0-min (p-value=0.2399).

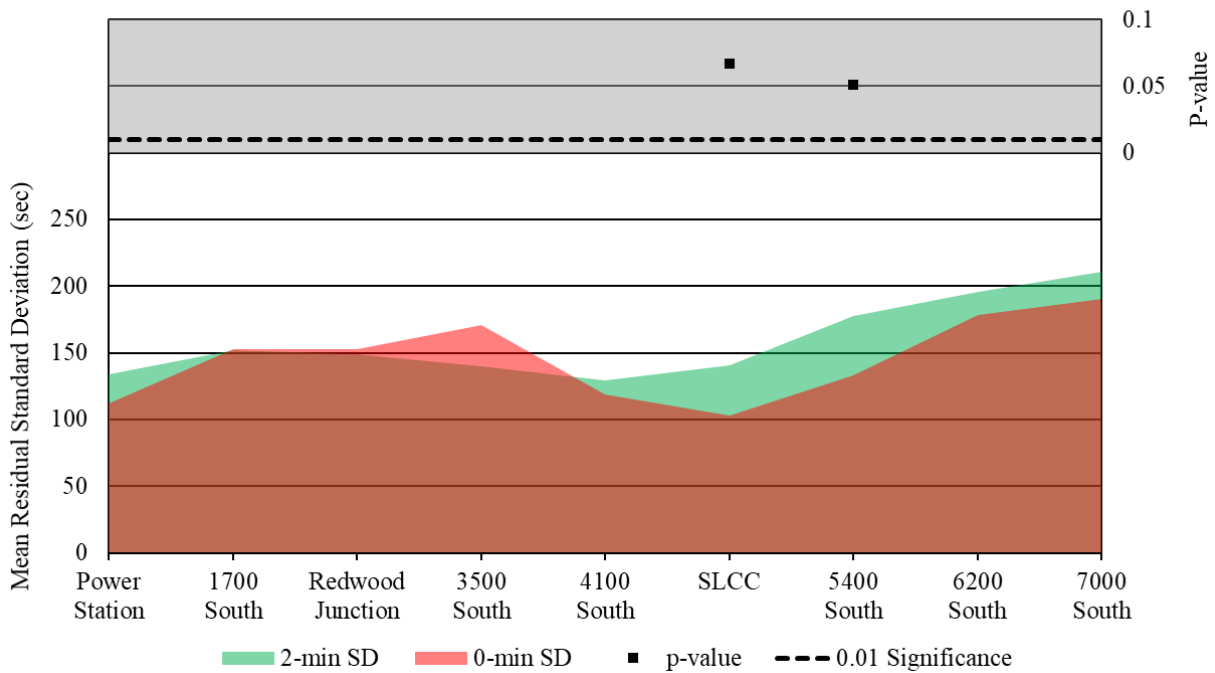


Figure A-46: Route 217 PM SB schedule deviation variability 2-min vs. 0-min (p-value=0.0730).

A.4.2 Route 217 PM NB Schedule Deviation Variability

Table A-6: Route 217 PM NB Schedule Deviation Variability

Timepoint	Mean Residual SD (sec)				% Change in Variability (p-value)		
	5 min	3 min	2 min	0 min	3 min vs 5 min	2 min vs 5 min	0 min vs 5 min
Power Station	134.0	135.2	140.4	122.6	0.9% (0.9517)	4.8% (0.6358)	-8.5% (0.4521)
1700 South	94.5	70.7	117.1	101.1	-25.2% (0.1195)	23.8% (0.2450)	7.0% (0.6965)
Redwood Junction	89.4	64.2	110.3	93.7	-28.2% (0.1519)	23.4% (0.2621)	4.9% (0.8114)
3500 South	62.4	57.0	94.2	80.8	-8.5% (0.5961)	51.1% (0.0782)	29.5% (0.3255)
4100 South	86.6	73.7	107.1	95.9	-14.8% (0.2301)	23.7% (0.3239)	10.8% (0.6476)
SLCC	91.4	101.1	115.8	105.5	10.6% (0.3394)	26.7% (0.2003)	15.5% (0.4630)
5400 South	84.5	82.2	119.7	103.9	-2.8% (0.8152)	41.6% (0.0636)	22.9% (0.3277)
6200 South	73.7	67.3	101.9	91.6	-8.8% (0.4613)	38.1% (0.0786)	24.3% (0.2938)
7000 South	64.3	63.3	91.3	85.0	-1.6% (0.8912)	42.1% (0.0794)	32.2% (0.2349)
Corridor	89.9	84.8	112.1	99.2	-5.8% (0.2432)	24.6% (0.0001)	10.3% (0.1138)

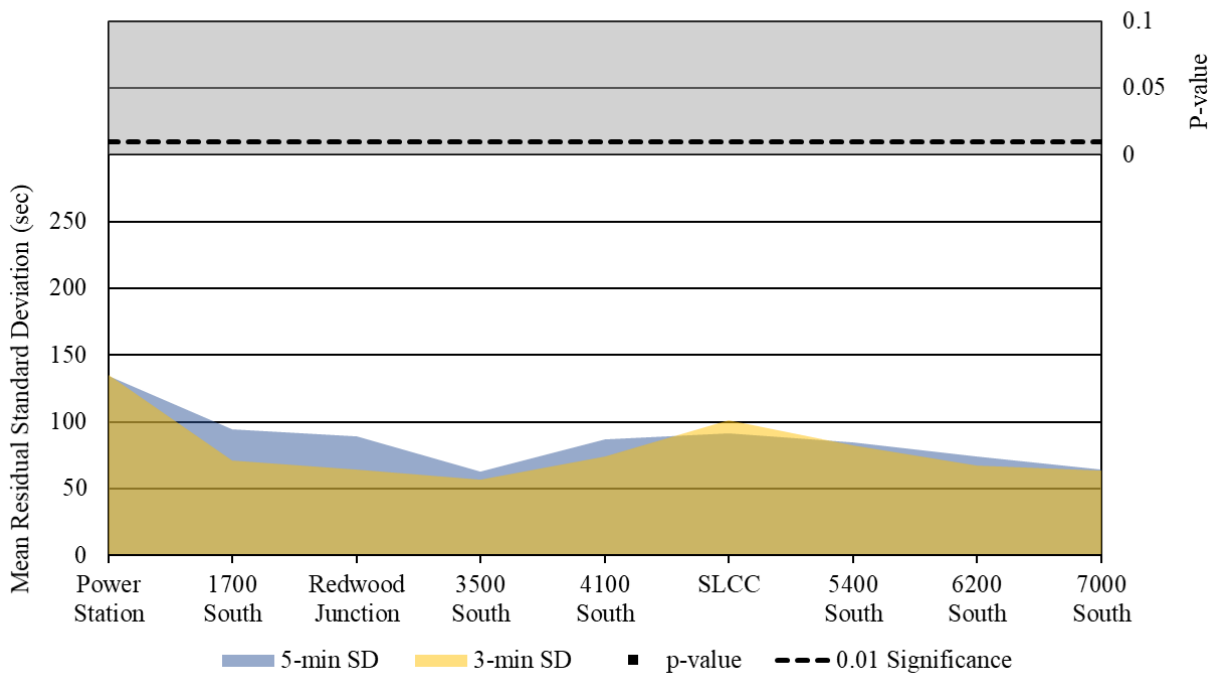


Figure A-47: Route 217 PM NB schedule deviation variability 5-min vs. 3-min (p-value=0.2432).

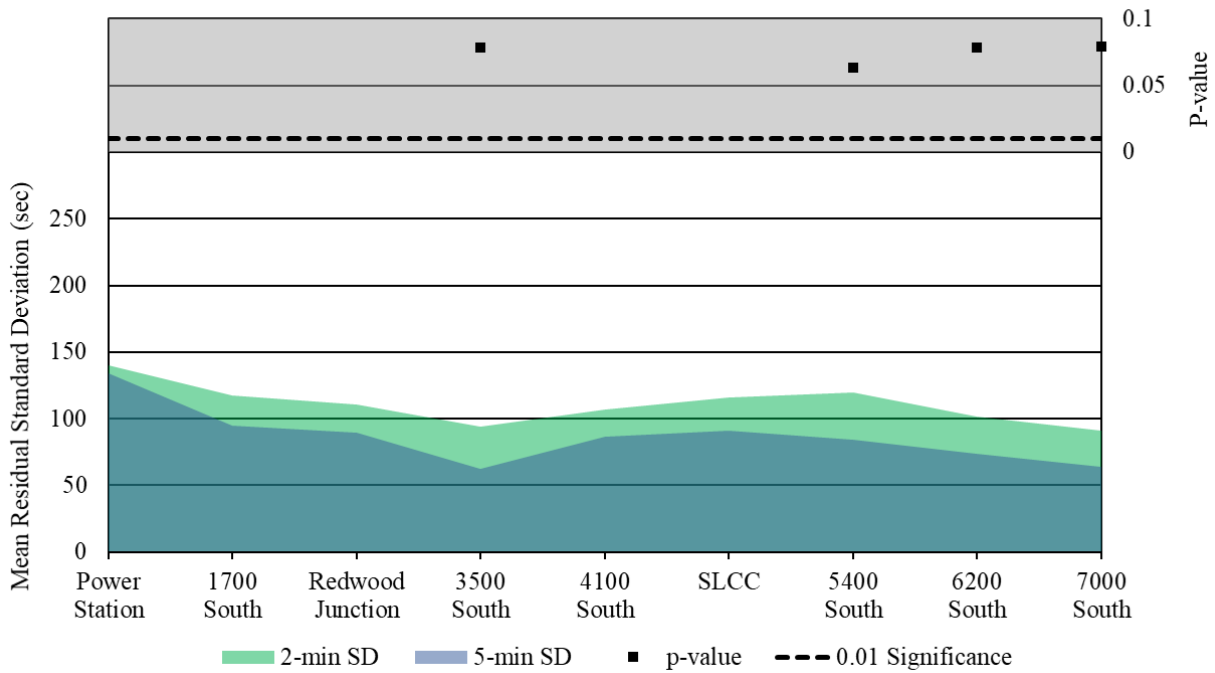


Figure A-48: Route 217 PM NB schedule deviation variability 5-min vs. 2-min (p-value=0.0001).

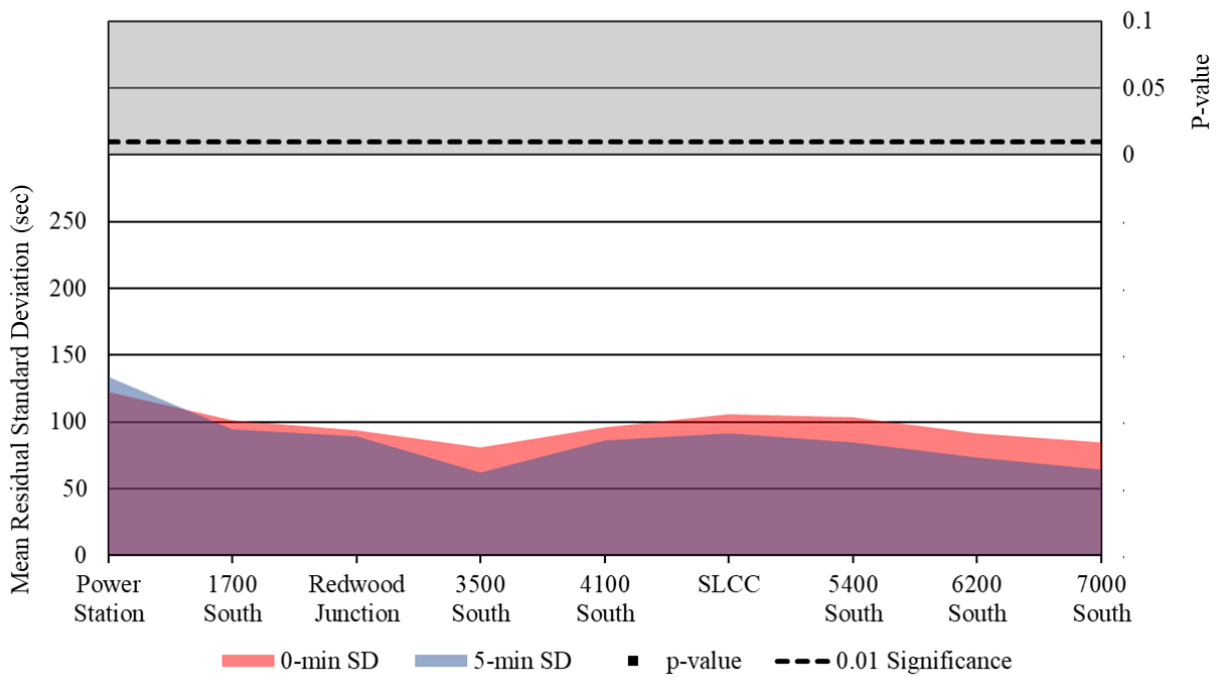


Figure A-49: Route 217 PM NB schedule deviation variability 5-min vs. 0-min (p-value=0.1138).

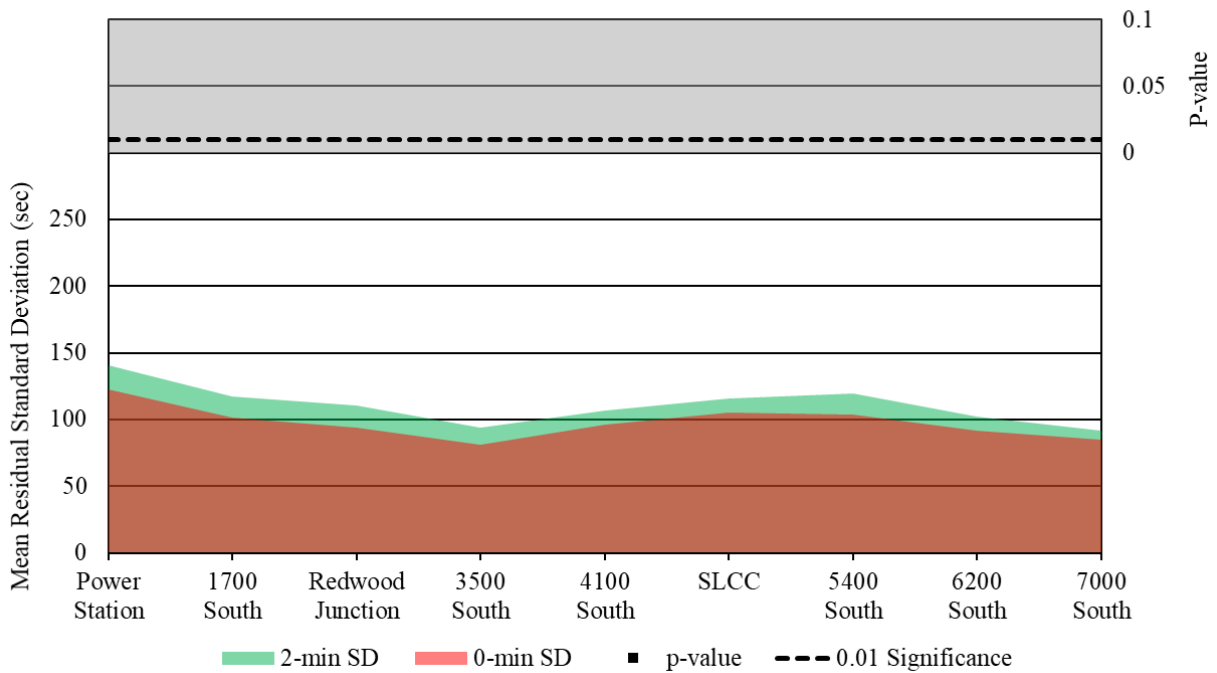


Figure A-50: Route 217 PM NB schedule deviation variability 2-min vs. 0-min (p-value=0.0531).

A.5 Route 217 PM Travel Time 95 Percent Prediction Interval

A.5.1 Route 217 PM SB Travel Time 95 Percent Prediction Interval

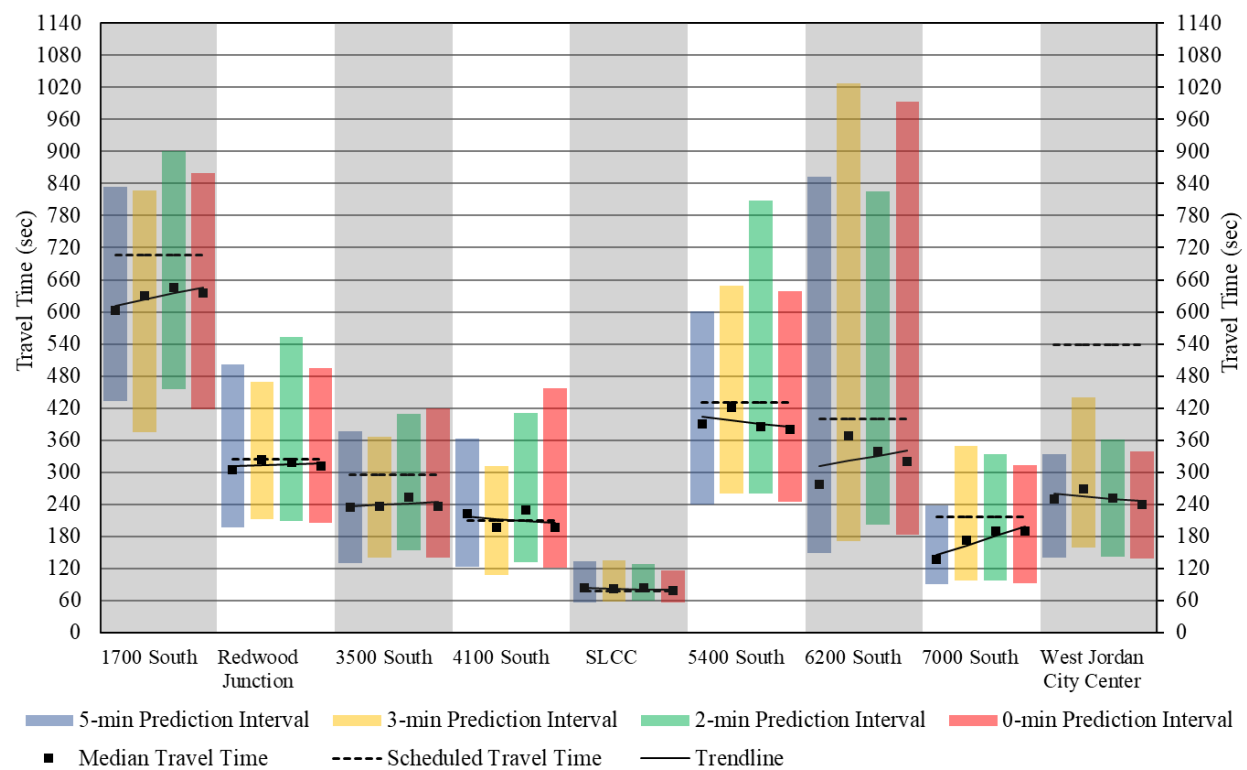


Figure A-51: Route 217 PM SB travel time 95 percent prediction interval.

A.5.2 Route 217 PM NB Travel Time 95 Percent Prediction Interval

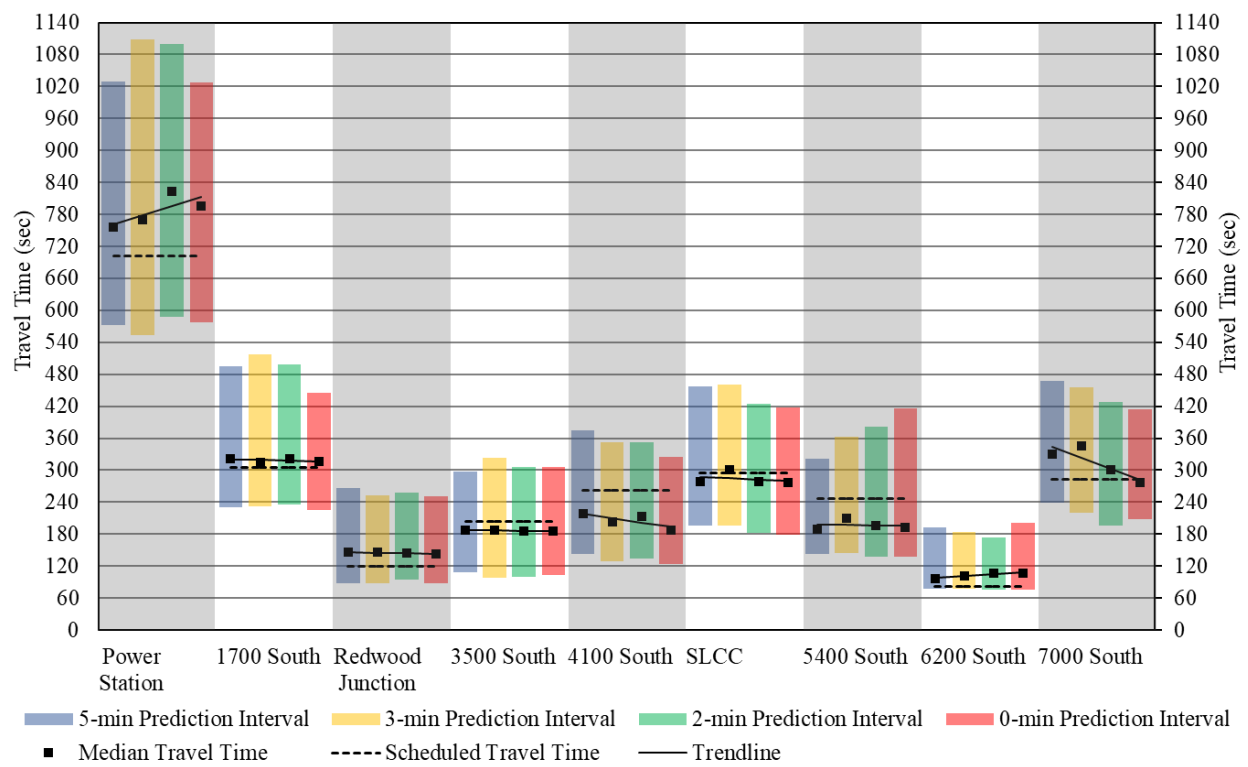


Figure A-52: Route 217 PM NB travel time 95 percent prediction interval.

A.6 Route 217 PM Travel-Time Variability

A.6.1 Route 217 PM SB Travel-Time Variability

Table A-7: Route 217 PM SB Travel-Time Variability

Timepoint	Mean Residual SD (sec)				% Change in Variability (p-value)		
	5 min	3 min	2 min	0 min	3 min vs 5 min	2 min vs 5 min	0 min vs 5 min
1700 South	82.8	102.4	110.2	92.0	23.6% (0.0369)	33.0% (0.0067)	11.1% (0.3204)
Redwood Junction	68.7	63.3	76.4	68.4	-7.8% (0.5873)	11.2% (0.4157)	-0.4% (0.9709)
3500 South	60.6	61.5	61.9	64.4	1.5% (0.9007)	2.1% (0.8085)	6.3% (0.5760)
4100 South	58.0	54.1	64.8	66.6	-6.7% (0.4745)	11.8% (0.1964)	14.8% (0.3003)
SLCC	20.7	20.9	20.1	15.8	0.8% (0.9666)	-2.7% (0.8059)	-23.5% (0.0113)
5400 South	74.2	80.1	111.7	82.1	7.9% (0.5704)	50.5% (0.0057)	10.6% (0.4083)
6200 South	167.1	189.3	122.6	137.5	13.2% (0.3321)	-26.7% (0.0031)	-17.8% (0.0900)
7000 South	48.8	60.8	59.0	53.7	24.5% (0.0180)	20.8% (0.0080)	10.0% (0.2172)
West Jordan City Center	49.5	64.6	50.4	51.2	30.5% (0.0997)	1.8% (0.8461)	3.3% (0.7863)

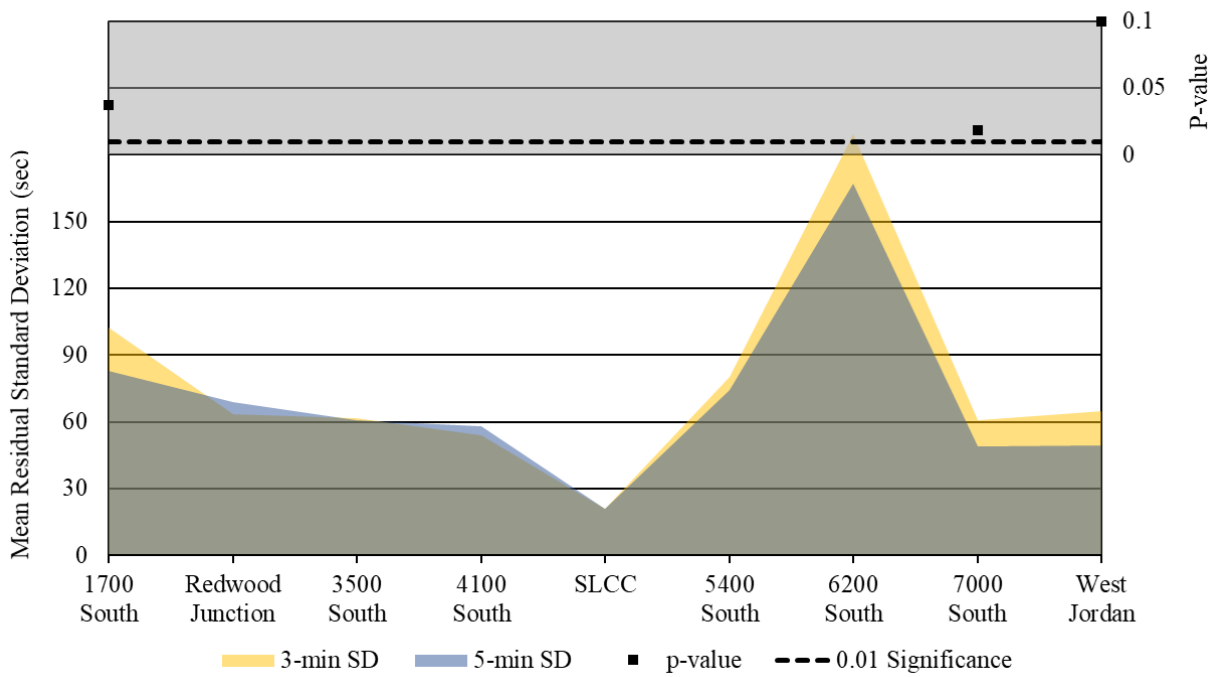


Figure A-53: Route 217 PM SB travel-time variability 5-min vs. 3-min.

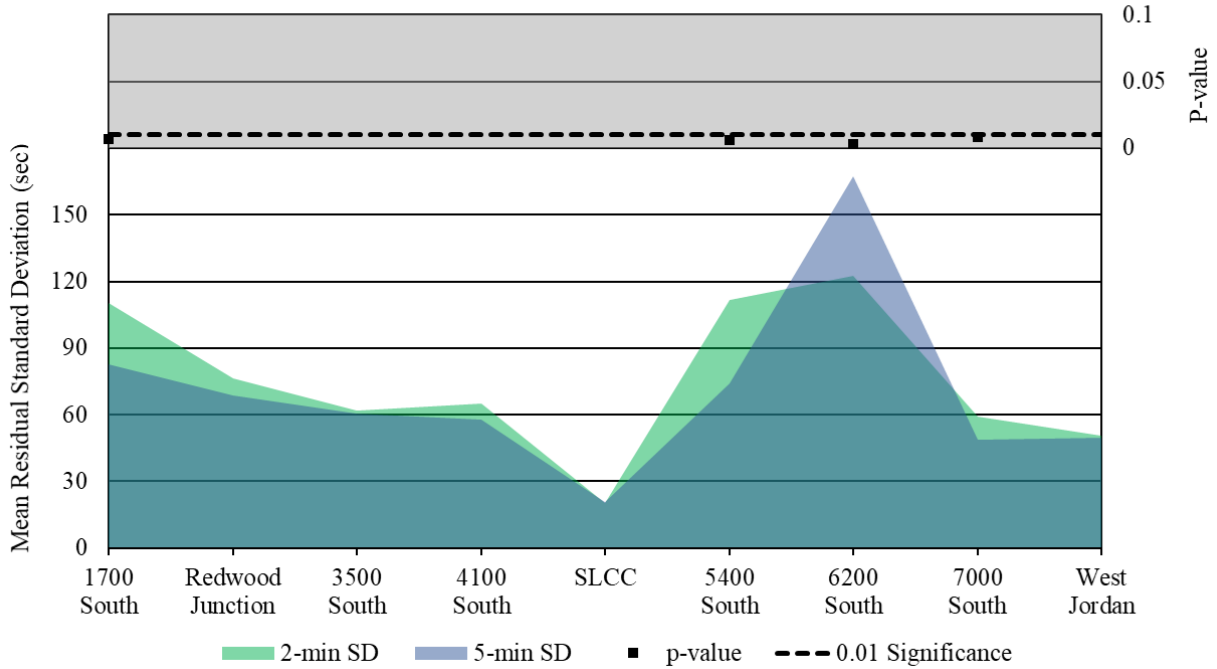


Figure A-54: Route 217 PM SB travel-time variability 5-min vs. 2-min.

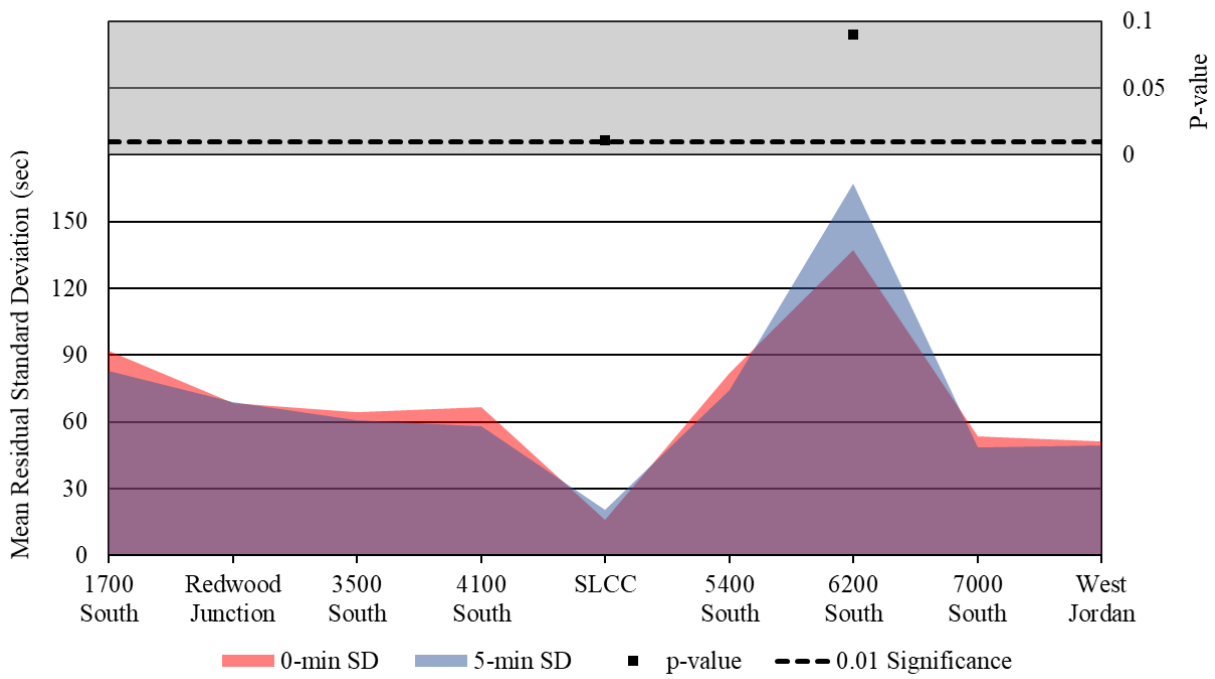


Figure A-55: Route 217 PM SB travel-time variability 5-min vs. 2-min.

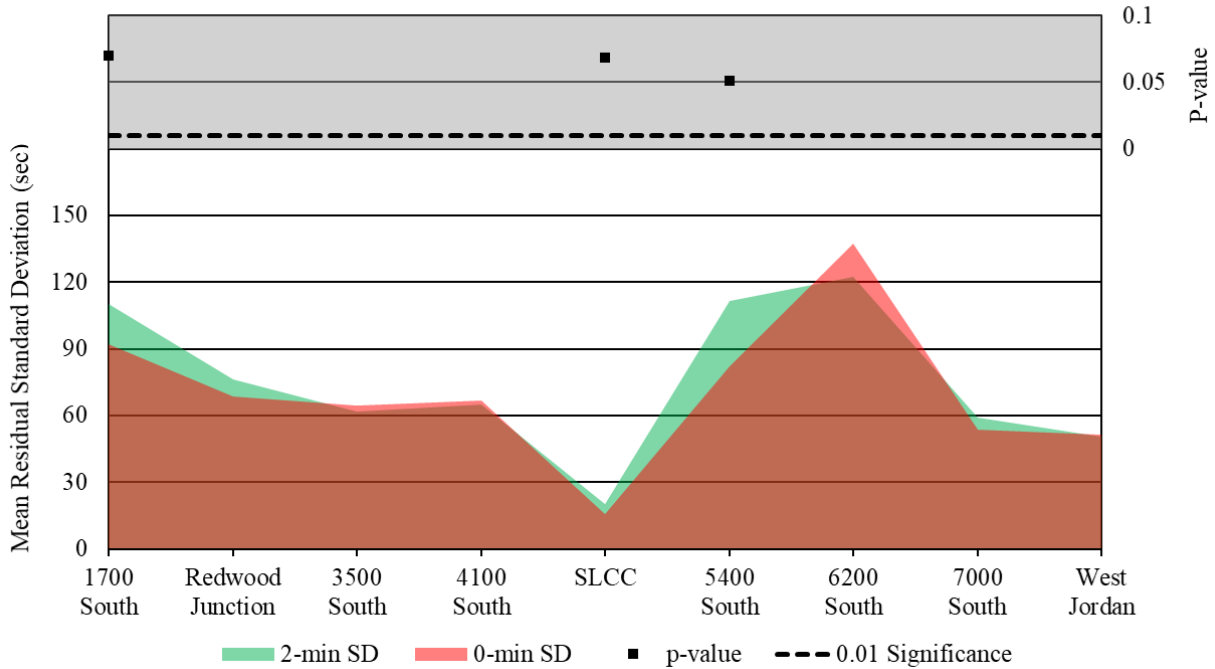


Figure A-56: Route 217 PM SB travel-time variability 2-min vs. 0-min.

A.6.2 Route 217 PM NB Travel-Time Variability

Table A-8: Route 217 PM NB Travel-time variability

Timepoint	Mean Residual SD (sec)				% Change in Variability (p-value)		
	5 min	3 min	2 min	0 min	3 min vs 5 min	2 min vs 5 min	0 min vs 5 min
Power Station	102.2	124.3	120.0	114.5	21.6% (0.0615)	17.4% (0.0488)	12.0% (0.1833)
1700 South	68.7	65.9	67.1	55.2	-4.1% (0.6697)	-2.4% (0.7566)	-19.6% (0.0284)
Redwood Junction	37.0	36.9	40.9	36.5	-0.4% (0.9607)	10.4% (0.3974)	-1.4% (0.9065)
3500 South	44.8	44.7	48.2	45.6	-0.2% (0.9635)	7.7% (0.4209)	1.8% (0.8653)
4100 South	60.8	54.0	56.2	50.0	-11.2% (0.2910)	-7.6% (0.3534)	-17.7% (0.0517)
SLCC	62.1	60.6	61.4	55.0	-2.4% (0.8189)	-1.2% (0.9022)	-11.5% (0.2444)
5400 South	54.7	66.2	64.8	66.7	21% (0.0403)	18.5% (0.0370)	21.9% (0.0192)
6200 South	30.2	28.3	27.9	29.7	-6.1% (0.6454)	-7.5% (0.4462)	-1.5% (0.9011)
7000 South	51.3	53.0	53.7	48.1	3.3% (0.7519)	4.8% (0.5287)	-6.1% (0.4839)

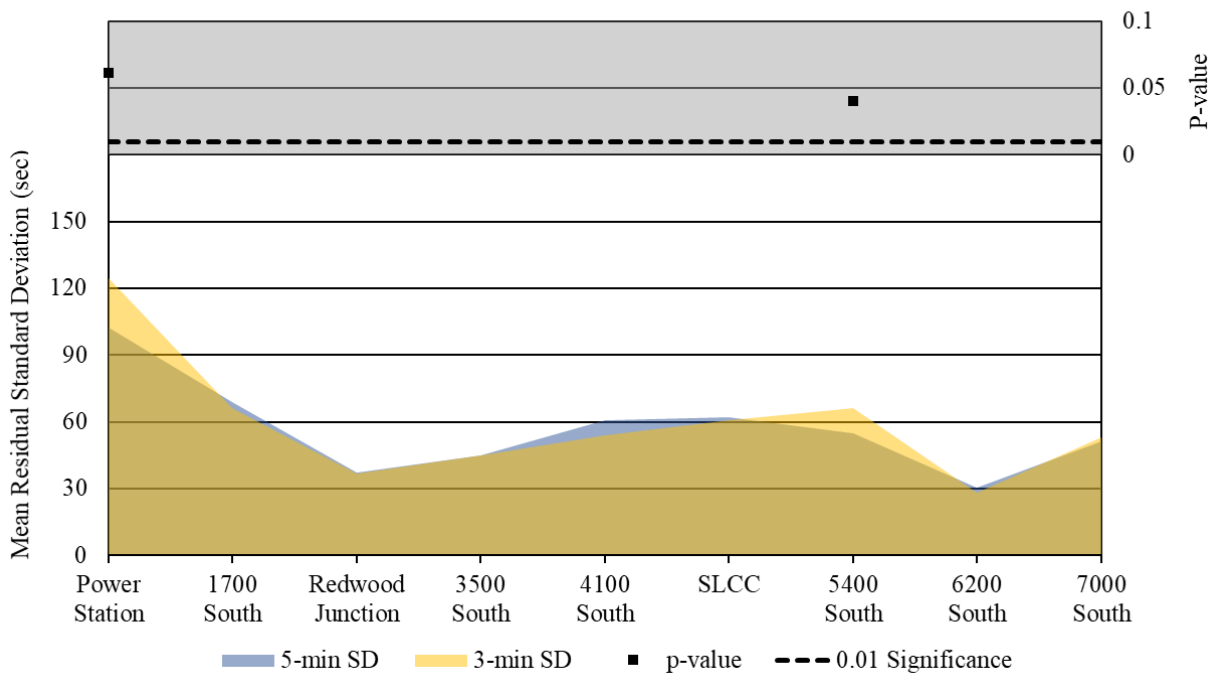


Figure A-57: Route 217 PM NB travel-time variability 5-min vs. 3-min.

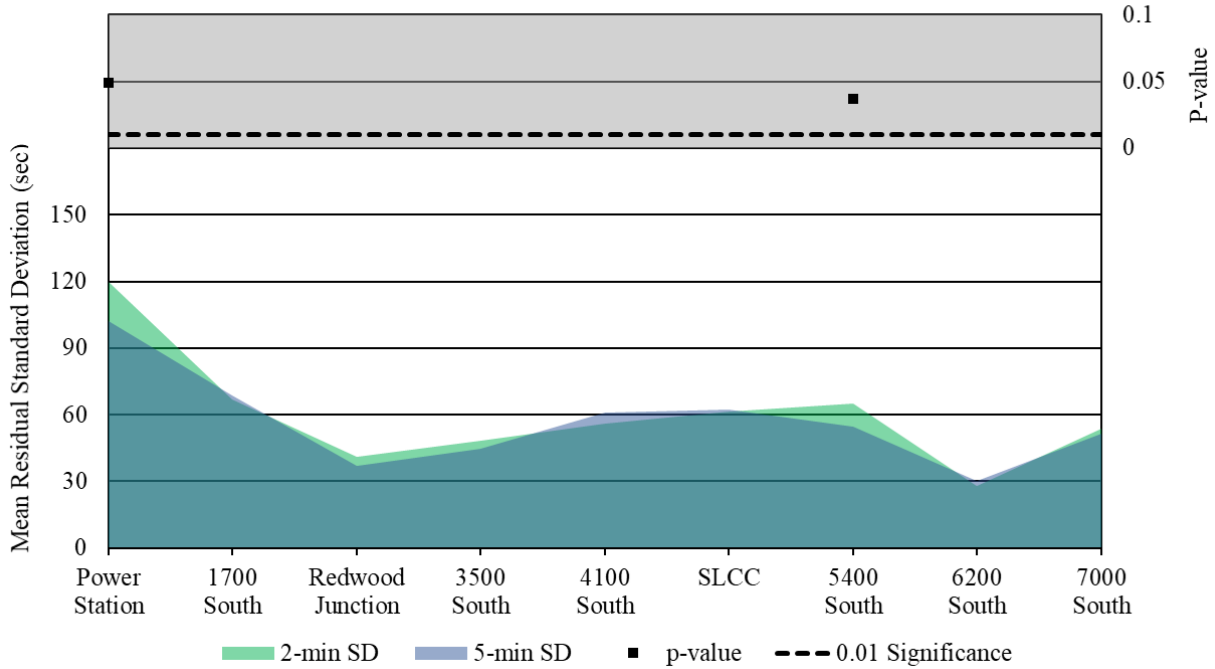


Figure A-58: Route 217 PM NB travel-time variability 5-min vs. 2-min.

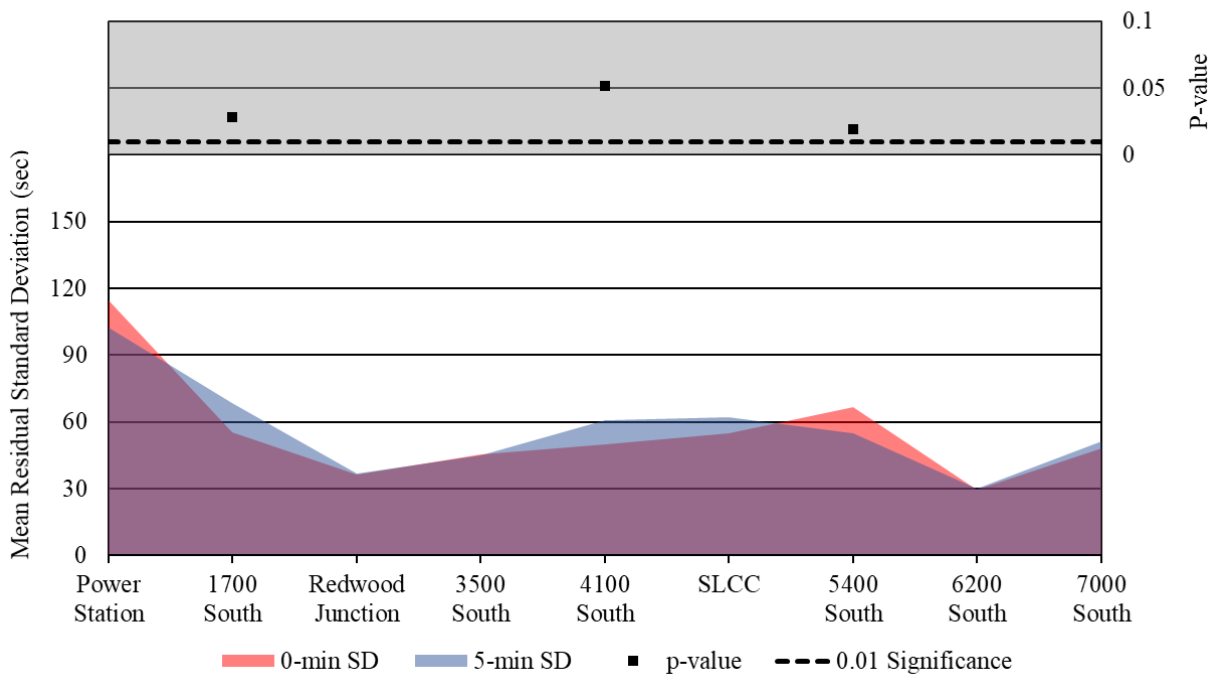


Figure A-59: Route 217 PM NB travel-time variability 5-min vs. 0-min.

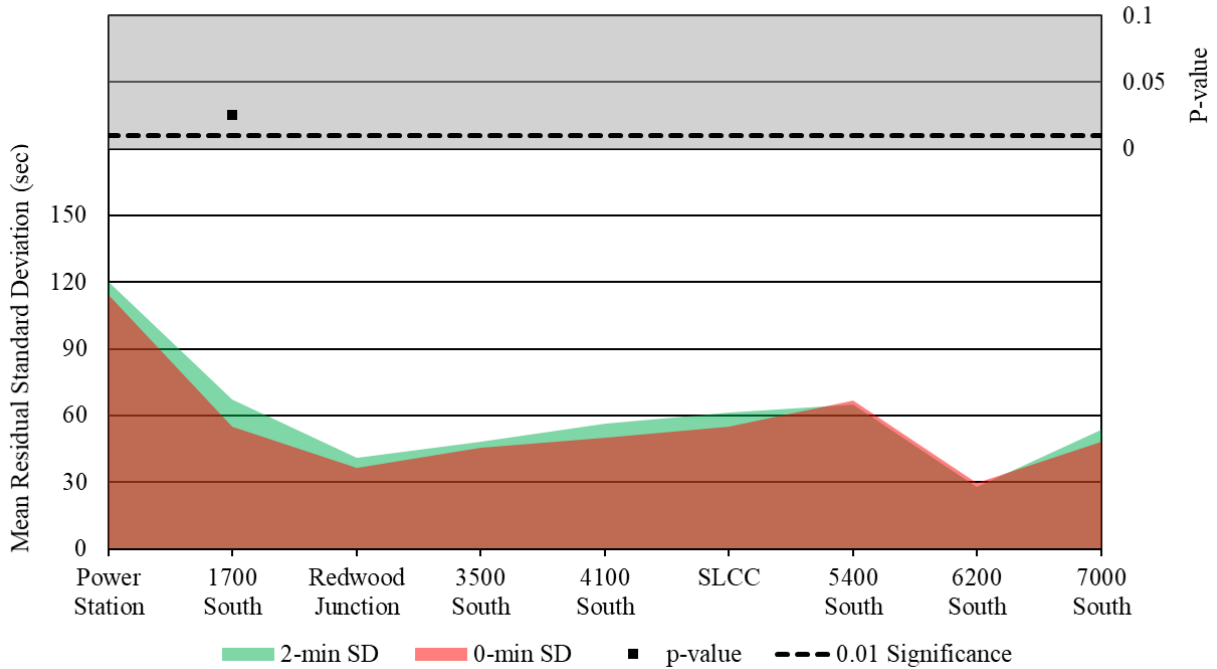


Figure A-60: Route 217 PM NB travel-time variability 2-min vs. 0-min.

APPENDIX B. UVX

Unless otherwise specified, all p-values contained in the appendix are the result of a two-sided t-test.

B.1 UVX Travel-Time Distribution

B.1.1 UVX SB Travel-Time Distribution

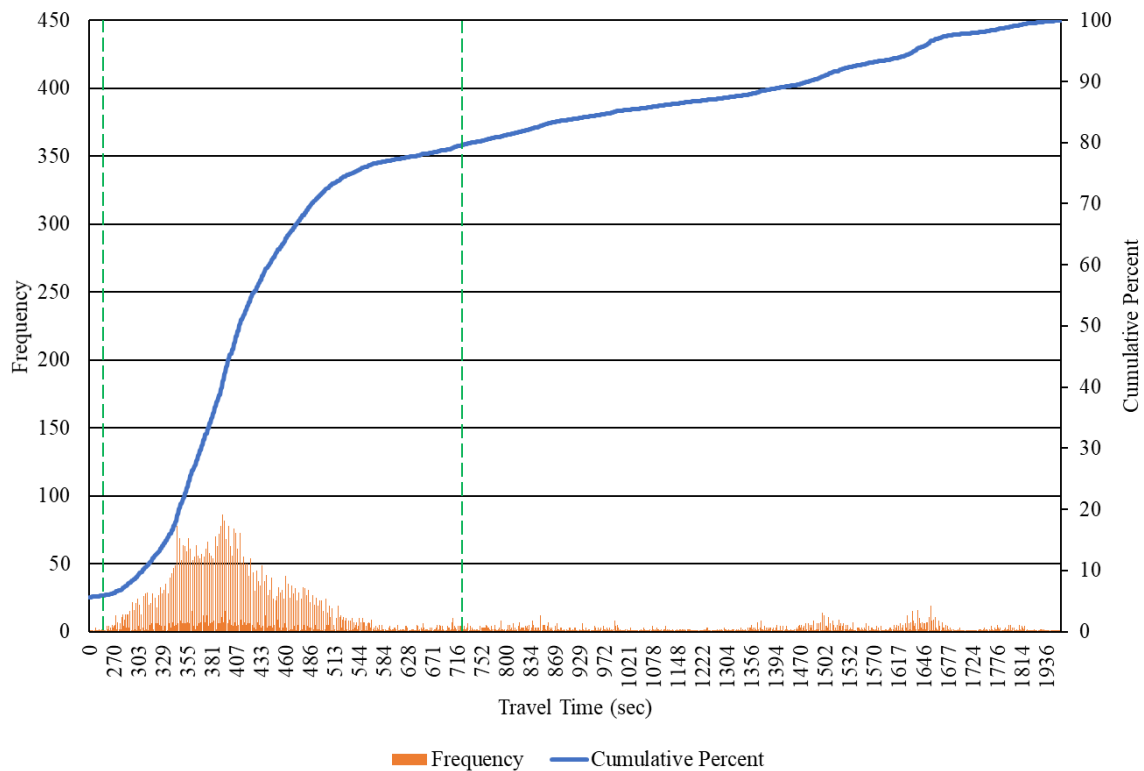


Figure B-1: UVX SB UVU Campus travel-time distribution.

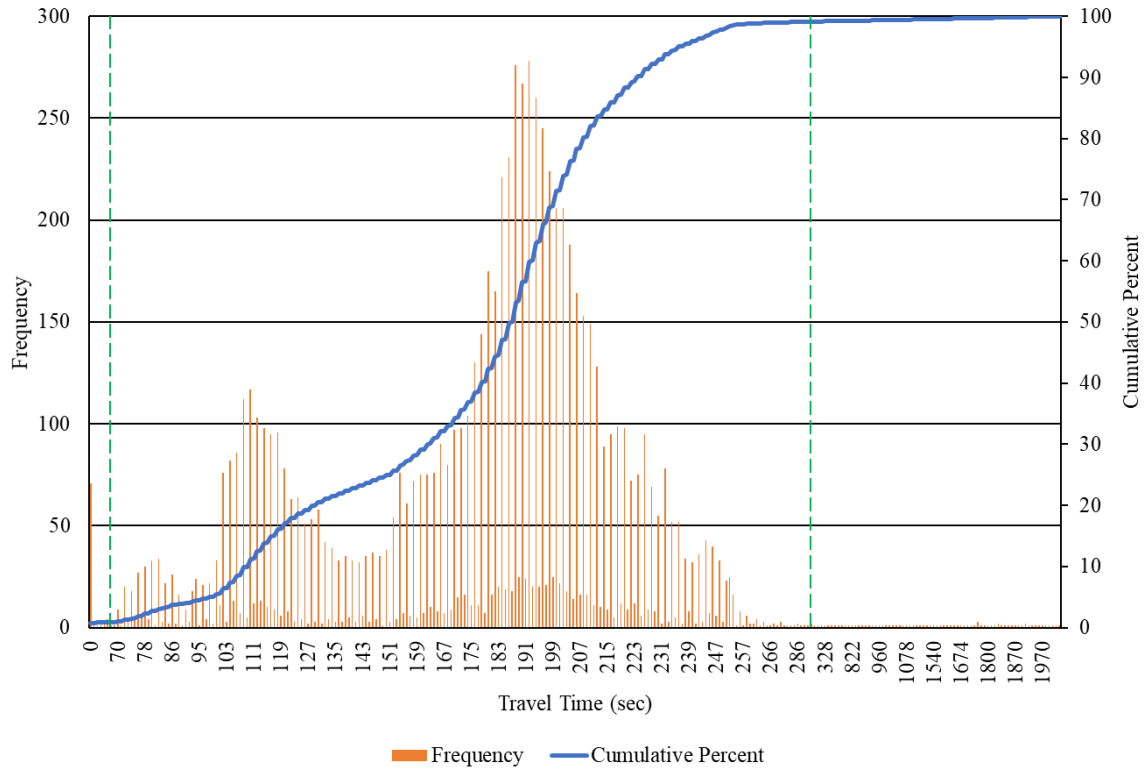


Figure B-2: UVX SB Lakeview travel-time distribution.

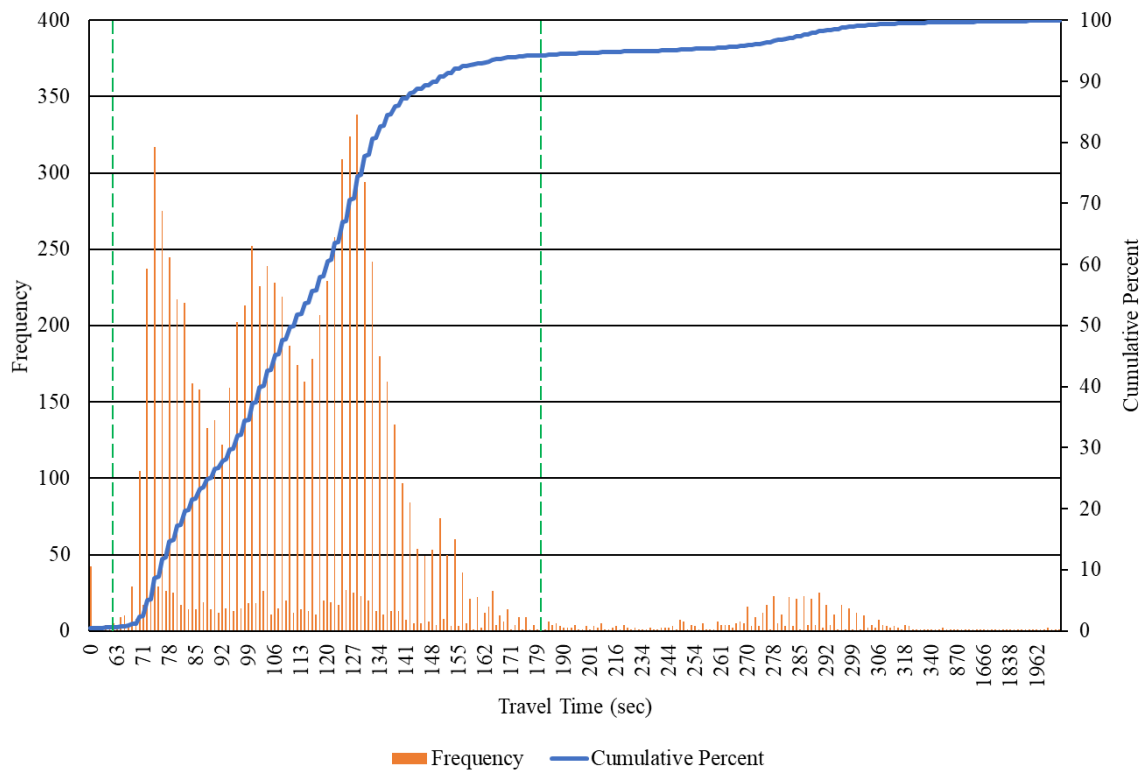


Figure B-3: UVX SB Main Street travel-time distribution.

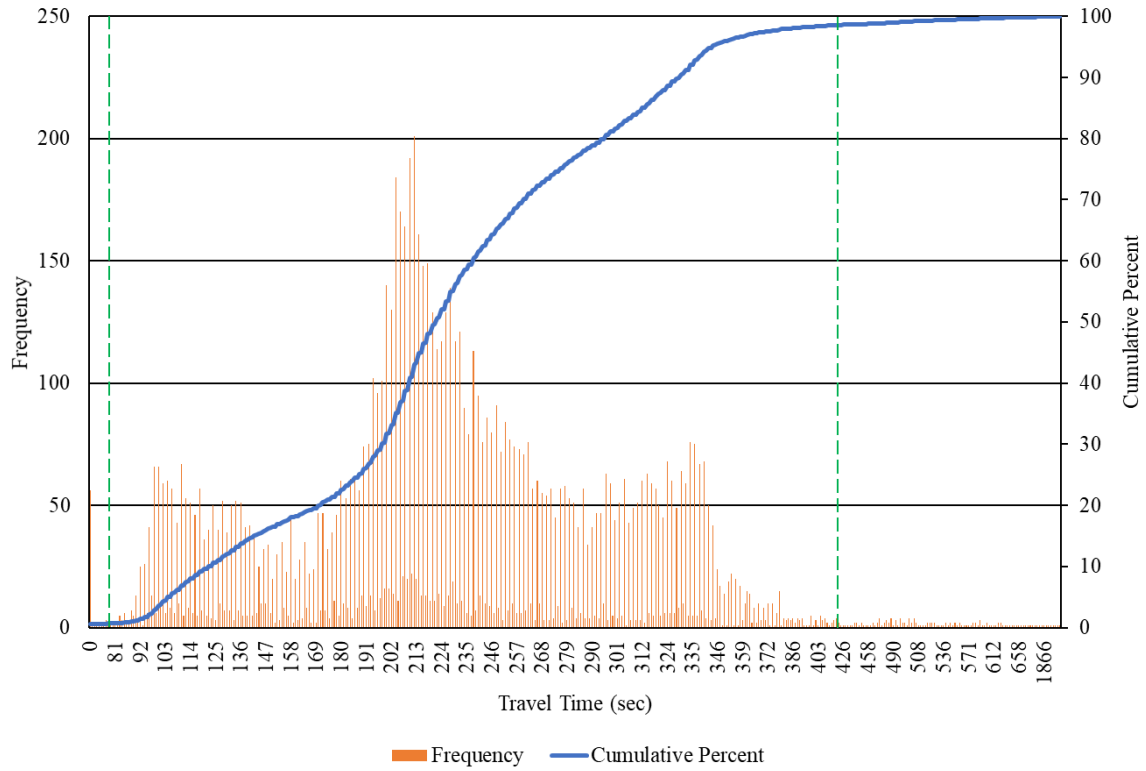


Figure B-4: UVX SB University Place travel-time distribution.

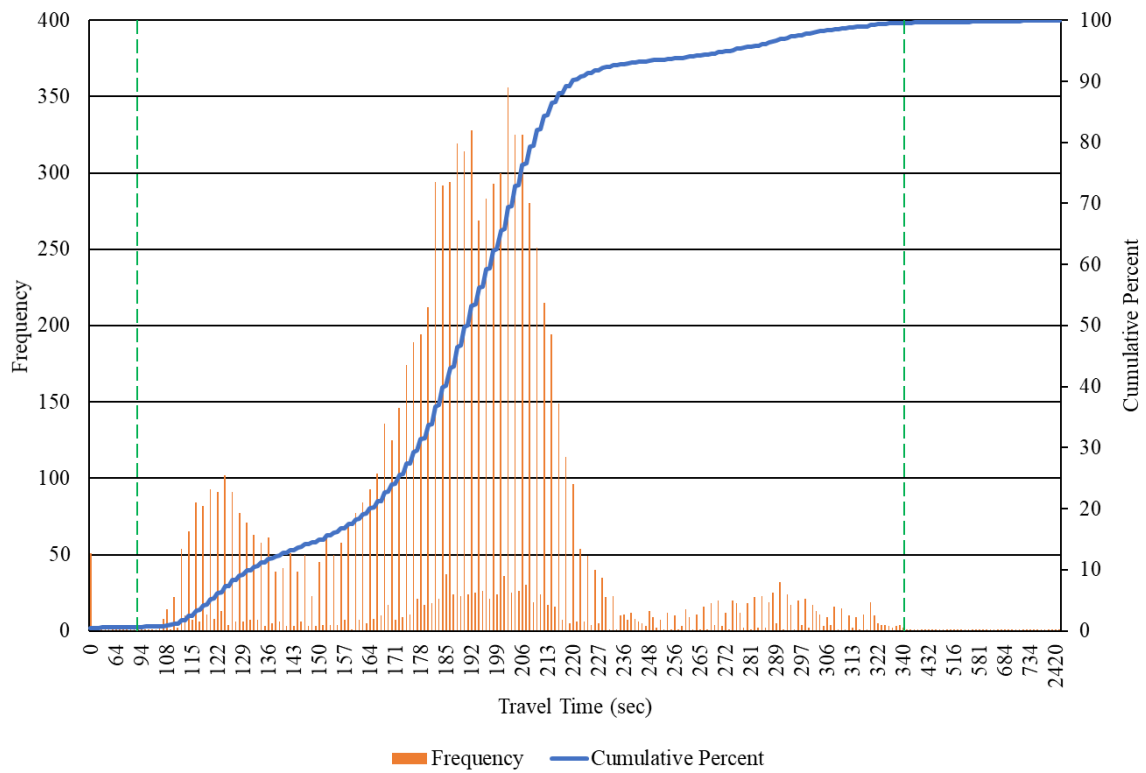


Figure B-5: UVX SB 2230 North travel-time distribution.

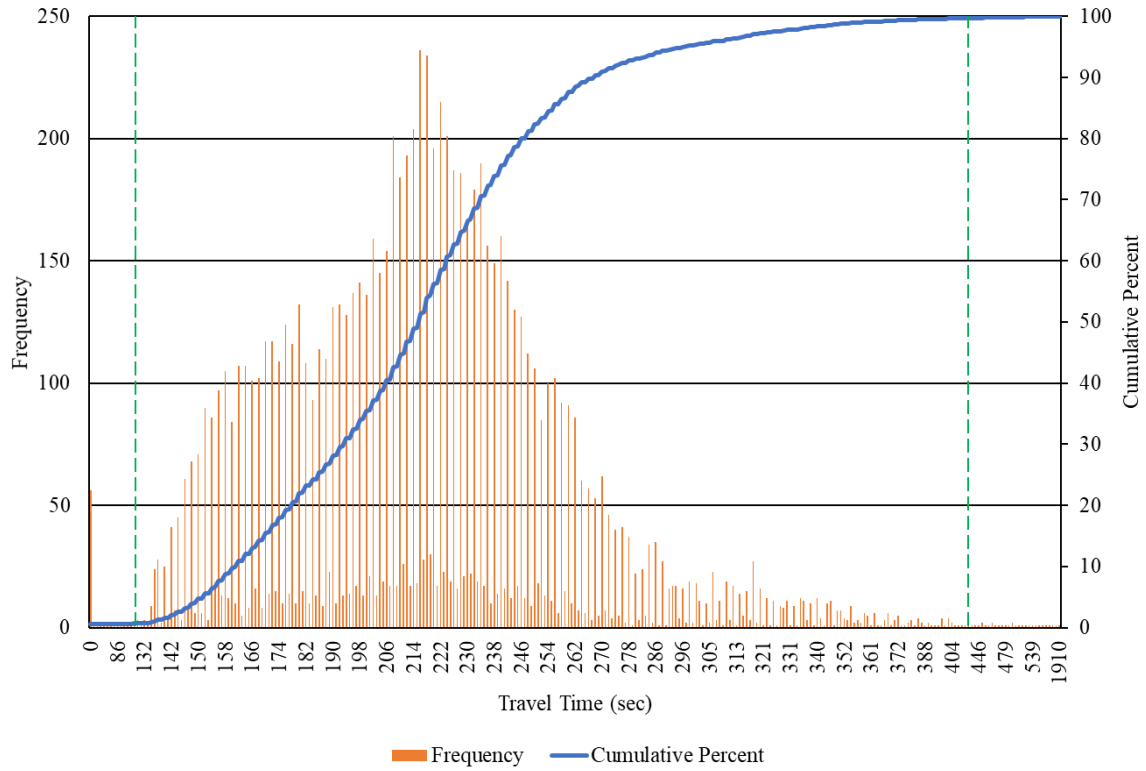


Figure B-6: UVX SB BYU Stadium travel-time distribution.

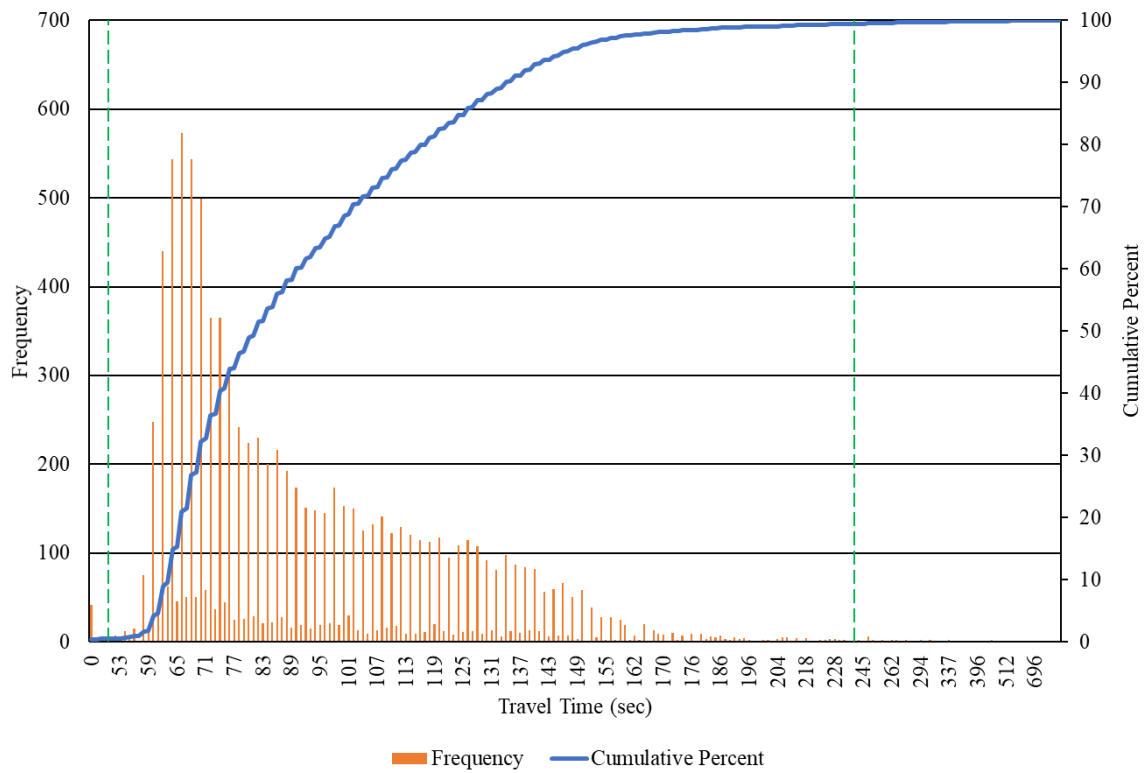


Figure B-7: UVX SB BYU North travel-time distribution.

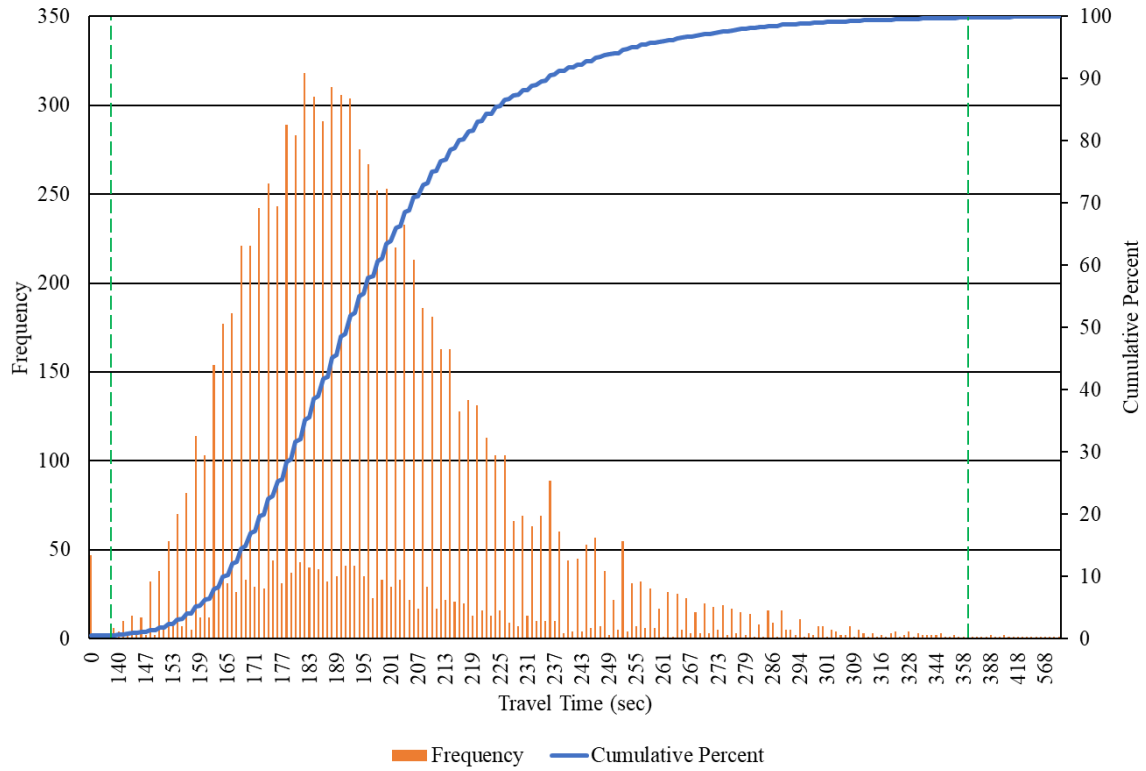


Figure B-8: UVX SB BYU Campus travel-time distribution.

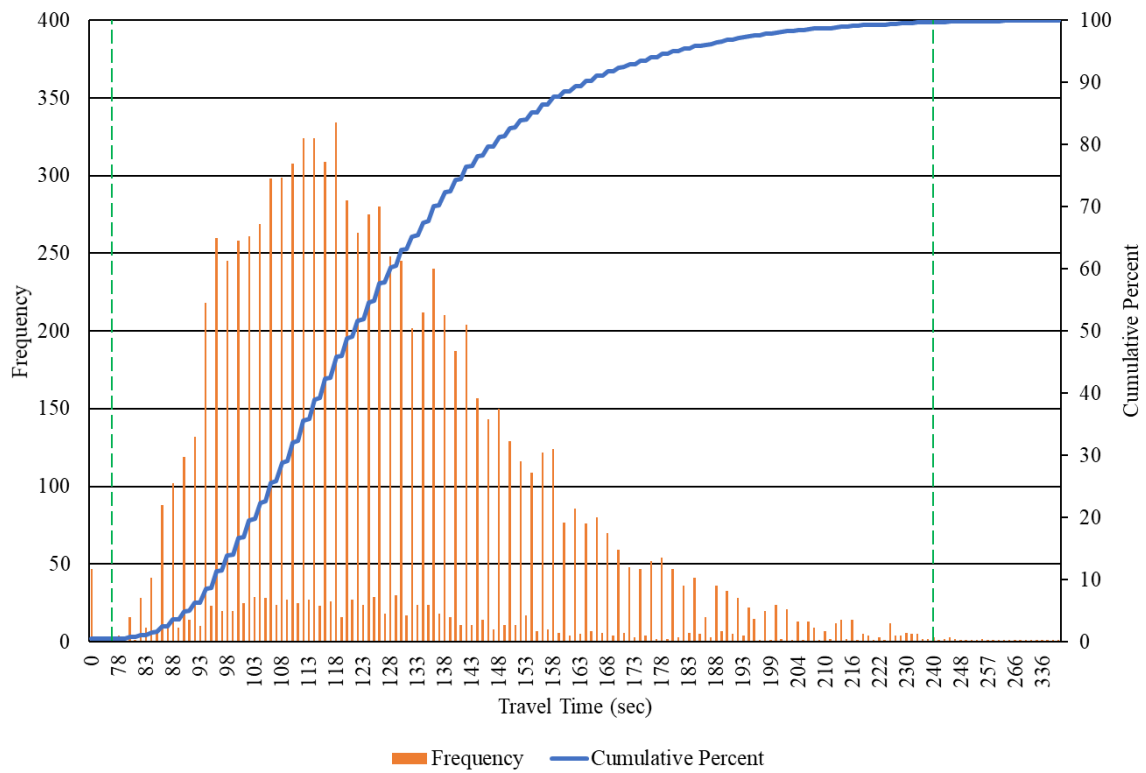


Figure B-9: UVX SB Joaquin travel-time distribution.

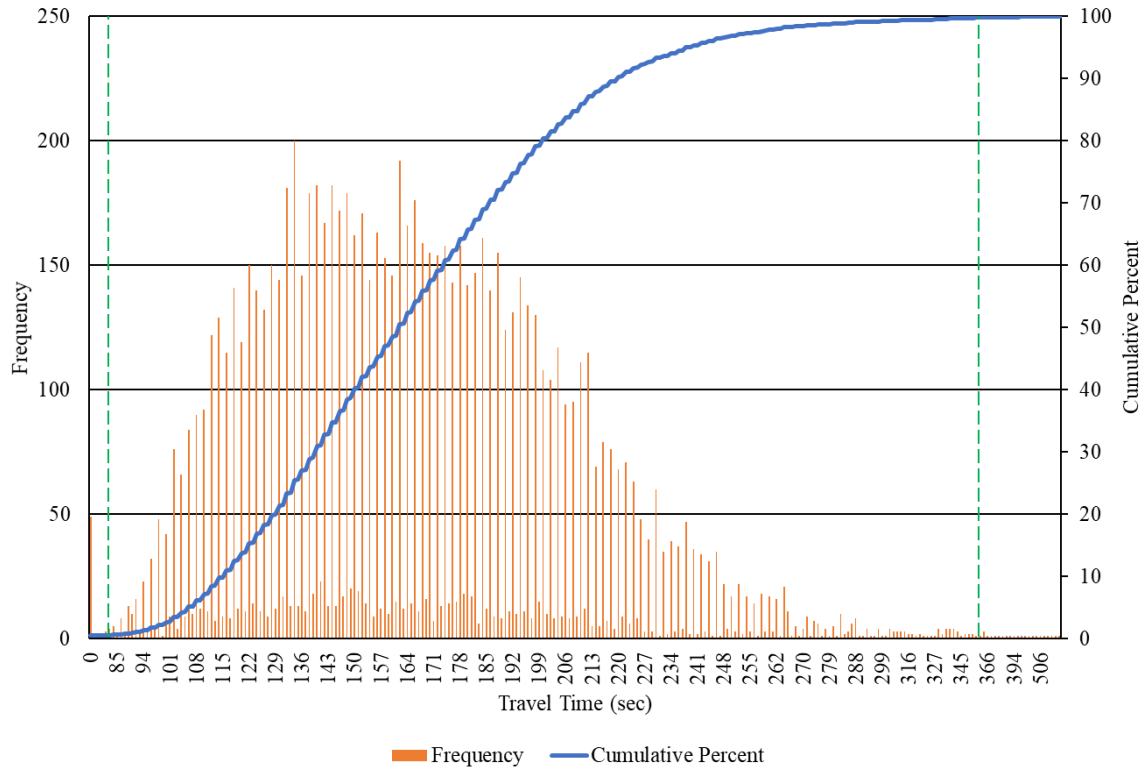


Figure B-10: UVX SB Academy Square travel-time distribution.

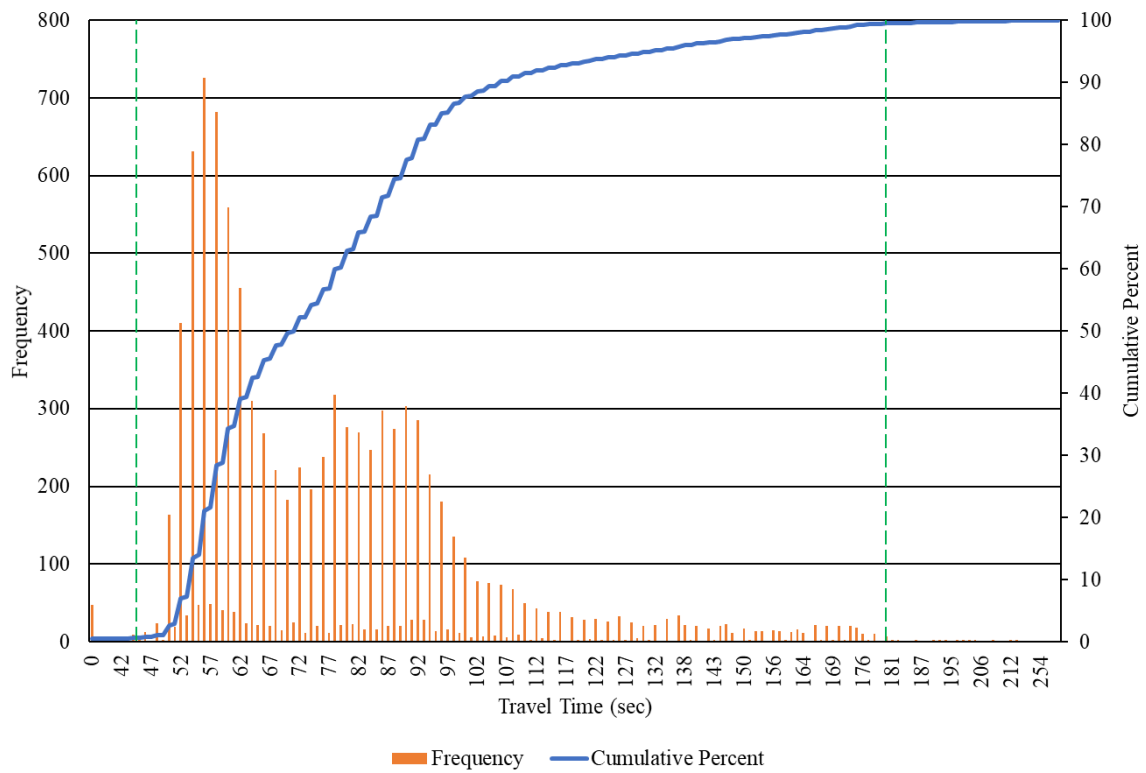


Figure B-11: UVX SB 300 North travel-time distribution.

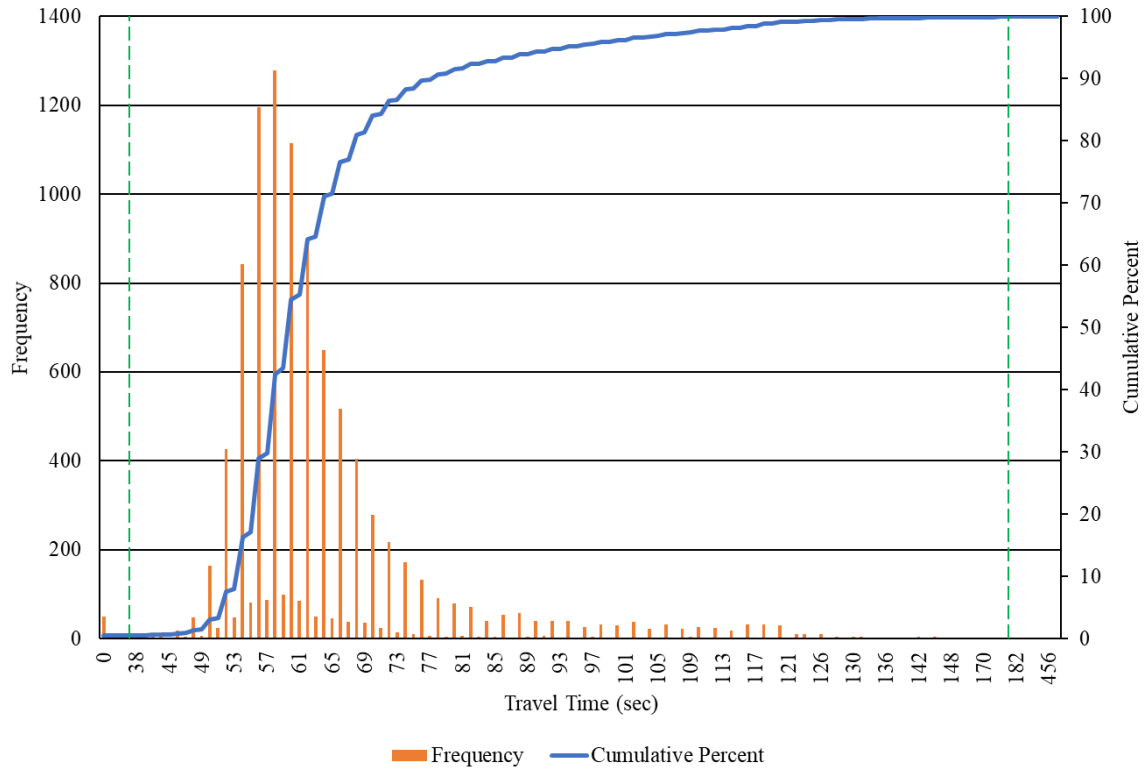


Figure B-12: UVX SB Center Street travel-time distribution.

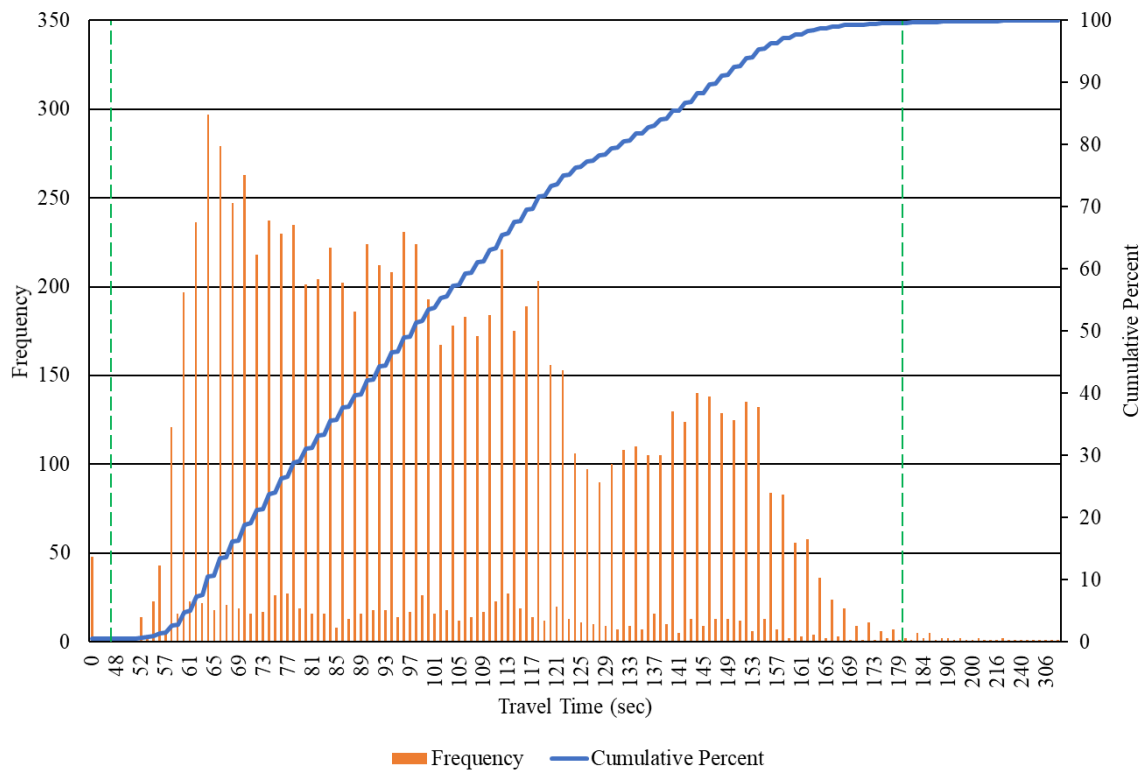


Figure B-13: UVX SB 400 South travel-time distribution.

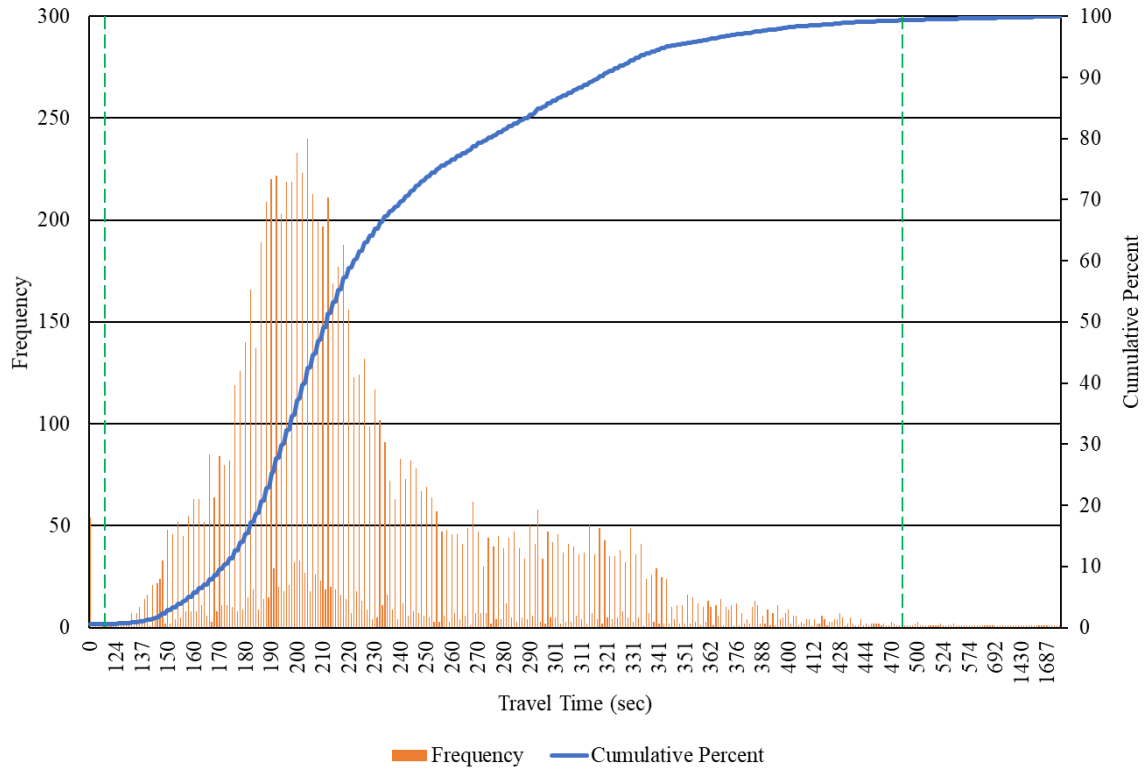


Figure B-14: UVX SB Provo Central-1 travel-time distribution.

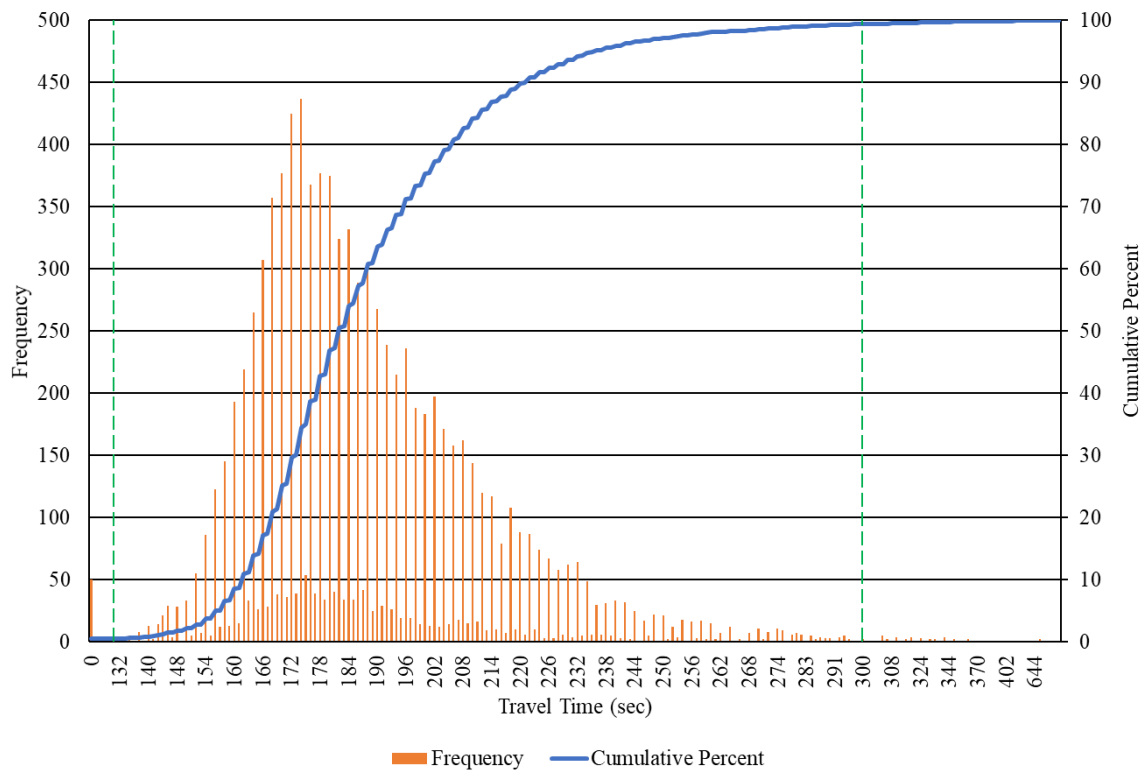


Figure B-15: UVX SB Towne Centre Boulevard-1 travel-time distribution.

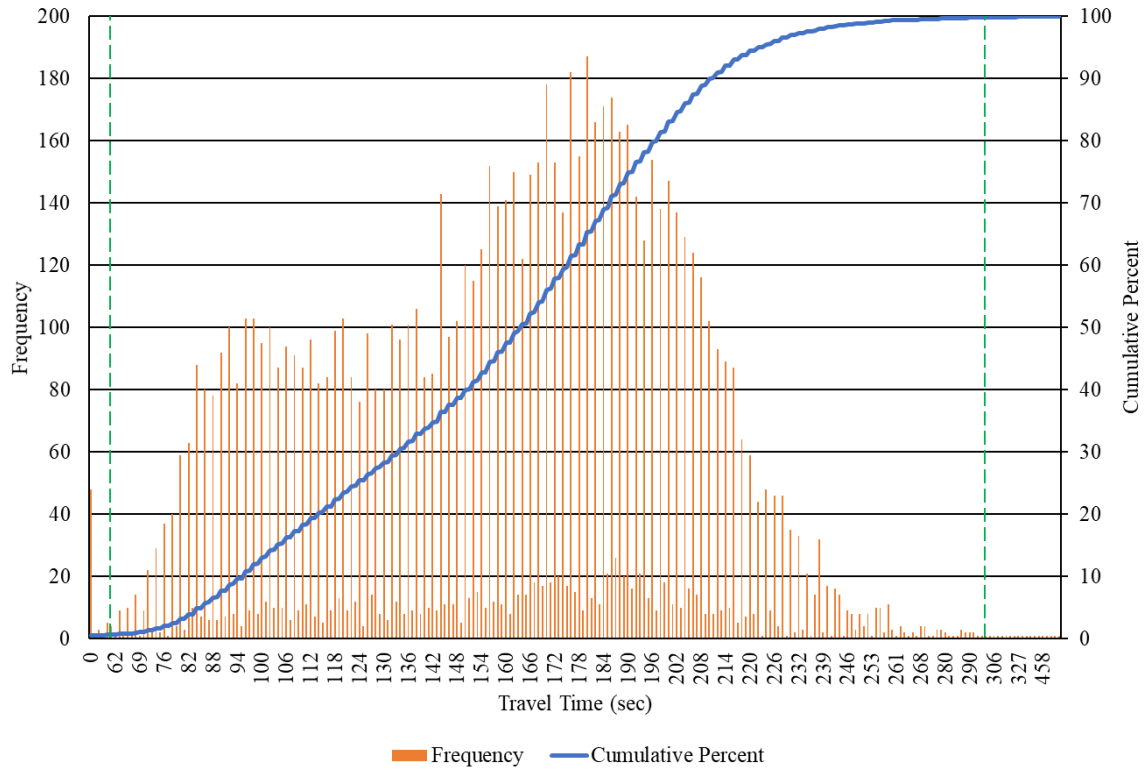


Figure B-16: UVX SB East Bay North travel-time distribution.

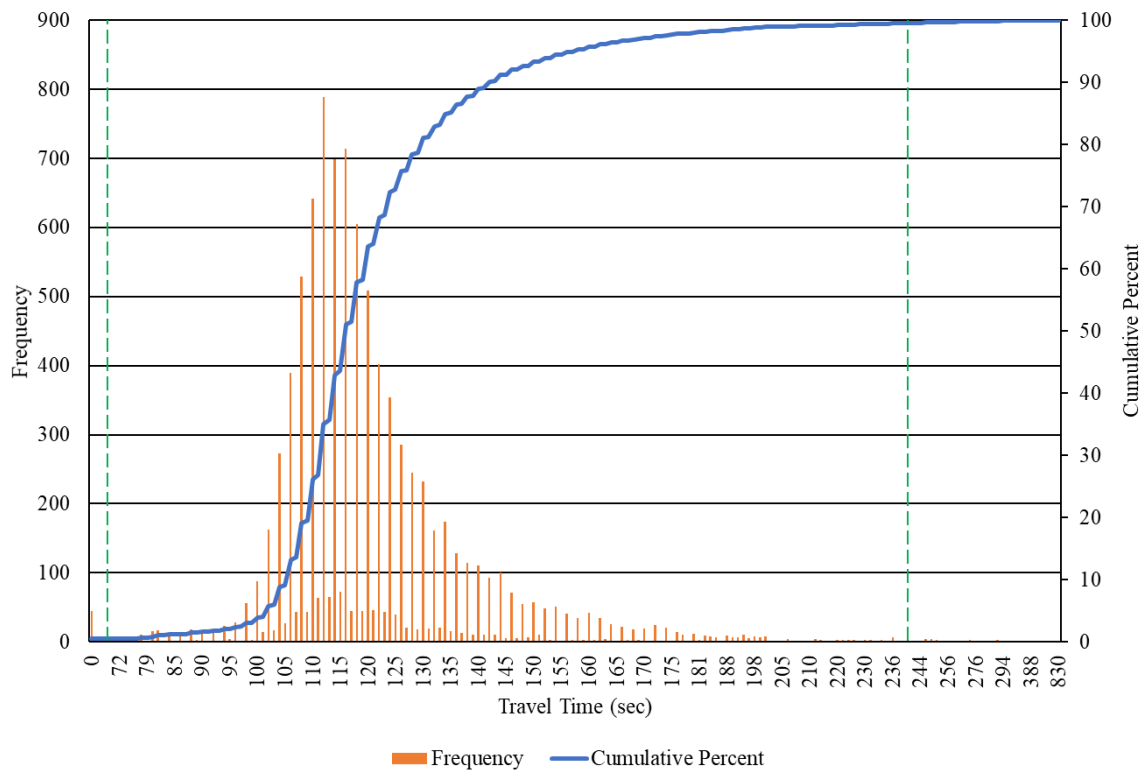


Figure B-17: UVX SB East Bay South travel-time distribution.

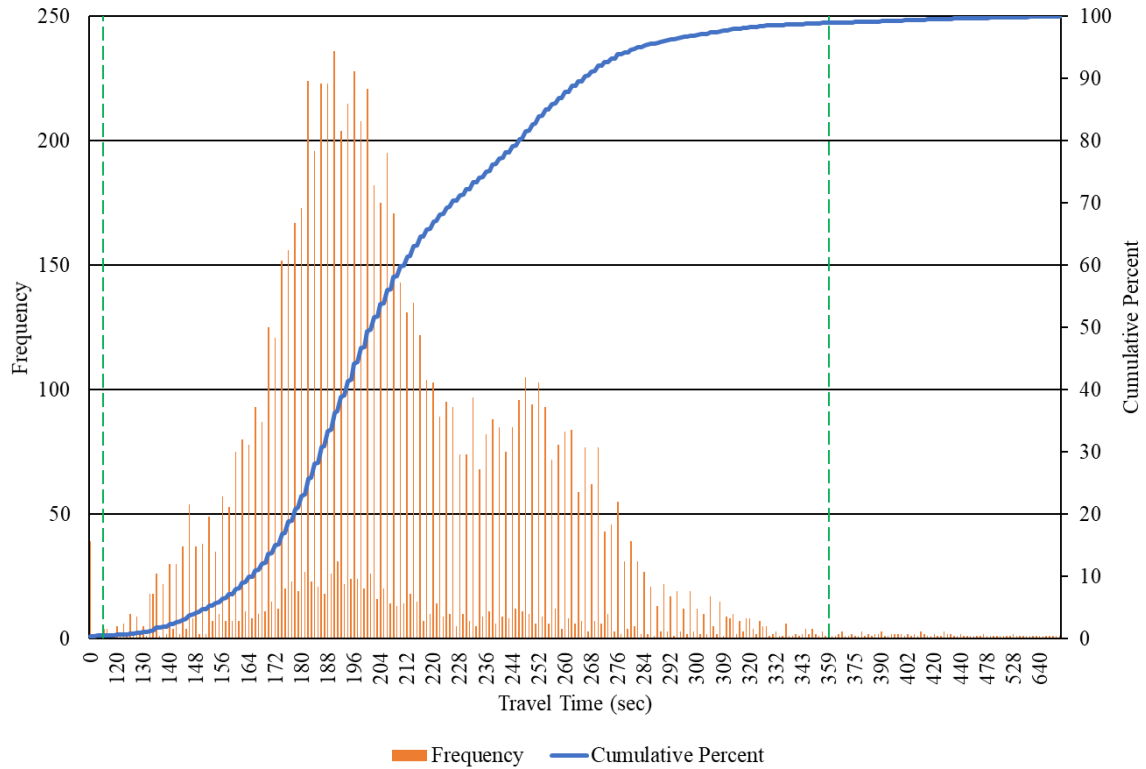


Figure B-18: UVX SB Towne Centre Boulevard-2 travel-time distribution.

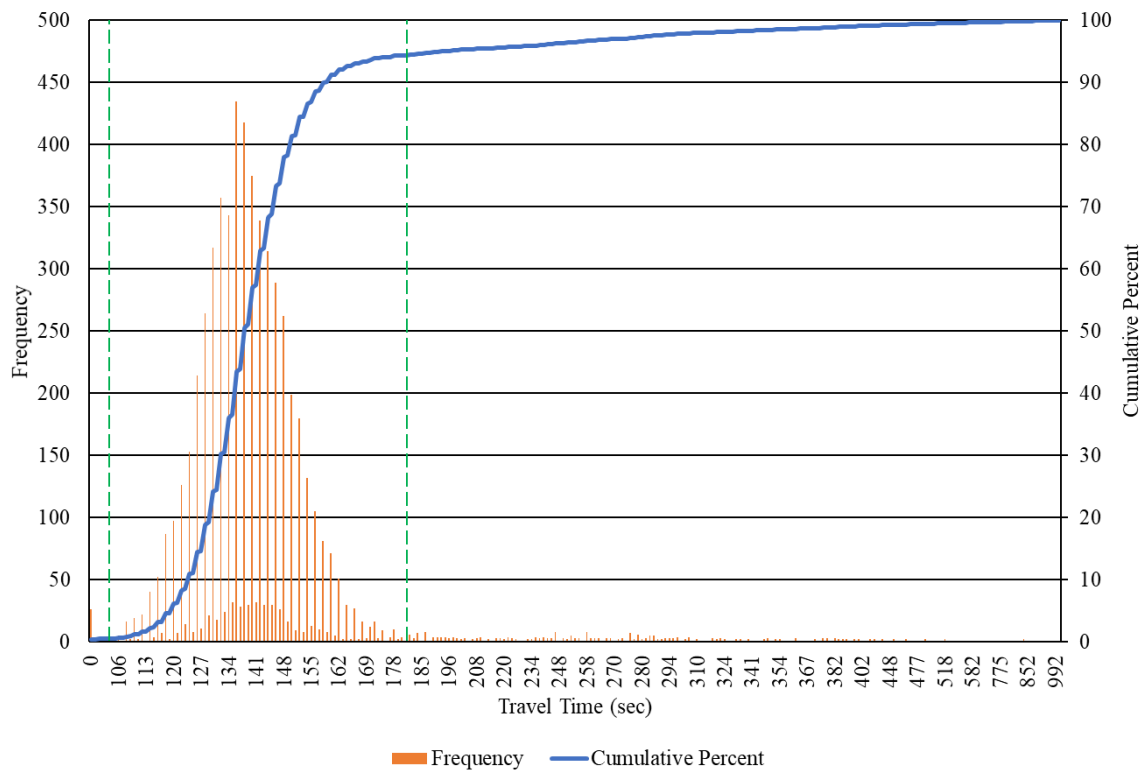


Figure B-19: UVX SB Provo Central-2 travel-time distribution.

B.1.2 UVX NB Travel-Time Distribution

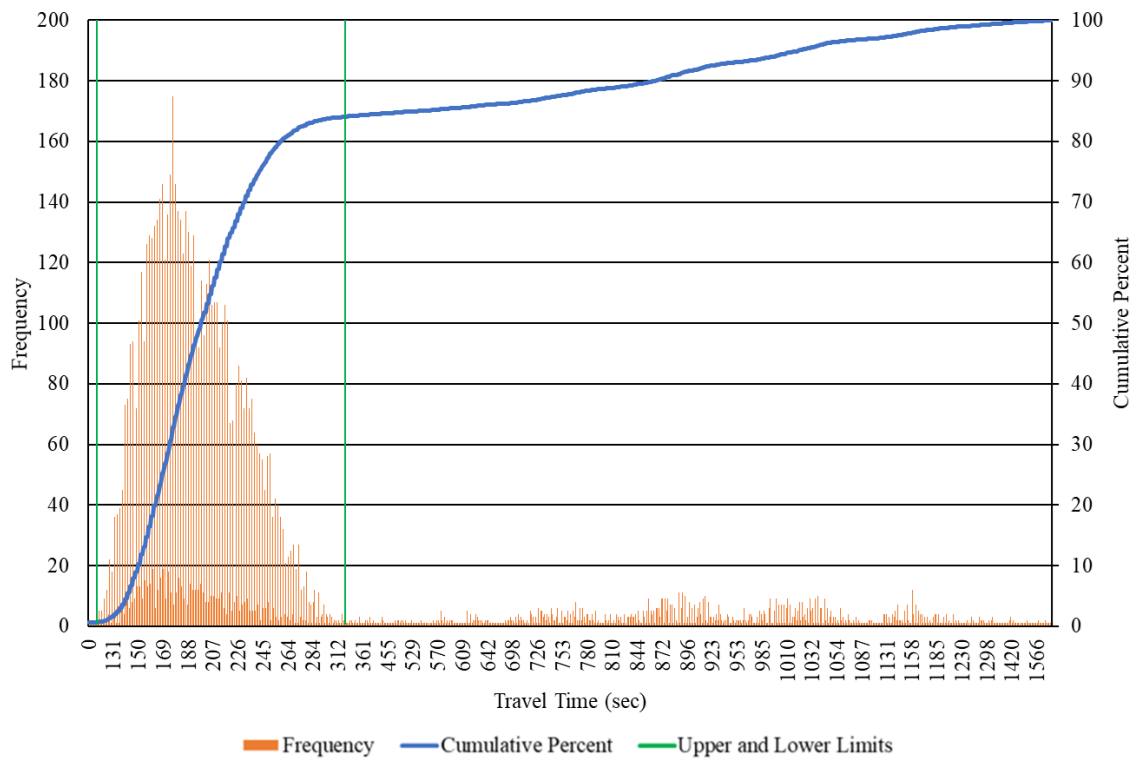


Figure B-20: UVX NB 400 South travel-time distribution.

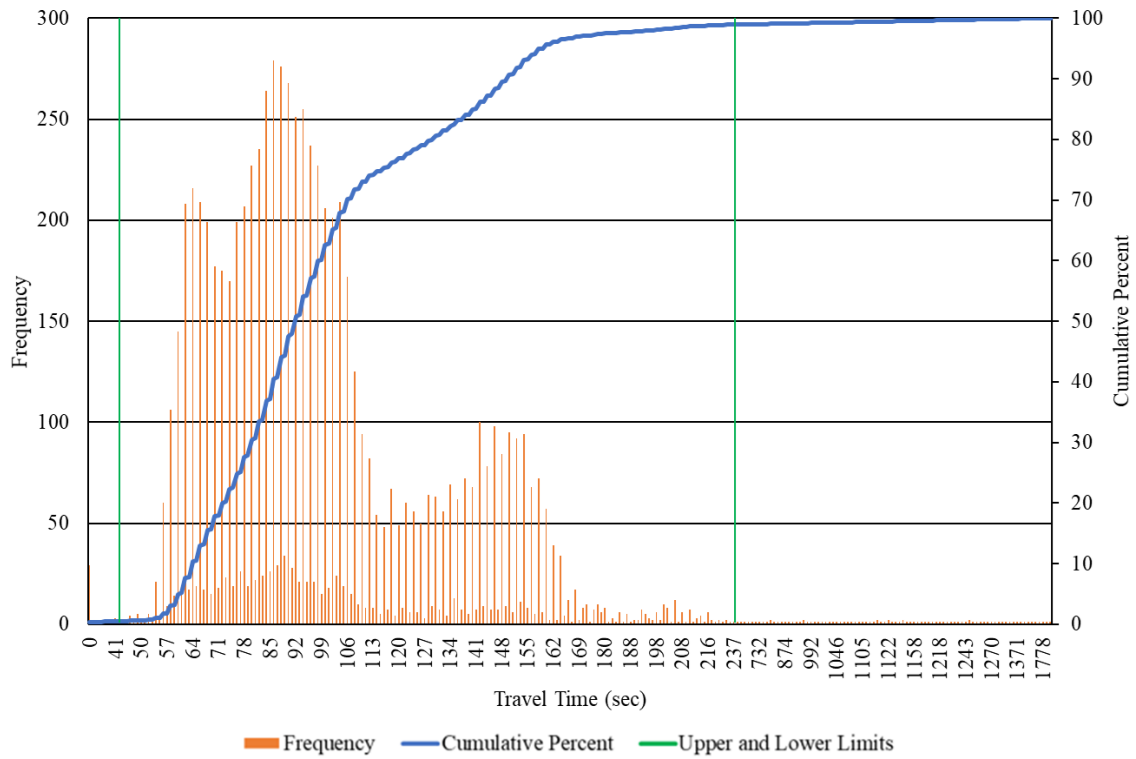


Figure B-21: UVX NB Center Street travel-time distribution.

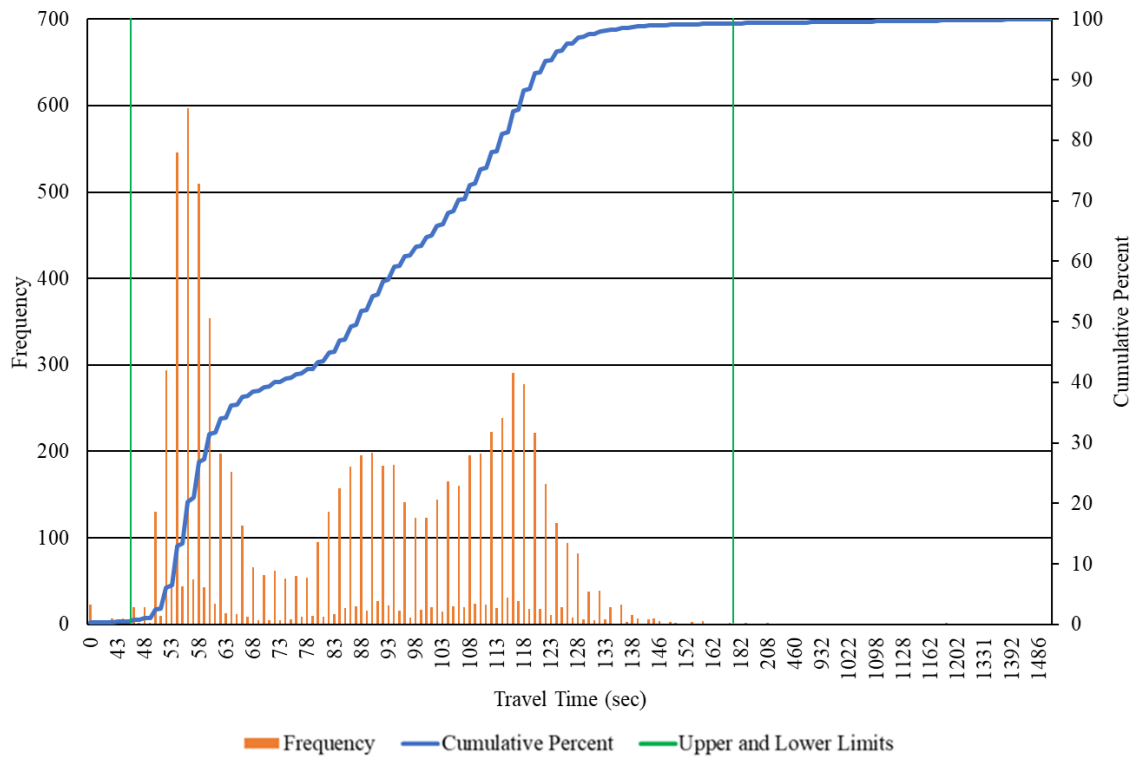


Figure B-22: UVX NB 300 North travel-time distribution.

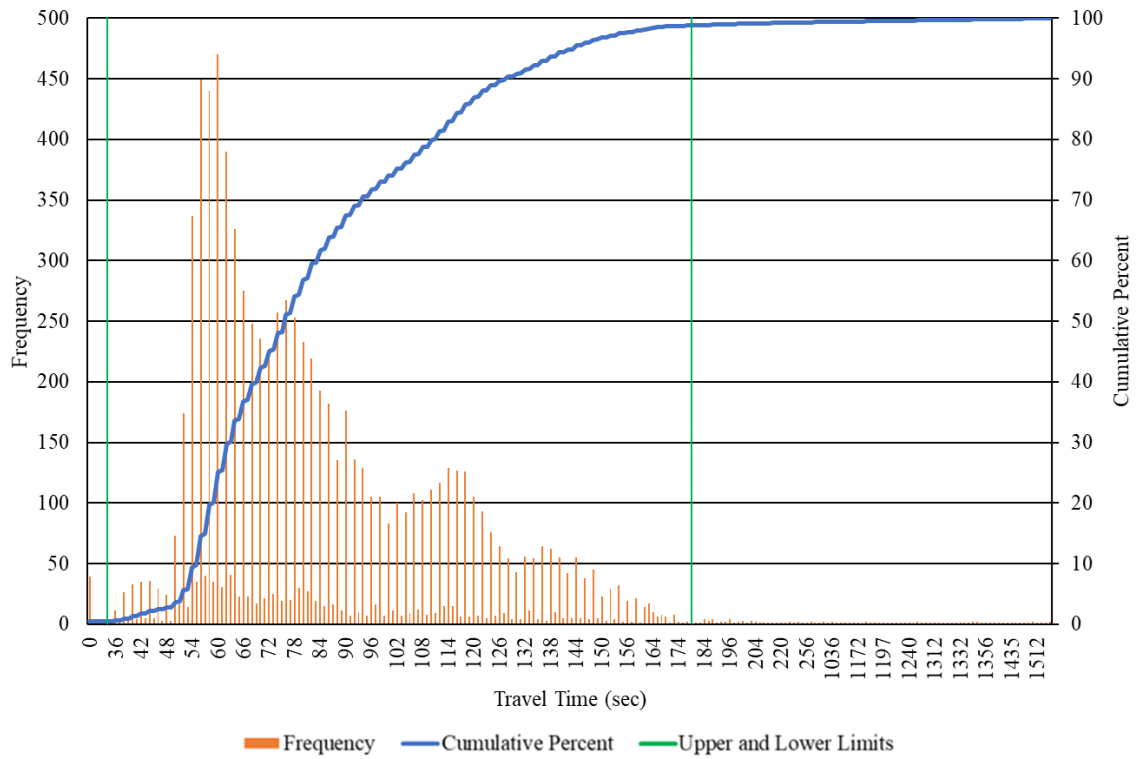


Figure B-23: UVX NB Academy Square travel-time distribution.

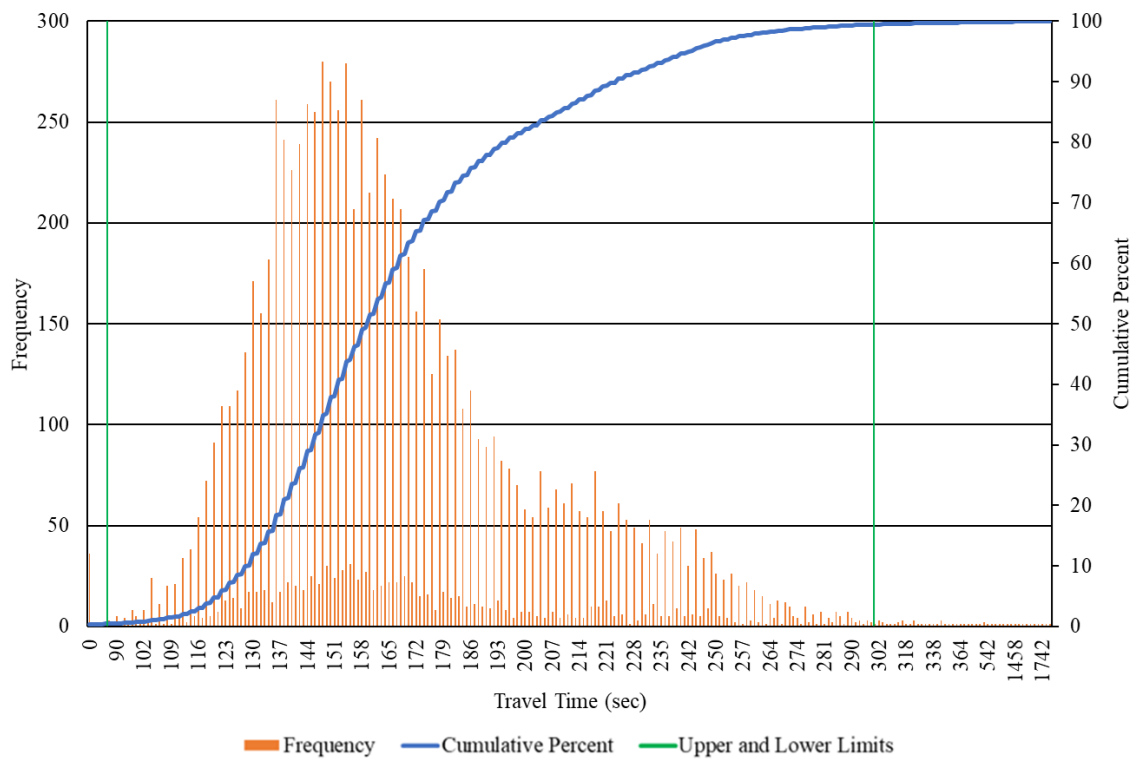


Figure B-24: UVX NB Joaquin travel-time distribution.

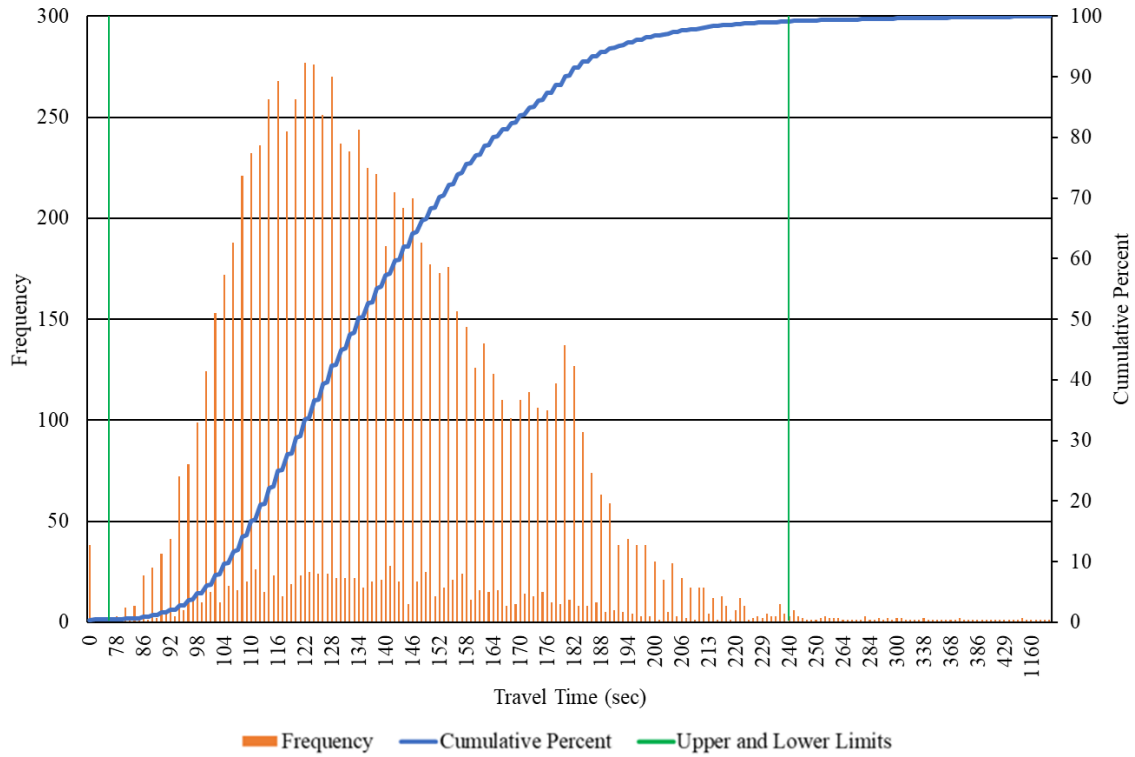


Figure B-25: UVX NB BYU Campus travel-time distribution.

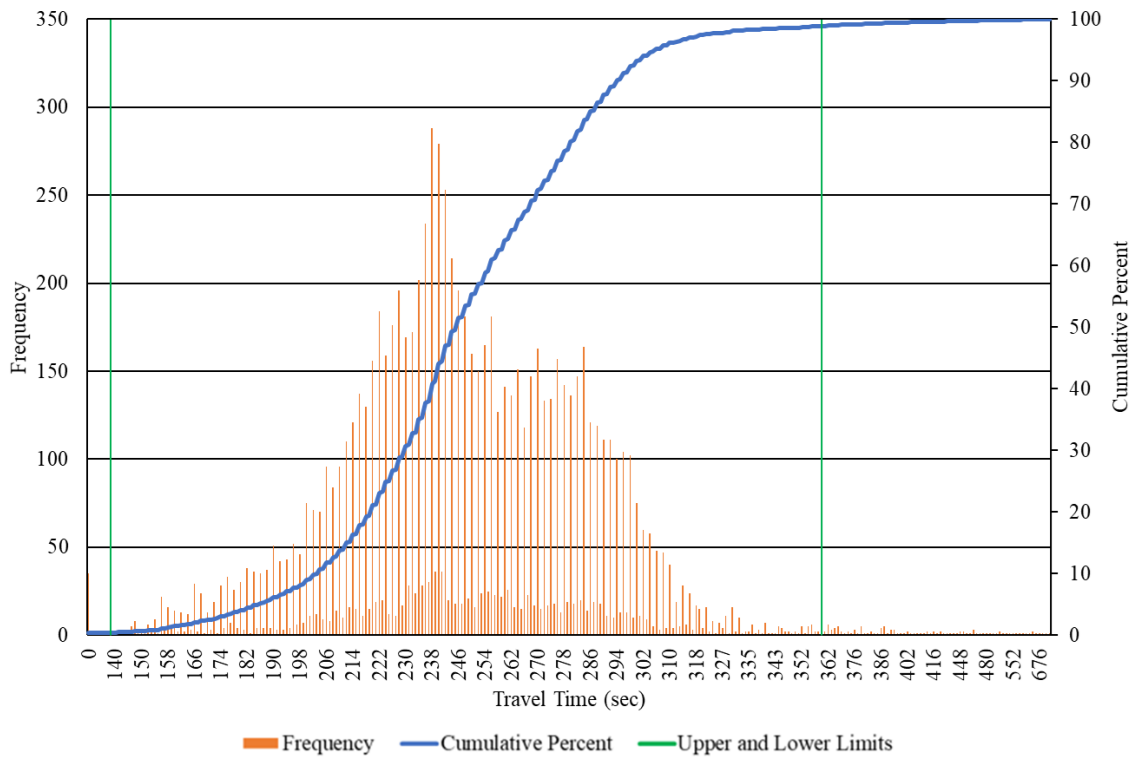


Figure B-26: UVX NB BYU North travel-time distribution.

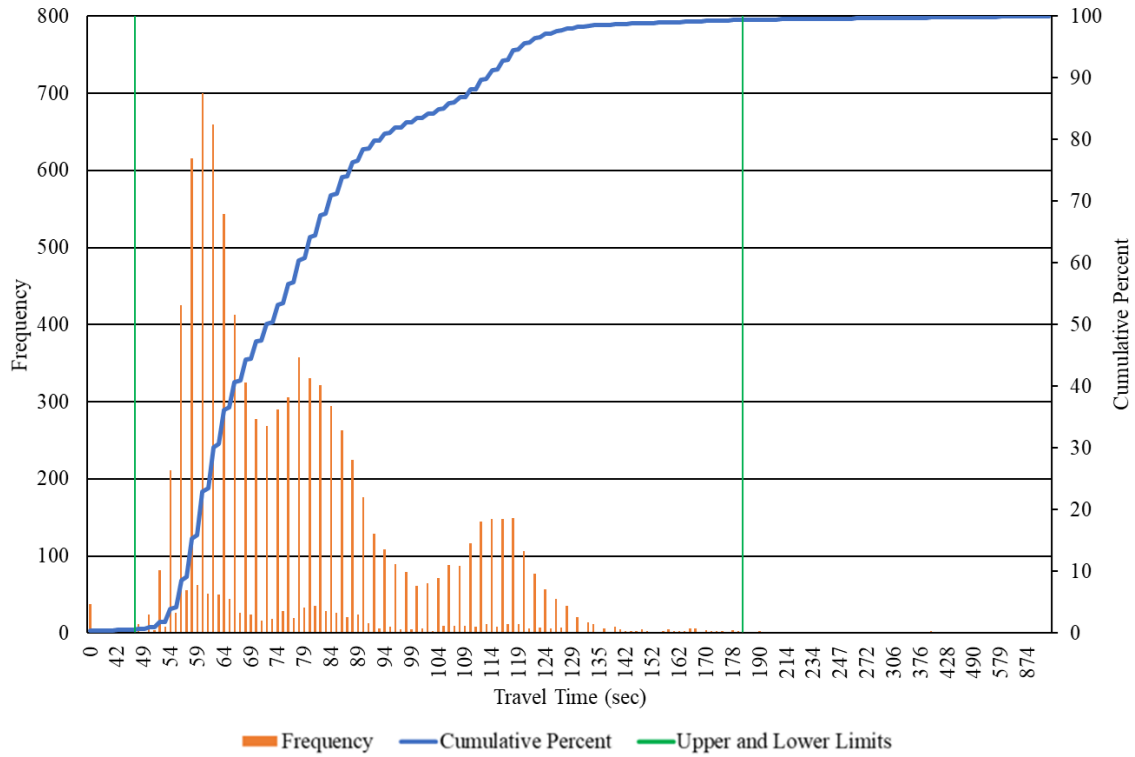


Figure B-27: UVX NB BYU Stadium travel-time distribution.

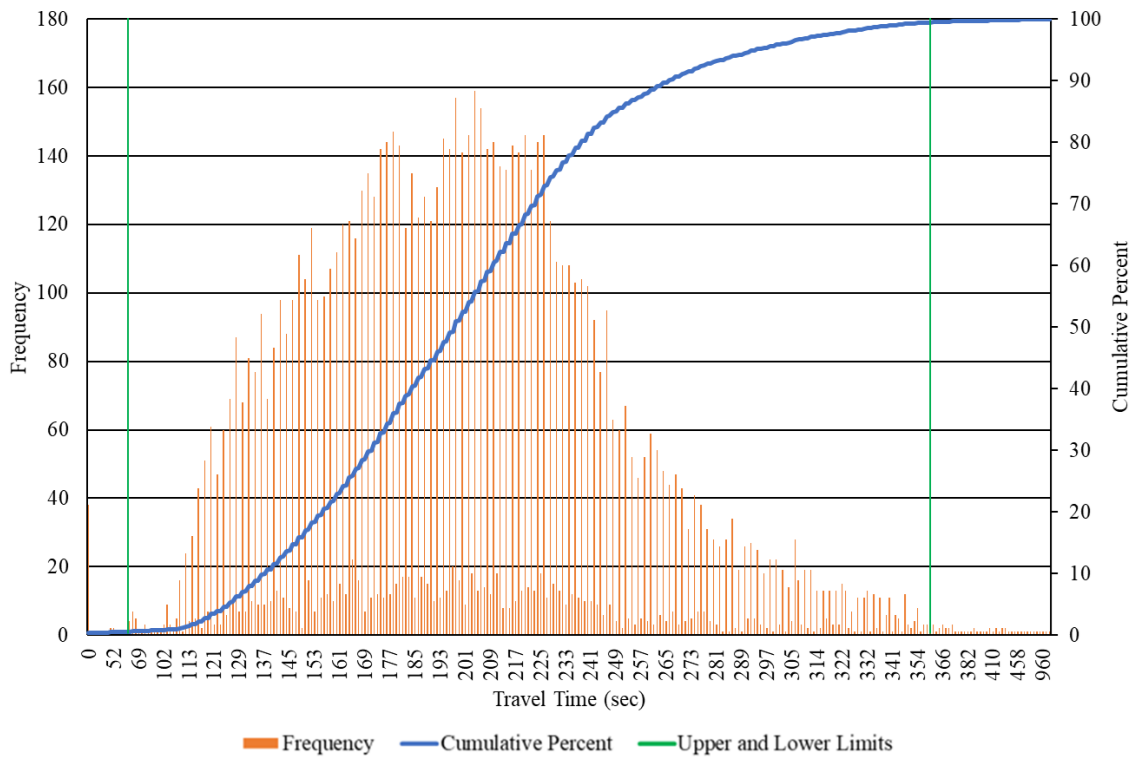


Figure B-28: UVX NB 2230 North travel-time distribution.

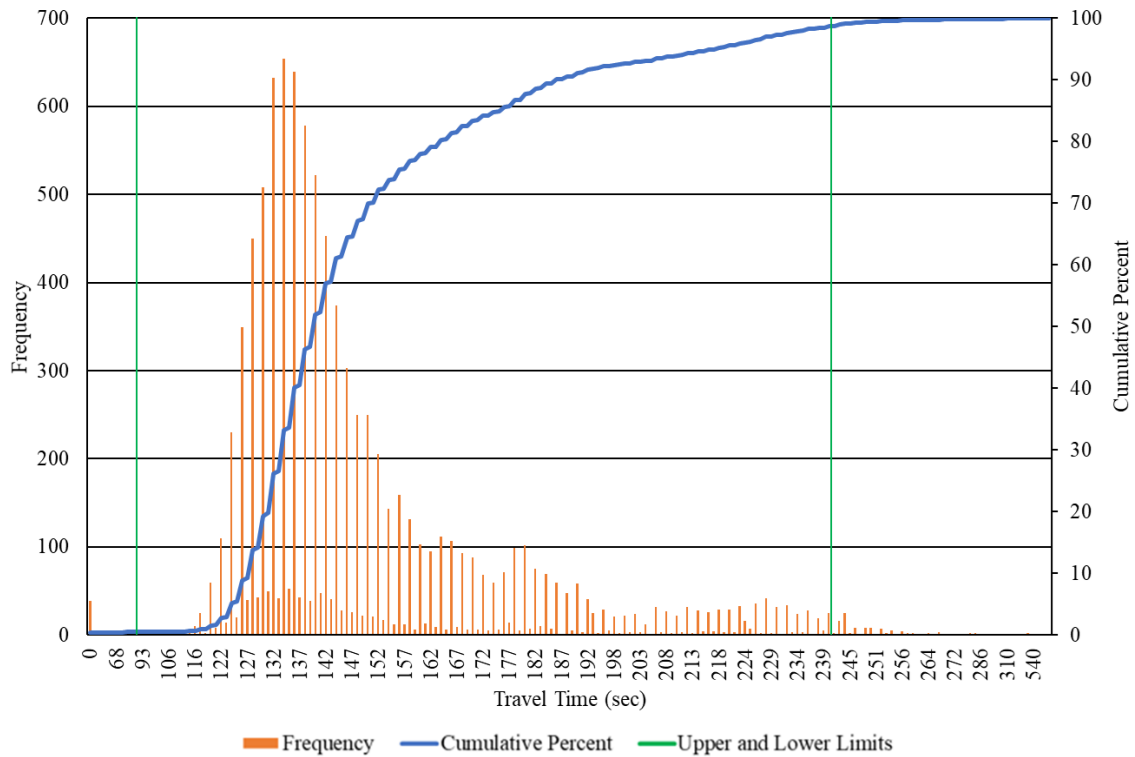


Figure B-29: UVX NB University Place travel-time distribution.

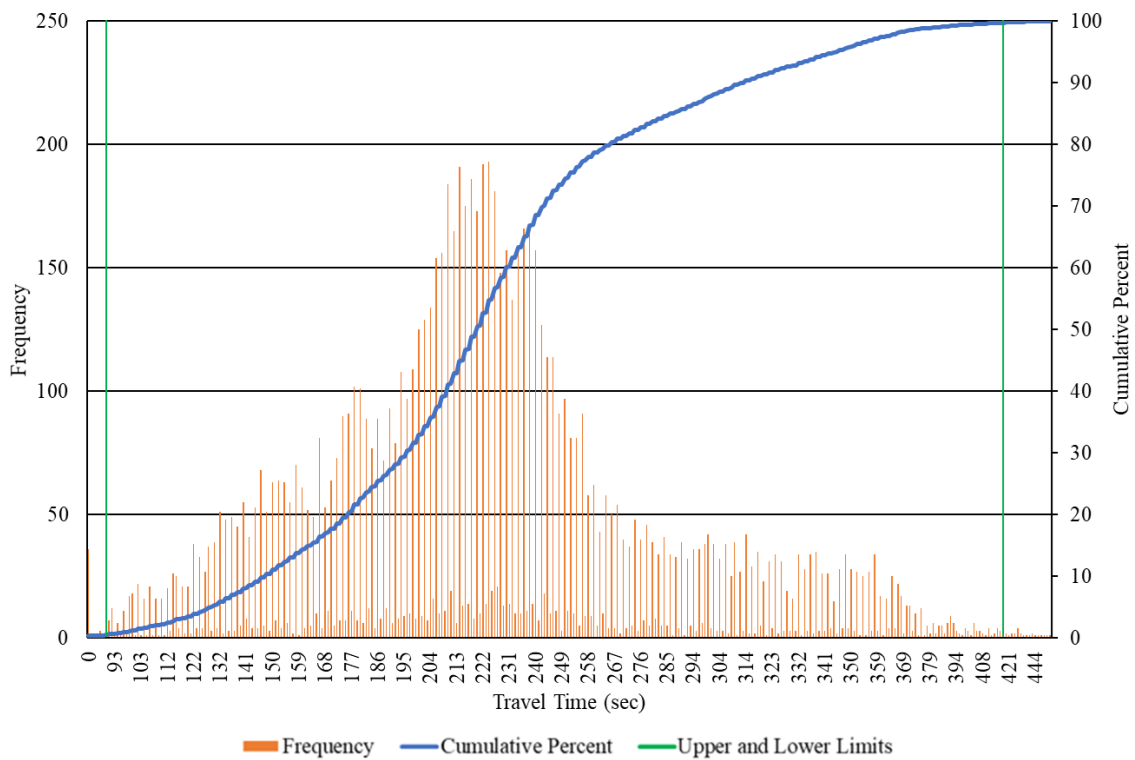


Figure B-30: UVX NB Main Street travel-time distribution.

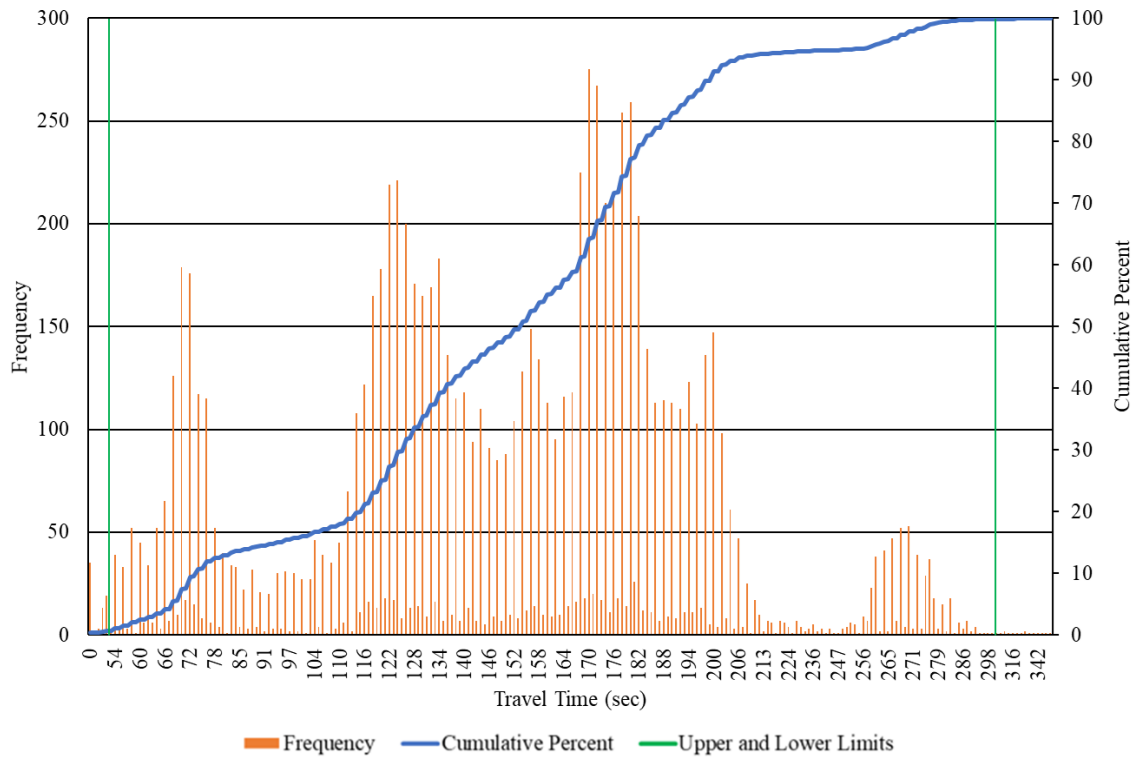


Figure B-31: UVX NB Lakeview travel-time distribution.

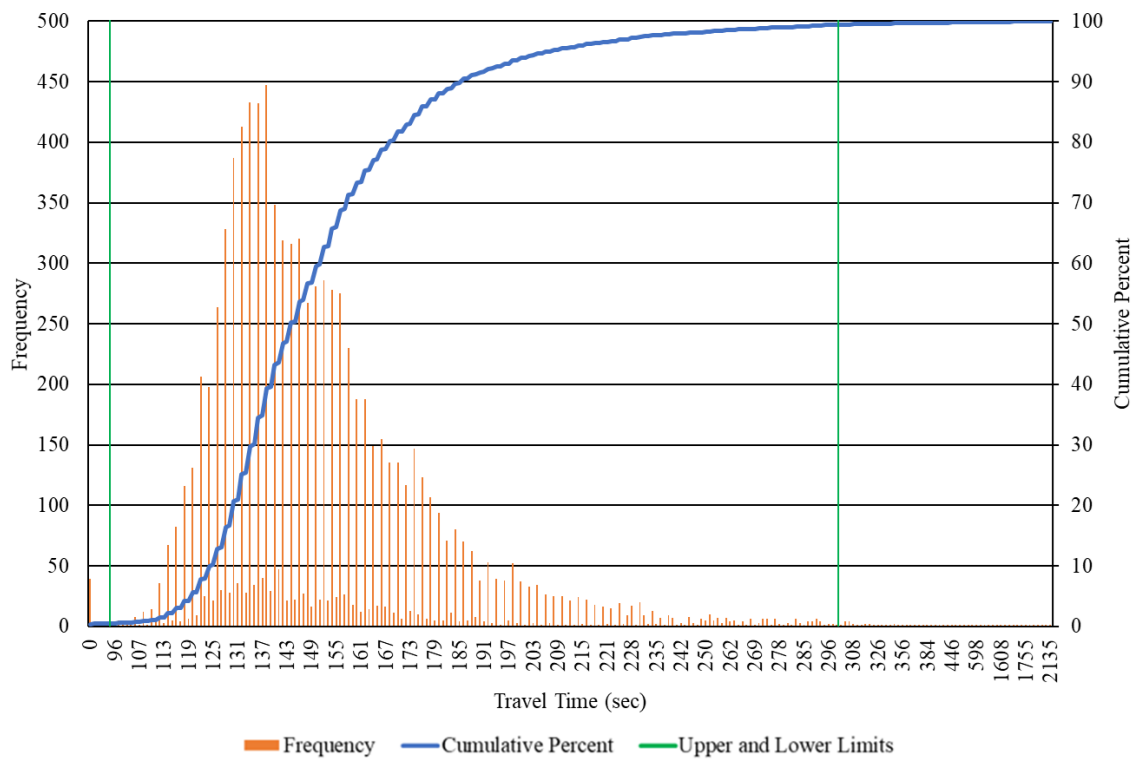


Figure B-32: UVX NB UVU Campus travel-time distribution.

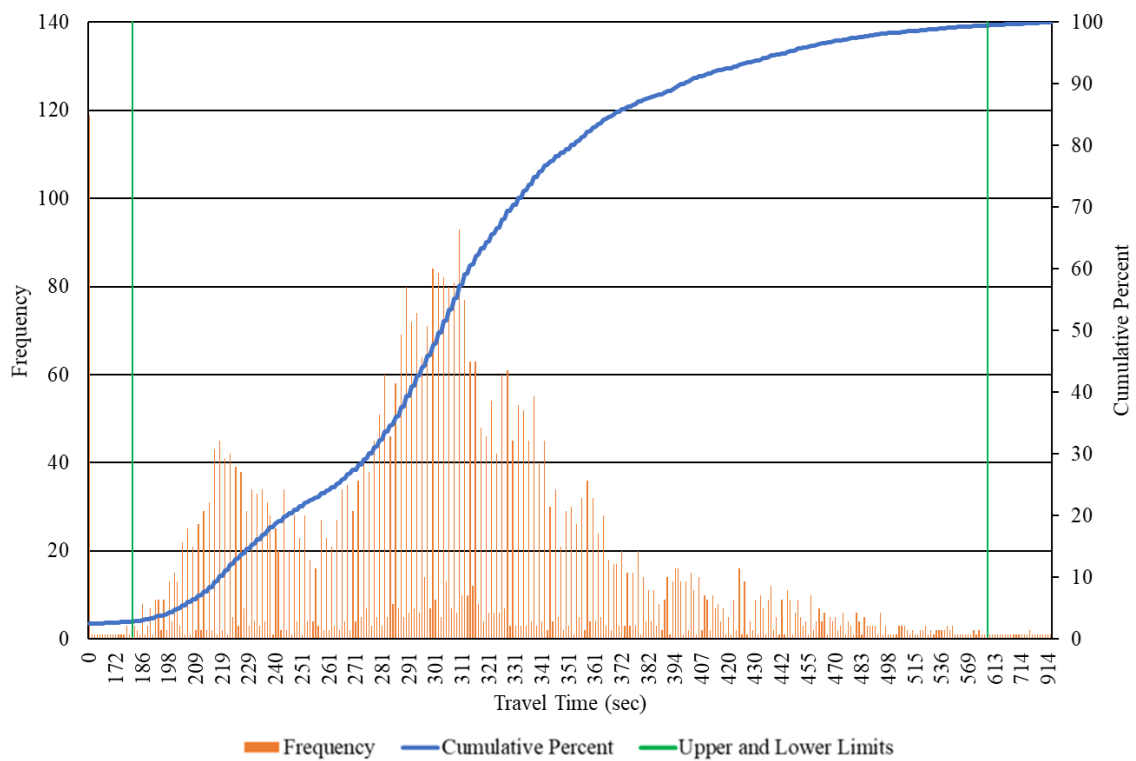


Figure B-33: UVX NB Orem Frontrunner travel-time distribution.

B.2 UVX Schedule Deviation Difference in Means

B.2.1 UVX AM SB Schedule Deviation Difference in Means

Table B-1: UVX AM SB Schedule Deviation Statistical Output Difference in Means

Corridor Level	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	53.1186	6.7709	177	7.85	<.0001	
	5	70.3014	6.6885	177	10.51	<.0001	
	OFF	78.2378	6.8757	177	11.38	<.0001	
	ON	23.4609	6.8693	177	3.42	0.0008	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-17.1828	3.0719	177	-5.59	<.0001
	2	OFF	-25.1192	3.4495	177	-7.28	<.0001
2	ON	29.6578	3.4439	177	8.61	<.0001	
OFF	ON	54.7769	3.6349	177	15.07	<.0001	
Orem Frontrunner	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	17.7859	13.7637	6	1.29	0.2438	
	5	13.4283	6.0493	6	2.22	0.0682	
	OFF	23.8073	7.4859	6	3.18	0.0191	
	ON	22.8524	7.0062	6	3.26	0.0172	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	4.3576	12.713	6	0.34	0.7435
	2	OFF	-6.0214	13.4546	6	-0.45	0.6702
	2	ON	-5.0665	13.1924	6	-0.38	0.7142
	OFF	ON	0.9549	6.3714	6	0.15	0.8858

Table B-1 (continued)

UVU Campus	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	35.2748	15.3239	6	2.3	0.0609	
	5	56.8725	4.7703	6	11.92	<.0001	
	OFF	46.4482	7.0156	6	6.62	0.0006	
	ON	13.4133	6.1889	6	2.17	0.0733	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-21.5977	14.9788	6	-1.44	0.1994
	2	OFF	-11.1734	15.8402	6	-0.71	0.507
	2	ON	21.8615	15.4911	6	1.41	0.2079
	OFF	ON	33.0348	7.3747	6	4.48	0.0042
Lakeview	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	79.2089	12.0363	6	6.58	0.0006	
	5	110.18	11.6106	6	9.49	<.0001	
	OFF	104.46	12.6882	6	8.23	0.0002	
	ON	68.1905	12.5513	6	5.43	0.0016	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-30.9755	4.8951	6	-6.33	0.0007
	2	OFF	-25.248	7.0751	6	-3.57	0.0118
	2	ON	11.0184	6.8257	6	1.61	0.1576
	OFF	ON	36.2664	7.9091	6	4.59	0.0037
Main Street	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	51.9074	12.695	6	4.09	0.0064	
	5	76.4332	12.3618	6	6.18	0.0008	
	OFF	87.6119	13.401	6	6.54	0.0006	
	ON	59.3248	13.2831	6	4.47	0.0043	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-24.5258	5.6582	6	-4.33	0.0049
	2	OFF	-35.7045	7.6539	6	-4.66	0.0034
	2	ON	-7.4174	7.4477	6	-1	0.3577
	OFF	ON	28.2871	8.5823	6	3.3	0.0165

Table B-1 (continued)

University Place	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	65.6666	28.2874	6	2.32	0.0593	
	5	81.9445	28.1513	6	2.91	0.027	
	OFF	89.4779	28.743	6	3.11	0.0208	
	ON	49.3352	28.7489	6	1.72	0.137	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-16.278	5.2698	6	-3.09	0.0214
	2	OFF	-23.8113	7.8404	6	-3.04	0.0229
	2	ON	16.3314	7.867	6	2.08	0.0832
	OFF	ON	40.1427	9.3799	6	4.28	0.0052
2230 North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	64.8357	31.8021	6	2.04	0.0876	
	5	82.5635	31.6676	6	2.61	0.0403	
	OFF	88.6011	32.2451	6	2.75	0.0334	
	ON	39.5739	32.2535	6	1.23	0.2658	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-17.7278	7.9997	6	-2.22	0.0686
	2	OFF	-23.7655	10.0133	6	-2.37	0.0553
	2	ON	25.2618	10.0346	6	2.52	0.0454
	OFF	ON	49.0272	11.3467	6	4.32	0.005
BYU Stadium	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	85.2041	44.6539	6	1.91	0.105	
	5	105.77	44.5469	6	2.37	0.0552	
	OFF	112.93	45.0201	6	2.51	0.046	
	ON	59.4633	45.0262	6	1.32	0.2348	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-20.561	10.2626	6	-2	0.092
	2	OFF	-27.7262	12.1166	6	-2.29	0.0621
	2	ON	25.7408	12.1367	6	2.12	0.0782
	OFF	ON	53.467	13.393	6	3.99	0.0072

Table B-1 (continued)

BYU North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	57.252	41.245	6	1.39	0.2145	
	5	77.3929	41.1063	6	1.88	0.1087	
	OFF	83.9437	41.724	6	2.01	0.0909	
	ON	33.372	41.7128	6	0.8	0.4542	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-20.1408	12.225	6	-1.65	0.1506
	2	OFF	-26.6916	14.1098	6	-1.89	0.1074
	2	ON	23.8801	14.0876	6	1.7	0.141
	OFF	ON	50.5717	15.3895	6	3.29	0.0167
BYU Campus	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	63.777	41.6513	6	1.53	0.1766	
	5	89.2633	41.4946	6	2.15	0.075	
	OFF	87.3496	42.1819	6	2.07	0.0838	
	ON	35.1511	42.2107	6	0.83	0.4369	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-25.4863	13.3891	6	-1.9	0.1057
	2	OFF	-23.5726	15.3282	6	-1.54	0.175
	2	ON	28.626	15.4005	6	1.86	0.1124
	OFF	ON	52.1986	16.7276	6	3.12	0.0206
Joaquin	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	66.3622	39.9407	6	1.66	0.1477	
	5	93.7327	39.7749	6	2.36	0.0565	
	OFF	98.5565	40.4862	6	2.43	0.0509	
	ON	24.5168	40.5585	6	0.6	0.5677	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-27.3705	17.0528	6	-1.61	0.1596
	2	OFF	-32.1943	18.6216	6	-1.73	0.1346
	2	ON	41.8453	18.7635	6	2.23	0.0673
	OFF	ON	74.0396	19.8645	6	3.73	0.0098

Table B-1 (continued)

Academy Square	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	51.0229	35.9605	6	1.42	0.2057	
	5	74.2097	35.7784	6	2.07	0.0834	
	OFF	82.6037	36.5545	6	2.26	0.0646	
	ON	17.2842	36.6754	6	0.47	0.6541	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-23.1868	18.5533	6	-1.25	0.2579
	2	OFF	-31.5808	19.991	6	-1.58	0.1652
	2	ON	33.7387	20.1976	6	1.67	0.1459
	OFF	ON	65.3195	21.215	6	3.08	0.0217
300 North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	64.454	35.9563	6	1.79	0.1232	
	5	89.0361	35.7734	6	2.49	0.0472	
	OFF	93.4122	36.5685	6	2.55	0.0432	
	ON	29.466	36.673	6	0.8	0.4523	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-24.5821	16.586	6	-1.48	0.1888
	2	OFF	-28.9582	18.2152	6	-1.59	0.163
	2	ON	34.988	18.4112	6	1.9	0.1061
	OFF	ON	63.9462	19.5514	6	3.27	0.017
Center Street	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	71.8248	31.5375	6	2.28	0.063	
	5	93.1708	31.3395	6	2.97	0.0249	
	OFF	99.3996	32.266	6	3.08	0.0216	
	ON	39.1132	32.3203	6	1.21	0.2717	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-21.346	17.2657	6	-1.24	0.2625
	2	OFF	-27.5748	18.8765	6	-1.46	0.1944
	2	ON	32.7117	18.9647	6	1.72	0.1353
	OFF	ON	60.2865	20.1279	6	3	0.0242

Table B-1 (continued)

400 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	60.8213	27.6353	6	2.2	0.07	
	5	71.0649	27.3814	6	2.6	0.0409	
	OFF	78.9604	28.468	6	2.77	0.0323	
	ON	20.9613	28.5513	6	0.73	0.4905	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-10.2436	16.6812	6	-0.61	0.5617
	2	OFF	-18.1391	18.3903	6	-0.99	0.3621
	2	ON	39.86	18.5127	6	2.15	0.0748
	OFF	ON	57.9991	19.7111	6	2.94	0.0259
Provo Central - 1	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	-10.722	22.7005	6	-0.47	0.6534	
	5	-13.4411	22.3868	6	-0.6	0.5702	
	OFF	11.5183	23.7293	6	0.49	0.6446	
	ON	-52.7076	23.7489	6	-2.22	0.0683	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	2.7191	16.4627	6	0.17	0.8742
	2	OFF	-22.2403	18.2102	6	-1.22	0.2678
	2	ON	41.9856	18.2363	6	2.3	0.0609
	OFF	ON	64.2259	19.4601	6	3.3	0.0164
Towne Centre Blvd - 1	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	43.0645	21.1405	6	2.04	0.0878	
	5	55.1201	20.817	6	2.65	0.0381	
	OFF	65.0844	22.2293	6	2.93	0.0264	
	ON	7.5266	22.2373	6	0.34	0.7465	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-12.0555	14.5251	6	-0.83	0.4383
	2	OFF	-22.0198	16.4413	6	-1.34	0.229
	2	ON	35.5379	16.4523	6	2.16	0.0741
	OFF	ON	57.5577	17.7882	6	3.24	0.0178

Table B-1 (continued)

East Bay North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	65.8723	24.139	6	2.73	0.0342	
	5	80.3551	23.8267	6	3.37	0.015	
	OFF	97.0809	25.1846	6	3.85	0.0084	
	ON	20.929	25.219	6	0.83	0.4384	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-14.4827	15.6754	6	-0.92	0.3912
	2	OFF	-31.2085	17.6299	6	-1.77	0.1271
	2	ON	44.9434	17.677	6	2.54	0.0439
	OFF	ON	76.1519	19.0378	6	4	0.0071
East Bay South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	65.9768	24.4755	6	2.7	0.0358	
	5	83.8772	24.155	6	3.47	0.0133	
	OFF	98.5436	25.5236	6	3.86	0.0084	
	ON	19.0535	25.5183	6	0.75	0.4835	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-17.9003	16.7358	6	-1.07	0.3259
	2	OFF	-32.5667	18.6209	6	-1.75	0.1309
	2	ON	46.9234	18.6135	6	2.52	0.0452
	OFF	ON	79.4901	19.9321	6	3.99	0.0072
Towne Centre Blvd - 2	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	79.405	26.3855	6	3.01	0.0237	
	5	94.4552	26.0571	6	3.62	0.011	
	OFF	108.07	27.4909	6	3.93	0.0077	
	ON	27.397	27.4909	6	1	0.3574	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-15.0503	18.4104	6	-0.82	0.4449
	2	OFF	-28.6678	20.3547	6	-1.41	0.2087
	2	ON	52.0079	20.3547	6	2.56	0.0432
	OFF	ON	80.6757	21.7274	6	3.71	0.0099

Table B-1 (continued)

Provo Central - 2	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	-18.307	24.8648	6	-0.74	0.4893	
	5	-10.8985	25.2113	6	-0.43	0.6806	
	OFF	11.7593	26.0566	6	0.45	0.6676	
	ON	-73.0754	26.026	6	-2.81	0.0308	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-7.4085	16.04	6	-0.46	0.6604
	2	OFF	-30.0662	17.3162	6	-1.74	0.1332
	2	ON	54.7684	17.2841	6	3.17	0.0194
	OFF	ON	84.8346	18.8964	6	4.49	0.0042

B.2.2 UVX AM NB Schedule Deviation Difference in Means

Table B-2: UVX AM NB Schedule Deviation Statistical Output Difference in Means

Corridor Level	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	14.9601	7.4515	132	2.01	0.0467	
	5	26.811	7.417	132	3.61	0.0004	
	OFF	15.9487	7.5205	132	2.12	0.0358	
	ON	4.6866	7.5201	132	0.62	0.5342	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-11.8509	2.2649	132	-5.23	<.0001
	2	OFF	-0.9886	2.5739	132	-0.38	0.7015
	2	ON	10.2735	2.5788	132	3.98	0.0001
	OFF	ON	11.262	2.7681	132	4.07	<.0001

Table B-2 (continued)

Orem Frontrunner	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	-104.6	43.2907	6	-2.42	0.0521	
	5	-87.871	32.6723	6	-2.69	0.0361	
	OFF	-178.85	34.0673	6	-5.25	0.0019	
	ON	-177.03	33.4054	6	-5.3	0.0018	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-16.7339	29.3748	6	-0.57	0.5896
	2	OFF	74.2405	30.9148	6	2.4	0.0532
	2	ON	72.4288	30.1902	6	2.4	0.0534
	OFF	ON	-1.8118	14.2344	6	-0.13	0.9029
UVU Campus	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	37.2291	14.5292	6	2.56	0.0428	
	5	59.7486	14.1293	6	4.23	0.0055	
	OFF	46.2854	15.6163	6	2.96	0.0252	
	ON	19.9208	15.7477	6	1.26	0.2528	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-22.5195	12.7759	6	-1.76	0.1284
	2	OFF	-9.0563	14.3732	6	-0.63	0.5519
	2	ON	17.3083	14.5054	6	1.19	0.2778
	OFF	ON	26.3646	15.5708	6	1.69	0.1414
Lakeview	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	67.0077	12.901	6	5.19	0.002	
	5	72.1731	12.5166	6	5.77	0.0012	
	OFF	70.8224	14.0523	6	5.04	0.0024	
	ON	43.9203	14.0814	6	3.12	0.0206	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-5.1654	8.3282	6	-0.62	0.5579
	2	OFF	-3.8147	10.4517	6	-0.36	0.7276
	2	ON	23.0874	10.4817	6	2.2	0.0698
	OFF	ON	26.9021	11.8493	6	2.27	0.0636

Table B-2 (continued)

Main Street	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	31.1318	11.5459	6	2.7	0.0357	
	5	51.0318	11.1925	6	4.56	0.0039	
	OFF	41.9547	12.6323	6	3.32	0.016	
	ON	27.3942	12.6745	6	2.16	0.0739	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-19.9	5.8342	6	-3.41	0.0143
	2	OFF	-10.8229	8.2551	6	-1.31	0.2378
	2	ON	3.7376	8.3133	6	0.45	0.6688
	OFF	ON	14.5606	9.7675	6	1.49	0.1866
University Place	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	2.7314	12.1902	6	0.22	0.8301	
	5	16.9378	11.9565	6	1.42	0.2064	
	OFF	13.9049	12.9121	6	1.08	0.3229	
	ON	-0.4163	12.9468	6	-0.03	0.9754	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-14.2064	6.0105	6	-2.36	0.056
	2	OFF	-11.1734	7.7207	6	-1.45	0.198
	2	ON	3.1477	7.7724	6	0.4	0.6995
	OFF	ON	14.3211	8.85	6	1.62	0.1567
2230 North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	23.9768	10.3199	6	2.32	0.0592	
	5	38.4669	10.0035	6	3.85	0.0085	
	OFF	31.7106	11.2871	6	2.81	0.0308	
	ON	23.4464	11.3277	6	2.07	0.0839	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-14.4901	7.0383	6	-2.06	0.0852
	2	OFF	-7.7338	8.7434	6	-0.88	0.4104
	2	ON	0.5304	8.7947	6	0.06	0.9539
	OFF	ON	8.2643	9.8959	6	0.84	0.4356

Table B-2 (continued)

BYU Stadium	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	18.3161	8.1958	6	2.23	0.0668	
	5	30.7139	7.884	6	3.9	0.008	
	OFF	18.997	9.1613	6	2.07	0.0835	
	ON	15.2408	9.1762	6	1.66	0.1478	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-12.3978	5.3985	6	-2.3	0.0614
	2	OFF	-0.6808	7.1192	6	-0.1	0.9269
	2	ON	3.0753	7.1341	6	0.43	0.6815
	OFF	ON	3.7561	8.2161	6	0.46	0.6636
BYU North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	5.1886	6.9496	6	0.75	0.4835	
	5	15.9155	6.6304	6	2.4	0.0533	
	OFF	8.2143	7.8936	6	1.04	0.3381	
	ON	-3.9259	7.9752	6	-0.49	0.64	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-10.7269	4.5465	6	-2.36	0.0563
	2	OFF	-3.0258	6.2334	6	-0.49	0.6446
	2	ON	9.1145	6.3406	6	1.44	0.2006
	OFF	ON	12.1402	7.3556	6	1.65	0.1499
BYU Campus	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	-11.8234	9.7389	6	-1.21	0.2703	
	5	-2.0632	9.5626	6	-0.22	0.8363	
	OFF	-9.8964	10.2792	6	-0.96	0.3728	
	ON	-25.7755	10.2878	6	-2.51	0.0462	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-9.7601	4.5866	6	-2.13	0.0774
	2	OFF	-1.9269	5.911	6	-0.33	0.7555
	2	ON	13.9521	5.9311	6	2.35	0.0569
	OFF	ON	15.8791	6.7661	6	2.35	0.0573

Table B-2 (continued)

Joaquin	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	16.8211	14.9934	6	1.12	0.3048	
	5	21.7418	14.8705	6	1.46	0.194	
	OFF	18.5696	15.4004	6	1.21	0.2733	
	ON	6.7287	15.4192	6	0.44	0.6778	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-4.9206	5.5438	6	-0.89	0.4089
	2	OFF	-1.7484	6.8184	6	-0.26	0.8062
	2	ON	10.0924	6.8605	6	1.47	0.1917
	OFF	ON	11.8409	7.6947	6	1.54	0.1748
Academy Square	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	23.7021	10.7272	6	2.21	0.0692	
	5	24.2636	10.5881	6	2.29	0.0618	
	OFF	22.5166	11.2892	6	1.99	0.0931	
	ON	23.9147	11.2898	6	2.12	0.0785	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-0.5615	3.5132	6	-0.16	0.8783
	2	OFF	1.1855	5.2572	6	0.23	0.8291
	2	ON	-0.2126	5.2662	6	-0.04	0.9691
	OFF	ON	-1.3981	6.3293	6	-0.22	0.8325
300 North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	63.9597	4.867	6	13.14	<.0001	
	5	67.0978	4.6812	6	14.33	<.0001	
	OFF	64.4627	5.8249	6	11.07	<.0001	
	ON	57.3516	5.8475	6	9.81	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-3.1381	3.3899	6	-0.93	0.3903
	2	OFF	-0.503	4.845	6	-0.1	0.9207
	2	ON	6.6081	4.8687	6	1.36	0.2235
	OFF	ON	7.1111	5.8278	6	1.22	0.2682

Table B-2 (continued)

Center Street	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	49.5879	3.5872	6	13.82	<.0001	
	5	52.1629	3.3739	6	15.46	<.0001	
	OFF	47.1733	4.6665	6	10.11	<.0001	
	ON	45.3378	4.7275	6	9.59	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-2.575	3.1975	6	-0.81	0.4514
	2	OFF	2.4145	4.5367	6	0.53	0.6137
	2	ON	4.25	4.5978	6	0.92	0.391
	OFF	ON	1.8355	5.4818	6	0.33	0.7491
400 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	19.799	8.9388	6	2.21	0.0687	
	5	24.7599	8.938	6	2.77	0.0324	
	OFF	18.6972	9.3537	6	2	0.0926	
	ON	13.0413	9.3796	6	1.39	0.2138	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-4.9608	3.2032	6	-1.55	0.1724
	2	OFF	1.1019	4.2169	6	0.26	0.8026
	2	ON	6.7578	4.2736	6	1.58	0.1649
	OFF	ON	5.6559	5.0843	6	1.11	0.3085
Provo Central	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	9.6797	2.6931	6	3.59	0.0114	
	5	23.1573	2.7	6	8.58	0.0001	
	OFF	8.9681	4.2324	6	2.12	0.0784	
	ON	-1.6003	4.3683	6	-0.37	0.7267	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-13.4775	3.8135	6	-3.53	0.0123
	2	OFF	0.7116	5.0166	6	0.14	0.8918
	2	ON	11.2801	5.1318	6	2.2	0.0703
	OFF	ON	10.5684	6.0824	6	1.74	0.133

B.2.3 UVX PM SB Schedule Deviation Difference in Means

Table B-3: UVX PM SB Schedule Deviation Statistical Output Difference in Means

Corridor Level	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	91.4275	7.5253	177	12.15	<.0001	
	5	147.22	7.4567	177	19.74	<.0001	
	OFF	93.6517	7.6452	177	12.25	<.0001	
	ON	101.45	7.637	177	13.28	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-55.7937	2.627	177	-21.24	<.0001
	2	OFF	-2.2242	3.1119	177	-0.71	0.4757
	2	ON	-10.0272	3.1016	177	-3.23	0.0015
OFF	ON	-7.803	3.3838	177	-2.31	0.0223	
Orem Frontrunner	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	16.6319	15.9443	6	1.04	0.3371	
	5	9.0873	9.3837	6	0.97	0.3702	
	OFF	19.3641	10.471	6	1.85	0.1139	
	ON	16.949	10.0901	6	1.68	0.144	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	7.5446	13.9709	6	0.54	0.6086
	2	OFF	-2.7322	14.7183	6	-0.19	0.8589
	2	ON	-0.3171	14.4487	6	-0.02	0.9832
OFF	ON	2.4151	8.0091	6	0.3	0.7732	
UVU Campus	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	16.1356	23.7364	6	0.68	0.522	
	5	44.4825	15.5385	6	2.86	0.0287	
	OFF	33.8121	16.7686	6	2.02	0.0904	
	ON	13.4377	16.3021	6	0.82	0.4413	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-28.3469	18.4238	6	-1.54	0.1748
	2	OFF	-17.6765	19.4745	6	-0.91	0.399
	2	ON	2.6979	19.077	6	0.14	0.8922
OFF	ON	20.3744	9.042	6	2.25	0.0651	

Table B-3 (continued)

Lakeview	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	83.5303	10.9689	6	7.62	0.0003	
	5	117.53	10.4533	6	11.24	<.0001	
	OFF	89.8013	12.1214	6	7.41	0.0003	
	ON	101.89	11.9521	6	8.52	0.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-33.9972	11.3742	6	-2.99	0.0244
	2	OFF	-6.271	12.9215	6	-0.49	0.6447
	2	ON	-18.3564	12.7634	6	-1.44	0.2004
	OFF	ON	-12.0854	13.7636	6	-0.88	0.4137
Main Street	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	88.1047	12.6089	6	6.99	0.0004	
	5	130.98	12.1596	6	10.77	<.0001	
	OFF	92.202	13.6314	6	6.76	0.0005	
	ON	106.42	13.5045	6	7.88	0.0002	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-42.8753	10.8988	6	-3.93	0.0077
	2	OFF	-4.0973	12.5163	6	-0.33	0.7545
	2	ON	-18.3158	12.3784	6	-1.48	0.1895
	OFF	ON	-14.2185	13.4155	6	-1.06	0.33
University Place	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	105.58	9.9185	6	10.64	<.0001	
	5	148.37	9.4342	6	15.73	<.0001	
	OFF	110.36	11.4036	6	9.68	<.0001	
	ON	118.19	11.4171	6	10.35	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-42.7933	9.5943	6	-4.46	0.0043
	2	OFF	-4.7888	11.5345	6	-0.42	0.6925
	2	ON	-12.619	11.5485	6	-1.09	0.3164
	OFF	ON	-7.8302	12.8447	6	-0.61	0.5645

Table B-3 (continued)

2230 North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	125.35	9.9001	6	12.66	<.0001	
	5	171.55	9.3833	6	18.28	<.0001	
	OFF	124.08	11.541	6	10.75	<.0001	
	ON	131.19	11.5724	6	11.34	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-46.1988	8.1834	6	-5.65	0.0013
	2	OFF	1.2668	10.5867	6	0.12	0.9087
	2	ON	-5.8447	10.6206	6	-0.55	0.602
	OFF	ON	-7.1115	12.1636	6	-0.58	0.5801
BYU Stadium	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	157.96	8.8034	6	17.94	<.0001	
	5	209.55	8.1458	6	25.73	<.0001	
	OFF	154.62	10.7794	6	14.34	<.0001	
	ON	163.84	10.8276	6	15.13	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-51.5959	6.2095	6	-8.31	0.0002
	2	OFF	3.3366	9.4022	6	0.35	0.7348
	2	ON	-5.8868	9.4564	6	-0.62	0.5565
	OFF	ON	-9.2234	11.3192	6	-0.81	0.4463
BYU North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	135.18	11.8468	6	11.41	<.0001	
	5	193.07	11.3485	6	17.01	<.0001	
	OFF	130.51	13.51	6	9.66	<.0001	
	ON	140.55	13.5506	6	10.37	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-57.8832	6.4037	6	-9.04	0.0001
	2	OFF	4.6773	9.7335	6	0.48	0.6479
	2	ON	-5.3707	9.7894	6	-0.55	0.6031
	OFF	ON	-10.0479	11.748	6	-0.86	0.4252

Table B-3 (continued)

BYU Campus	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	160.57	15.7022	6	10.23	<.0001	
	5	232.98	15.2742	6	15.25	<.0001	
	OFF	160.26	17.1597	6	9.34	<.0001	
	ON	172.68	17.1694	6	10.06	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-72.4122	6.8432	6	-10.58	<.0001
	2	OFF	0.3081	10.3915	6	0.03	0.9773
	2	ON	-12.113	10.4067	6	-1.16	0.2886
	OFF	ON	-12.4211	12.4974	6	-0.99	0.3587
Joaquin	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	110.99	20.2956	6	5.47	0.0016	
	5	195.05	19.9583	6	9.77	<.0001	
	OFF	113.16	21.4904	6	5.27	0.0019	
	ON	113.7	21.4987	6	5.29	0.0018	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-84.0636	9.0976	6	-9.24	<.0001
	2	OFF	-2.1728	12.0932	6	-0.18	0.8633
	2	ON	-2.7109	12.1079	6	-0.22	0.8303
	OFF	ON	-0.5381	14.0176	6	-0.04	0.9706
Academy Square	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	118.69	21.5139	6	5.52	0.0015	
	5	199.09	21.1862	6	9.4	<.0001	
	OFF	116.36	22.6316	6	5.14	0.0021	
	ON	125.25	22.6539	6	5.53	0.0015	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-80.3978	6.9652	6	-11.54	<.0001
	2	OFF	2.3317	10.5751	6	0.22	0.8328
	2	ON	-6.5612	10.6222	6	-0.62	0.5595
	OFF	ON	-8.8929	12.7338	6	-0.7	0.5111

Table B-3 (continued)

300 North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	130.86	21.5003	6	6.09	0.0009	
	5	213.57	21.1662	6	10.09	<.0001	
	OFF	133.3	22.6351	6	5.89	0.0011	
	ON	150.31	22.6561	6	6.63	0.0006	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-82.7107	7.1578	6	-11.56	<.0001
	2	OFF	-2.4365	10.7503	6	-0.23	0.8282
	2	ON	-19.4521	10.7947	6	-1.8	0.1216
	OFF	ON	-17.0156	12.9068	6	-1.32	0.2355
Center Street	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	84.8338	21.1633	6	4.01	0.0071	
	5	162.22	20.8263	6	7.79	0.0002	
	OFF	82.8963	22.3362	6	3.71	0.01	
	ON	99.8334	22.3575	6	4.47	0.0043	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-77.3859	7.0928	6	-10.91	<.0001
	2	OFF	1.9375	10.7457	6	0.18	0.8628
	2	ON	-14.9996	10.7906	6	-1.39	0.2139
	OFF	ON	-16.9371	12.9398	6	-1.31	0.2385
400 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	92.808	20.1721	6	4.6	0.0037	
	5	170.67	19.8155	6	8.61	0.0001	
	OFF	91.2445	21.4318	6	4.26	0.0053	
	ON	114.88	21.4317	6	5.36	0.0017	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-77.8648	7.1966	6	-10.82	<.0001
	2	OFF	1.5635	10.8843	6	0.14	0.8905
	2	ON	-22.0744	10.8844	6	-2.03	0.0889
	OFF	ON	-23.6379	13.072	6	-1.81	0.1206

Table B-3 (continued)

Provo Central - 1	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	44.255	20.9823	6	2.11	0.0795	
	5	93.8133	20.6882	6	4.53	0.004	
	OFF	35.7222	22.0517	6	1.62	0.1564	
	ON	42.6668	22.0722	6	1.93	0.1014	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-49.5583	8.2041	6	-6.04	0.0009
	2	OFF	8.5328	11.2061	6	0.76	0.4752
	2	ON	1.5881	11.2463	6	0.14	0.8923
OFF	ON	-6.9446	13.1339	6	-0.53	0.616	
Towne Centre Blvd - 1	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	46.9012	17.2237	6	2.72	0.0345	
	5	102.88	16.8756	6	6.1	0.0009	
	OFF	39.3231	18.5638	6	2.12	0.0785	
	ON	54.2789	18.568	6	2.92	0.0265	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-55.9757	9.2011	6	-6.08	0.0009
	2	OFF	7.5781	12.0195	6	0.63	0.5516
	2	ON	-7.3778	12.0267	6	-0.61	0.5621
OFF	ON	-14.9559	13.8762	6	-1.08	0.3225	
East Bay North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	93.1188	14.7222	6	6.33	0.0007	
	5	147.37	14.3134	6	10.3	<.0001	
	OFF	93.1024	16.313	6	5.71	0.0013	
	ON	95.5285	16.322	6	5.85	0.0011	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-54.254	6.8196	6	-7.96	0.0002
	2	OFF	0.01644	10.3793	6	0	0.9988
	2	ON	-2.4097	10.3945	6	-0.23	0.8244
OFF	ON	-2.4261	12.5452	6	-0.19	0.853	

Table B-3 (continued)

East Bay South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	98.5653	14.6751	6	6.72	0.0005	
	5	151.09	14.2484	6	10.6	<.0001	
	OFF	98.3086	16.2501	6	6.05	0.0009	
	ON	99.9743	16.3002	6	6.13	0.0009	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-52.5214	6.7173	6	-7.82	0.0002
	2	OFF	0.2567	10.3029	6	0.02	0.9809
	2	ON	-1.409	10.3817	6	-0.14	0.8965
	OFF	ON	-1.6657	12.5057	6	-0.13	0.8984
Towne Centre Blvd - 2	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	156.58	15.3418	6	10.21	<.0001	
	5	203.61	14.9177	6	13.65	<.0001	
	OFF	164.2	16.8454	6	9.75	<.0001	
	ON	161.12	16.8867	6	9.54	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-47.0274	6.8405	6	-6.87	0.0005
	2	OFF	-7.6221	10.3956	6	-0.73	0.4911
	2	ON	-4.543	10.4602	6	-0.43	0.6792
	OFF	ON	3.0791	12.5617	6	0.25	0.8145
Provo Central - 2	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	2.4551	17.1363	6	0.14	0.8908	
	5	31.8609	17.4401	6	1.83	0.1175	
	OFF	10.8936	18.3908	6	0.59	0.5753	
	ON	10.7399	18.4915	6	0.58	0.5825	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-29.4058	9.678	6	-3.04	0.0228
	2	OFF	-8.4385	11.2909	6	-0.75	0.4831
	2	ON	-8.2849	11.4481	6	-0.72	0.4965
	OFF	ON	0.1536	13.2504	6	0.01	0.9911

B.2.4 UVX PM NB Schedule Deviation Difference in Means

Table B-4: UVX PM NB Schedule Deviation Statistical Output Difference in Means

Corridor Level	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	65.0919	13.2848	132	4.9	<.0001	
	5	82.17	13.2581	132	6.2	<.0001	
	OFF	63.2359	13.3366	132	4.74	<.0001	
	ON	54.1685	13.3348	132	4.06	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-17.0782	3.1394	132	-5.44	<.0001
	2	OFF	1.856	3.4528	132	0.54	0.5918
2	ON	10.9234	3.4515	132	3.16	0.0019	
OFF	ON	9.0674	3.6448	132	2.49	0.0141	
Orem Frontrunner	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	-223.66	32.9786	6	-6.78	0.0005	
	5	-159.52	19.5592	6	-8.16	0.0002	
	OFF	-227.72	21.5803	6	-10.55	<.0001	
	ON	-248.16	20.7314	6	-11.97	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-64.137	27.5428	6	-2.33	0.0588
	2	OFF	4.0646	29.0134	6	0.14	0.8932
2	ON	24.506	28.3894	6	0.86	0.4212	
OFF	ON	20.4415	13.5627	6	1.51	0.1825	
UVU Campus	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	82.7968	23.6268	6	3.5	0.0128	
	5	127.6	23.3869	6	5.46	0.0016	
	OFF	82.7133	24.4997	6	3.38	0.0149	
	ON	62.1389	24.505	6	2.54	0.0443	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-44.8069	6.3439	6	-7.06	0.0004
	2	OFF	0.08347	9.6715	6	0.01	0.9934
2	ON	20.6579	9.685	6	2.13	0.0769	
OFF	ON	20.5744	11.6537	6	1.77	0.1279	

Table B-4 (continued)

Lakeview	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	108.37	24.3278	6	4.45	0.0043	
	5	141.29	24.0949	6	5.86	0.0011	
	OFF	108.53	25.175	6	4.31	0.005	
	ON	81.6036	25.1854	6	3.24	0.0177	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-32.9197	10.0142	6	-3.29	0.0167
	2	OFF	-0.1593	12.3894	6	-0.01	0.9902
	2	ON	26.7668	12.4106	6	2.16	0.0744
	OFF	ON	26.9261	13.9972	6	1.92	0.1027
Main Street	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	130.51	26.4333	6	4.94	0.0026	
	5	163.36	26.2309	6	6.23	0.0008	
	OFF	136.83	27.1656	6	5.04	0.0024	
	ON	115.27	27.1652	6	4.24	0.0054	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-32.8497	7.0383	6	-4.67	0.0034
	2	OFF	-6.3283	9.9716	6	-0.63	0.5491
	2	ON	15.2371	9.9712	6	1.53	0.1773
	OFF	ON	21.5654	11.7758	6	1.83	0.1168
University Place	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	87.8782	24.7788	6	3.55	0.0121	
	5	114.79	24.591	6	4.67	0.0034	
	OFF	87.6257	25.4323	6	3.45	0.0137	
	ON	84.8412	25.4405	6	3.33	0.0157	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-26.9107	5.6353	6	-4.78	0.0031
	2	OFF	0.2525	8.5923	6	0.03	0.9775
	2	ON	3.0369	8.6173	6	0.35	0.7366
	OFF	ON	2.7844	10.3465	6	0.27	0.7969

Table B-4 (continued)

2230 North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	115.96	21.4943	6	5.39	0.0017	
	5	145.63	21.3007	6	6.84	0.0005	
	OFF	113.76	22.2329	6	5.12	0.0022	
	ON	111.58	22.2184	6	5.02	0.0024	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-29.6729	5.4693	6	-5.43	0.0016
	2	OFF	2.1932	8.3957	6	0.26	0.8027
	2	ON	4.3772	8.359	6	0.52	0.6193
	OFF	ON	2.184	10.1073	6	0.22	0.8361
BYU Stadium	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	72.8512	20.5407	6	3.55	0.0121	
	5	98.8616	20.3967	6	4.85	0.0029	
	OFF	71.6027	21.0661	6	3.4	0.0145	
	ON	71.879	21.0728	6	3.41	0.0143	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-26.0105	4.582	6	-5.68	0.0013
	2	OFF	1.2485	6.9828	6	0.18	0.864
	2	ON	0.9722	7.0024	6	0.14	0.8941
	OFF	ON	-0.2763	8.4202	6	-0.03	0.9749
BYU North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	47.9853	18.2199	6	2.63	0.0389	
	5	69.4455	18.0782	6	3.84	0.0085	
	OFF	53.2733	18.7177	6	2.85	0.0293	
	ON	39.0307	18.7956	6	2.08	0.0831	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-21.4602	4.2095	6	-5.1	0.0022
	2	OFF	-5.288	6.423	6	-0.82	0.4418
	2	ON	8.9547	6.6465	6	1.35	0.2265
	OFF	ON	14.2426	7.9105	6	1.8	0.1219

Table B-4 (continued)

BYU Campus	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	34.0262	13.2177	6	2.57	0.0421	
	5	47.7911	13.0575	6	3.66	0.0106	
	OFF	36.5937	13.7909	6	2.65	0.0379	
	ON	18.2545	13.8022	6	1.32	0.2342	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-13.7649	7.0369	6	-1.96	0.0982
	2	OFF	-2.5675	8.3188	6	-0.31	0.768
	2	ON	15.7717	8.3374	6	1.89	0.1074
	OFF	ON	18.3392	9.2187	6	1.99	0.0938
Joaquin	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	81.378	9.9687	6	8.16	0.0002	
	5	83.8257	9.7572	6	8.59	0.0001	
	OFF	82.3227	10.7093	6	7.69	0.0003	
	ON	74.2349	10.7078	6	6.93	0.0004	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-2.4477	8.1441	6	-0.3	0.7739
	2	OFF	-0.9447	9.2632	6	-0.1	0.9221
	2	ON	7.1431	9.2618	6	0.77	0.4698
	OFF	ON	8.0878	10.0545	6	0.8	0.4519
Academy Square	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	107.34	10.29	6	10.43	<.0001	
	5	96.749	10.1273	6	9.55	<.0001	
	OFF	103.63	11.0495	6	9.38	<.0001	
	ON	105.06	11.0348	6	9.52	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	10.595	8.537	6	1.24	0.2609
	2	OFF	3.7183	9.6126	6	0.39	0.7122
	2	ON	2.2798	9.5957	6	0.24	0.8201
	OFF	ON	-1.4386	10.4054	6	-0.14	0.8946

Table B-4 (continued)

300 North	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	160.61	9.7293	6	16.51	<.0001	
	5	155.3	9.5869	6	16.2	<.0001	
	OFF	155.96	10.5131	6	14.83	<.0001	
	ON	157.39	10.4977	6	14.99	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	5.3128	6.0231	6	0.88	0.4117
	2	OFF	4.6529	7.409	6	0.63	0.5531
	2	ON	3.2224	7.3872	6	0.44	0.6779
	OFF	ON	-1.4305	8.3914	6	-0.17	0.8702
Center Street	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	116.76	8.9766	6	13.01	<.0001	
	5	108.8	8.839	6	12.31	<.0001	
	OFF	110.01	9.7473	6	11.29	<.0001	
	ON	113.3	9.7618	6	11.61	<.0001	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	7.9593	5.8382	6	1.36	0.2217
	2	OFF	6.7479	7.1384	6	0.95	0.381
	2	ON	3.4656	7.1585	6	0.48	0.6455
	OFF	ON	-3.2823	8.102	6	-0.41	0.6994
400 South	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	33.1041	7.0097	6	4.72	0.0032	
	5	22.0694	7.0689	6	3.12	0.0205	
	OFF	26.0798	7.6385	6	3.41	0.0142	
	ON	30.5976	7.6425	6	4	0.0071	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	11.0347	5.3287	6	2.07	0.0838
	2	OFF	7.0243	6.0632	6	1.16	0.2907
	2	ON	2.5065	6.0674	6	0.41	0.6939
	OFF	ON	-4.5179	6.7818	6	-0.67	0.5301

Table B-4 (continued)

Provo Central	Least Squares Means						
	Threshold	Estimate	Standard Error	DF	t Value	Pr > t	
	2	6.3085	5.0614	6	1.25	0.2591	
	5	13.2376	5.1309	6	2.58	0.0418	
	OFF	1.4412	5.7873	6	0.25	0.8116	
	ON	-3.2222	5.8569	6	-0.55	0.6021	
	Differences of Least Squares Means						
	Threshold	Threshold	Estimate	Standard Error	DF	t Value	Pr > t
	2	5	-6.9291	3.2993	6	-2.1	0.0805
	2	OFF	4.8674	4.2487	6	1.15	0.2956
	2	ON	9.5307	4.3419	6	2.2	0.0706
	OFF	ON	4.6634	5.1702	6	0.9	0.4018