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Transit Signal Progression Algorithm for Supporting Redwood Road Transit Signal Priority (TSP)

Prepared For:

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Qinzheng Wang, Xianfeng Terry Yang, Yun Yuan

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University of Utah
Department of Civil & Environmental Engineering
110 Central Campus Drive, Suite 2000
Salt Lake City, UT 84112

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16. Abstract
In 2017, a connected vehicle (CV) corridor utilizing dedicated short-range communication (DSRC) technology was built along Redwood Road in Salt Lake County, Utah. The main purpose of the CV corridor was to implement transit signal priority (TSP) when a bus is running behind its published schedule. The performance data was generated by the transit vehicles. It was then transmitted through the DSRC system, logged by the traffic signal controller, and coupled with the Utah Transit Authority (UTA) data from the transit operation system. Then, it was analyzed including requested and served TSP, indicating bus reliability, travel time, and running time. To provide better signal coordination for buses, the signal plan for this CV corridor underwent retiming in October 2018. The goal of this project was to compare the TSP performance before and after the signal retiming. The field data of August, September, November, and December 2018 were selected for use in this evaluation. Although some negative impacts of TSP on street traffic are unavoidable in most cases, they can be minimized if the base signal control plan is properly designed. From an operational aspect, the best method for achieving this goal is to support bus progression along the corridor. Hence, another primary goal of this project was to develop a web-based tool to assist UDOT employees to design a signal progression plan to benefit both buses and passenger vehicles. This tool also helps to visualize bus running time, travel time, reliability, the bus served/requested ratio, and bus trajectory.

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Connected Vehicle, Transit Signal Priority, Traffic Reliability, Bus Travel Time, Bus Running Time, Bus Progression, Bus Trajectory

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LIST OF ACRONYMS

ATSPM	Automated Traffic Signal Performance Measures
APT	Application Programming Interface
BSM	Basic Safety Message
CV	Connected Vehicle
DSRC	Dedicated Short-Range Communications
FCC	Federal Communications Commission
GMT	Greenwich Mean Time
GPS	Global Positioning System
MMITSS	Multi-Modal Intelligent Traffic Signal System
OBU	Onboard Unit
RSU	Roadside Unit
SAE	Society of Automotive Engineers
SRM	Signal Request Message
SPaT	Signal Phase and Timing
SSM	Signal Status Message
TSP	Transit Signal Priority
UDOT	Utah Department of Transportation
USEPA	U.S. Environmental Protection Agency
UTA	Utah Transit Authority
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle

EXECUTIVE SUMMARY

Recent breakthroughs in wireless communication have led to several new technological advances in traffic control, among which connected vehicle (CV) technology is believed to be one of the most promising. CV technology is a combination of wireless communication, on-board unit (OBU) processing, and global positioning system (GPS) navagation that is used to construct a connected environment. Through a variety of communication technologies such as C-V2X, Wi-Fi, and dedicated short-range communication (DSRC), CVs are able to communicate with each other (vehicle to vehicle or V2V) and with the infrastructure such as traffic signals (vehicle to infrastructure or V2I). Such communication technology enables system users and operators to make informed decisions. Moreover, the safety and operational efficiency of the transportation system will be improved accordingly. To leverage this new technology, engineers at the Utah Department of Transportation (UDOT) launched a project to build a full-scale DSRC CV corridor beginning in 2016. The initial application equipped all transit vehicles with onboard processors and GPS to enable V2I communications, which can provide transit signal priority (TSP) to buses that are running behind their published schedules.

TSP has great potential to reduce bus delays at intersections, improve operational transit reliability, and consequently increase transit ridership due to improved service. However, activated TSP control may also have a negative impact on intersection traffic due to changed signal timings (e.g., red truncation, green extension, and phase insertions). To evaluate the performance of the Redwood Road CV corridor, UDOT officials hired Avenue Consultants to collect and compare all generated data. In the research project described in this paper, our research team assisted UDOT in conducting an in-depth evaluation of the Redwood Road CV corridor. Based on analysis of data from various sources, the first goal of this project was to examine the system performance before and after the signal retiming that was put into place in October 2018.

Despite the myriad benefits associated with TSP, it may cause additional delay to minor street traffic, which is not avoidable in most cases. However, this delay can be minimized if the base signal control plan is properly designed. For example, one useful strategy is to decrease the frequency of TSP control activation. From an operational aspect, the best way to achieve this goal is to support bus progression along the corridor, taking into account their unique travel characteristics (e.g., slower travel speed compared to cars and significant dwell time at stops), which is different from conventional passenger car progression plans. Therefore, another primary goal of this project was to develop a web-based tool to assist UDOT designers to create a signal progression plan that would benefit both buses and passenger vehicles. In addition, this tool can also visualize the related system performance of TSP, including travel time, running time, bus status (critically early, early, on time, late, critically late), bus served/requested ratios, and trajectories.

1.0 INTRODUCTION

1.1 Problem Statement

Due to rapidly increasing travel demand and the limited capacity of existing roads, current transportation systems are facing tremendous challenges such as traffic congestion, high energy consumption, and severe environmental pollution. According to Schrank et al., 8.8 billion hours of time and 3.3 billion gallons of fuel were wasted while sitting in traffic in 2017 (Schrank et al., 2019). The U.S. Environmental Protection Agency (USEPA) estimated that approximately 34% of carbon dioxide emissions and 28% of total greenhouse gas emissions were produced by daily transportation (Hockstad and Hanel, 2018). In response to this environmental crisis, large transit buses with the ability to transport considerable numbers of passengers have been introduced in many cities. Also, according to the literature, TSP strategies have been demonstrated to be efficient techniques for improving the quality of bus service by reducing travel time. TSP is often achieved by giving control preference to buses at signalized intersections and adjusting signal timing based on bus arrival information. Although this technology provides many benefits, conventional TSP has been associated with several challenges such as difficulty in predicting bus arrival time accurately. To address these challenges, a new TSP control logic based on CV technology is proposed later in this report. This new type of TSP will enable traffic signals and buses to communicate, allowing several types of data including signal status and accurate bus travel information to be obtained in real-time. Hence, the effectiveness of TSP will be greatly improved.

In late 2014, UDOT and Utah Transit Authority (UTA) officials planned to utilize CV technology to improve the reliability of bus service. In 2017, an approximately 11-mile long CV corridor with 30 signalized intersections was built along Redwood Road in Salt Lake County, Utah. As of 2016, DSRC radios have been installed at these intersections to broadcast/receive messages to/from UTA buses which are also equipped with DSRC OBUs to provide intelligent TSP to buses. When a bus comes into DSRC communication range at an intersection, the V2I function will gather CV information, which activates TSP control algorithms if the bus is behind schedule.

The effectiveness of TSP is subject to several factors, such as signal timing plans and TSP implementation rules. In order to provide more effective TSP service and minimize the corresponding negative impacts to the minor street traffic, it is essential to evaluate the performance of CV-based TSP along the deployed corridor under various scenarios. Therefore, the purpose of this project was to evaluate the system's performance under two different signal timing plans. Moreover, in order to assist UDOT employees to design signal progression and evaluate related performance more conveniently, the other goal of this project was to design a web-based tool that can visualize the bus progression and their transit operation performances (e.g., travel time, trajectories, etc.).

1.2 Objectives

The primary objective of this research project was to compare the bus travel times and reliability, the number of TSP activations, and intersection delays before and after signal retiming, which took place in the summer of 2018.

The secondary objectives of this research project were to develop a web-based tool that can assist in the design of integrated signal coordination plans (for both buses and cars) along signalized corridors and evaluate the related TSP system performances.

1.3 Scope

1: Data Collection

TSP data was collected on Redwood Road from UDOT Automated Traffic Signal Performance Measures (ATSPM) and DSRC records. Bus dwell times were collected from UTA.

2: Comparison of System Performance

The system performance (e.g., bus travel time and reliability, number of TSP activations, intersection delays, etc.) before and after the signal retiming in October 2018 was compared based on the collected field data from both UDOT and UTA.

3: Website Frame Design

The web-based tool was designed and improved based on feedback from UDOT.

4: Web-Based Tool Development and Testing

The tool functions were designed and its performance was tested.

2.0 CONNECTED VEHICLE TECHNOLOGY AND TRANSIT SIGNAL PRIORITY

2.1 Overview

This chapter introduces the current state-of-the-art CV technology. We first present an overview of TSP and then discuss the most recent developments of CV technology. Lastly, we provide a review of its applications.

2.2 An Overview of Transit Signal Priority

TSP is a set of technologies that provide buses with control preference at signalized intersections (Lin et al., 2015). By providing extra green time to buses based on their arrival information, TSP has been found to effectively improve transit service quality and increase ridership due to fewer delays and a reduction in travel time. TSP strategies can be broken into two categories: passive and active TSP (Urbanik, 1977). The former is based on knowledge of bus routes and ridership patterns without the use of detectors. Its purpose is to improve the performance of TSP operation by utilizing pre-timed signal plans, including splitting signal phases, implementing dedicated bus lanes, or extending green times for buses (Sunkari et al., 1995). Compared to passive TSP, active TSP operates priority controls using detectors, sensors, or other technologies. Active TSP can be further classified into unconditional and conditional controls. In the case of unconditional active TSP, signal priority is based on the presence of buses at signalized intersections and does not take into account bus lateness (Lin et al., 2015). However, the conditional active TSP uses rules to provide signal priority based on the lateness of buses. Hence, the level of service at intersections was not severely impacted after implementation.

TSP was first studied in 1975 by Ludwick and John using a microscopic simulation model known as UTCS-1 to evaluate the initial Urban Traffic Control System-Bus Priority System (UTCS-BPS) in Washington, D.C. Since then, it has become a popular research topic. Several strategies, including adjustment of cycle length and signal timings (Zhang et al., 2004; Ji et al., 2004; Feng et al., 2007), splitting phases (Garrow and Machemehl, 1999), and metering of vehicles (Urbanik, 1977), have been proposed as the most effective implementation of TSP. The early studies focused on passive TSP control. As technology has progressed, a great many scholars have proposed several active TSP strategies or rule-based TSP (Ludwick and John, 1975; Francois and Hesham, 2005; Zhou and Gan, 2009; Evans and Skiles, 1970; Allsop, 1977; Hounsell et al., 1996; Hounsell et al., 2000; Skabardonis, 2000; Janos and Furth, 2002; Satiennam et al., 2005; Ma and Bai, 2008; He and Head, 2011; Altun and Furth, 2009), and model-based TSP (Lin et al., 2013; Head et al., 2006; Ma et al., 2010; Chang et al., 1996; Mirchandani et al., 2001; Liu et al., 2003; Li et al., 2011). Although this apporoach has been demonstrated to be one of the most effective methods for decreasing bus travel time and delays, it is not fully responsive to traffic conditions and bus status due to limited information (Hu et al., 2015). However, the emergence of CV technology shows promise for solving these challenges since it permits traffic controllers and buses to communicate with each other, allowing the bus arrival information to be obtained accurately in real-time. Until recently, only a few scholars have conducted simulations or field tests for TSP utilizing CV technology (Ma et al., 2010; Hu et al., 2015; Wang et al., 2014; Ahn et al., 2015; Hu et al., 2014). However, as previously mentioned, there is a large body of research on traditional TSP control. A summary is given in Table 2.1.

Table 2.1 Summary of the effectiveness of TSP applications.

Scenario selection	Method	Measurements and results	Reference
Newark, New Jersey	Simulation	Bus travel time reduced by12% to 21%	(Hu et al., 2014)
Snohomish County, Washington	Simulation	Bus travel time reduced by 5% and the average person delay decreased	(Smith et al., 2005)
Jinan, China	Field test	Average bus delay decreased by 34.7% and the average motor vehicle delay increased by 8.9%	(Muthuswamy et al., 2007)
Tucson, Arizona	Simulation	Average bus delay reduced by 50% in congestion conditions	(Wang et al., 2007)

Arizona	Field test	Bus travel time reduced by 6.1%-8.2%	(Ma et al., 2010)
Fairfax, Virginia	Simulation	Average bus delay reduced by 59%	(He et al., 2011)
Ann Arbor, Michigan	Simulation	Bus travel time reduced by 13.5%	(Khasnabis et al., 1996)
Central Avenue, Minneapolis	Field test	Bus travel time reduced by 3-6%	(Liao et al., 2007)
Vancouver, Canada	Simulation	Bus travel time reduced by 33%	(Ekeila et al., 2009)
Atascadero, California	Simulation	CO_2 emissions of all vehicles reduced by about 1%	(Yelchuru et al., 2014)
Taicang City, China	Field test	Bus travel time reduced by 33 – 40%	(Wang et al., 2014)
Portland, Oregon	Simulation	Bus travel time reduced by 10%	(Kimpel et al., 2005)
King County, Washington	Field test	Total crashes reduced by 13%, property-damage-only crashes reduced by 16%, and fatal crashes reduced by 5%	(Ahn et al., 2015)

2.3 Connected Vehicles

CV technology refers to a series of state-of-the-art equipment that enables information to be transmitted between vehicles and roadway infrastructures. In a fully CV-deployed environment, vehicles can broadcast a variety of traffic information, such as their location and speed, to the surrounding infrastructure. Simultaneously, information transmitted by the infrastructure, such as the current traffic status, can also be received by vehicles. Full implementation of CV technology can alleviate traffic congestion, reduce crashes, improve mobility, and decrease the environmental impacts of traffic. Moreover, it helps travelers to make more informed decisions by warning them of potential hazards and giving advice about the speeds at which they should enter and exit intersections with the least number of stops.

Wireless Communication Technology

The most distinctive feature of CV is wireless communication with other vehicles and infrastructures by transmitting or receiving real-time information. Without the help of any physical medium like cables and wires, it can transmit information between two or more locations via electromagnetic waves. Due to the flexibility and convenience, a wide variety of wireless communication systems are now on the market and play a significant role in our daily lives. Although these wireless technologies vary significantly from each other, communication range (the distance the communication signals can travel) and latency (the time interval between the stimulation and response) remain universal concerns. The range is affected by several factors and may vary significantly from the design phase to implementation and from one point to another (Zeng et al., 2012). Table 2.2 summarizes the characteristics of several commonly used wireless technologies (Crash Avoidance Metrics Partnership-CAMP Vehicle Safety Communications Consortium, 2005).

Table 2.2 Comparison of wireless technologies.

Wireless Technologies	Communication Range	Latency	Advantage	Disadvantage
DSRC	1000 m	200 micro sec	Improved flexibility and collision avoidance	Low scalability
Digital cellular	~ 4 – 6 km	1.5 - 3.5 sec	High capacity and less transmission power	Massive infrastructure and more complex management

Bluetooth	10 m	3 - 4 sec	High availability and efficiency	Low security and lower bandwidth
Digital Television	~ 40 km	10 – 30 sec	Better picture and sound quality	Easy loss of signals and high devices requirement
Radar	2 km	NA	Radar can penetrate and see through the medium	The time to distinguish an object is long
Two-Way Satellite	NA	60+ sec	Coverage over geographical area is large	High cost and large propagation delay
IEEE 802.11 Wireless LAN	1000 m	3 – 5 sec	Higher frequency range and less cost	Traffic disruptions

DSRC

DSRC is the predominant wireless communication technology in the CV market today. It was implemented in 1997 when the American Intelligent Transportation Association requested that Congress deploy a 75 MHZ spectrum in the 5.9 GHz band for ITS. Since 2004, the Federal Communications Commission (FCC) has dedicated itself to using this spectrum to increase communications between vehicles and infrastructure. Figure 2.1 shows the integration of the DSRC vehicle infrastructure network (Zeng et al., 2009).

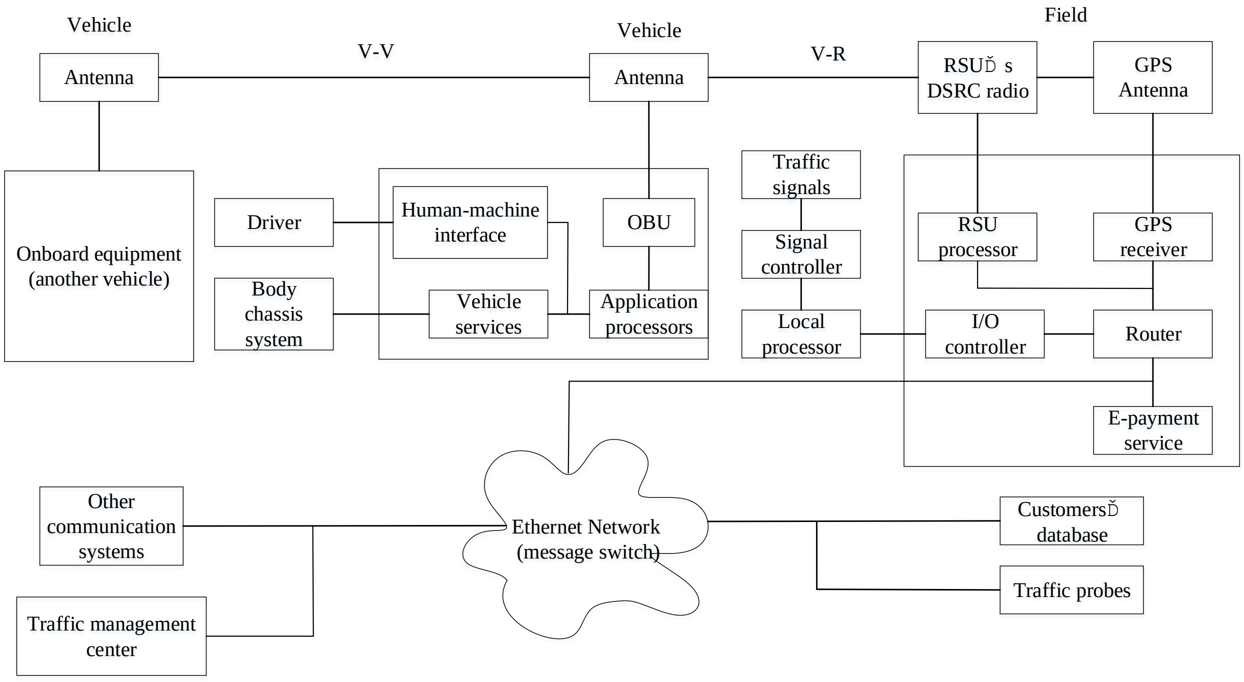

Figure 2.1 The DSRC network of vehicle infrastructure integration.

Compared to other wireless technologies, the unique technological advantages of DSRC make it ideal for transportation applications. Specifically, it has its own designated licensed bandwidth that ensures the safe transmission of information and can prevent the abuse of communication resources. For example, its low latency can ensure messages are transmitted with little delay. Another advantage of DSRC is that it is not affected by adverse weather conditions or illumination, ensuring system stablity. Moreover, DSRC is capable of long-distance perception between vehicles, which is critical in cases when vehicles must maintain hundreds of feet of headway for safety.

Hardware

To guarantee successful V2V and V2I communication, two types of in-vehicle and infrastructure-based devices must be installed. In-vehicle devices, commonly referred to as OBUs, are mounted on vehicles to allow communication with other devices. These mainly include the original equipment and aftermarket devices. The original equipment includes the devices integrated into the vehicle during its production. Aftermarket devices refer to those added to the vehicle after it is sold. With regard to functional capability, aftermarket devices can be categorized into three types (Harding, 2014):

- Vehicle awareness devices connected to the vehicle as a power source and able to transmit information to surrounding vehicles.
- Aftermarket safety devices that provide vehicles with power sources, transmit information to surrounding vehicles, and receive information from other vehicles to comply with safety regulations.
- Retrofitted safety devices connected to vehicle databases to offer additional applications.

The infrastructure-based devices, known as roadside units (RSU), communicate with vehicle on-board devices via DSRC radio communications. RSUs can be installed in various transportation facilities, such as traffic signals and road signs.

2.4 CV Applications

Over the past few years, scholars have proposed a set of CV applications and industry oversight groups. According to the USDOT, they can be grouped into six areas based on the following operational objectives: safety, mobility, environmental factors, agency data, weather on the road, and smart roadsides. Each area has multiple subcategories. This section provides an overview of the applications of three main areas: safety, mobility, and environmental factors.

Safety Applications[1][2]

- Red-light violation warning allows RSUs to transmit information regarding signal phase and timing (SPaT) and other data to warn of impending red-light violations.
- Curve speed warning informs drivers of potentially dangerous driving conditions.
- Stop sign gap assist transmits warnings to drivers of potential collisions at stop sign intersections.

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[1] https://www.its.dot.gov/pilots/pilots_v2i.htm

[2] https://www.its.dot.gov/pilots/pilots_v2v.htm

- Spot weather impact warning occurs when RSUs broadcast warnings of local hazardous weather conditions to nearby vehicles.
- Reduced speed/work zone warns drivers to slow down, change lanes, or come to a stop within work zones.
- Pedestrian in signalized crosswalk warns bus drivers that pedestrians are in their path.
- Emergency electronic brake lights alert drivers of hard braking in the traffic stream ahead, which offers them additional time to assess the situation.
- Forward collision warning occurs when OBUs broadcast information to help drivers avoid or mitigate the severity of rear-end crashes.
- Intersection movement assist sends warnings to drivers when it’s not safe to enter an intersection.
- Left-turn assist helps drivers to avoid crashes when making unprotected left turns.
- Blind spot/lane change warns drivers about the presence of same-direction traffic in an adjacent lane or of host vehicle lane changes.
- The application for turning right in front of a bus informs bus drivers when a vehicle is attempting to go around the bus to make a right turn when the driver departs from a bus stop.

Mobility Applications[3]

- Advanced traveler information system acquires, analyzes, and sends information to help drivers prepare for various hazardous road conditions.
- Intelligent traffic signal system is an optimization application that can accommodate signal priority, preemption, and pedestrian movement.
- TSP provides signal priority to buses at individual intersections or along a corridor.
- Emergency vehicle preemption gives priority to emergency vehicles.
- Dynamic speed harmonization application recommends optimal speeds for drivers under various traffic conditions such as in congested areas and near crashes.
- Queue warning sends real-time information about existing and impending queues.

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[3] https://www.its.dot.gov/pilots/pilots_mobility.htm

- Cooperative adaptive cruise control enables vehicles to drive in groups with small gaps to increase throughput and dynamically adjust their speeds to improve traffic stability.
- Dynamic transit operations links travelers with transportation service resources.
- Dynamic ridesharing enables riders to connect with drivers through their smartphones and utilize traveler information for real-time carpooling decisions.
- Drayage optimization application can increase the efficiency of truck movement between freight facilities and balance early and late arrivals.

Environmental Applications[4]

- Eco-approach and departure application broadcasts current signal states and sends recommendations to drivers to approach and depart intersections for minimum environmental impact.
- Eco-traffic signal priority gives precedence to buses and freight vehicles based on several environmental factors such as vehicle type and passenger count.
- Eco-traffic signal timing uses data collected from vehicles to optimize the signal timing as well as to reduce fuel consumption and emissions.
- Connected eco-driving application provides real-time driving advice, such as suggesting an optimal speed and when to accelerate and decelerate to reduce the drivers' environmental impacts.
- Eco-speed harmonization application takes environmental impacts into consideration by recommending driving speeds in response to various traffic conditions, such as congestion.
- Eco-ramp metering uses collected data to optimize the operation of traffic signals at freeway on-ramps to manage vehicle entries and reduce fuel consumption and emissions.
- Eco-smart parking application decreases search time and emissions by providing real-time information about parameters such as location availability and price.
- Dynamic eco-routing analyzes real-time traffic conditions to provide the most eco-friendly route in order to minimize fuel consumption and emissions.

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[4] https://www.its.dot.gov/pilots/pilots_environment.htm

3.0 PERFORMANCE EVALUATION OF CV-BASED TSP BETWEEN TWO SIGNAL PLANS

3.1 Overview

This chapter provides a description of the deployment of DSRC along the Redwood Road corridor in Salt Lake County, Utah. Then, TSP performance is analyzed using collected data from both UDOT and UTA. Finally, TSP performance of two different signal timing plans is compared.

3.2 Introduction of the DSRC Corridor in Utah

Connected Vehicles have great potential to enhance safety, improve mobility, and alleviate the environmental impact of road travel (Hill and Garrett, 2011). To achieve these benefits, many CV applications have been tested over the past several years in locations such as New York City and at the Tampa-Hillsborough Expressway Authority. From their humble beginnings as pilot participants in the CV Pooled Fund, the American Association of State Highway Transportation Officials and UDOT began to discuss the potential of deploying CV technology and V2I systems late in 2014. The steps of the original deployment included:

- Obtaining experience in purchasing and installing DSRC equipment.
- Identifing the installation costs of deploying a program that could generate tangible benefits.
- Building a test CV corridor with multiple CV applications (Leonard et al., 2019).

For the initial application, UDOT and UTA deployed the TSP system along Redwood Road in Salt Lake County to enhance schedule reliability. Several transit vehicles were equipped with onboard processors, GPS systems for communicating with traffic signals, and DSRC radios. Such V2I communication can enable transit vehicles to request TSP at intersections if a bus is behind its published schedule. This conditional control system provides a good opportunity to assess the potential benefits of this technology.

The 11-mile long deployment site with 30 signalized intersections extends from 400 South Redwood Road to 8040 South Redwood Road in Salt Lake County, as shown in Figure 3.1. This corridor runs through commercial/retail areas, residential areas, and near educational institutions (Leonard et al., 2017). Bus Route 217 travels along this corridor. It, like other buses along this route, operates with a 30-minute headway in the early morning and late evening hours, a 60-minute headway after 9:00 PM, and a 15-minute headway during the rest of the day.

Figure 3.1 DSRC corridor for transit signal priority in Salt Lake County.

3.2.1 Application Hardware

For this CV-based TSP application, DSRC radios from four vendors (Savari, Arada, Cohda, and Lear) were installed at 30 intersections along the corridor for testing. Those four types of radios were also fitted on several buses to allow support information to be transmitted between buses and roadside infrastructure. According to the Society of Automotive Engineers

(SAE), there are four types of transmitted basic safety messages (BSM): SPaT, MAP, Signal Request Message (SRM), and Signal Status Message (SSM) (SAE, 2016). A detailed introduction of those messages is provided in Table 3.1.

Table 3.1 Introduction of V2I broadcasted messages.

Message type	Function	Message information
BSM	Information related to the real-time operating status of vehicles	Vehicle positions; speed; heading; brake status; windshield wiper status; headlight status
SPaT	Information about the current status of traffic signals	Intersection ID; signal status; active priority and preemption state data
MAP	Geometric information of the intersection defined at the lane level	Intersection ID; Refpoint; lane number; lane width
SRM	Information sent by several types of vehicles (e.g., transit) to request signal priority.	Vehicle type; time of service; type of request
SSM	Information to reply to a service request sent by the SRM message	All active priority and preemption states; all pending requests; signal state

Since the selected four vendors manage the transmitted messages in different ways, yet remain compatable with each other, UDOT installed small stand-alone Linux computers at each intersection to collect information. BeagleBone Black industrial-grade Linux boards with 1GHz CPU with 4GB of flash memory were selected due to excellent performance and processing capability (Leonard et al., 2019).

3.2.2 Application Software

The software supporting this TSP application along the DSRC corridor is based on the Multi-Modal Intelligent Traffic Signal System (MMITSS), which was developed for the CV Pooled Fund Study by the University of Arizona and the University of California Partners for Advanced Transportation Technology (PATH) program. MMITSS is a general system capable of accommodating TSP, emergency vehicle preemption, and pedestrian movement to maximize network performance along signalized corridors. Only TSP was selected for the initial deployment in Utah. According to the standards of MMITSS, agencies can manage bus service by granting bus drivers priority based on arrival time and occupancy. More specifically, if the arrival time to a bus station is more than five minutes behind schedule and the bus occupancy is over 20%, the bus will receive priority to help it get back on schedule. Since various modifications were made to the original MMITSS software to accommodate the Utah traffic system, the version that was applied in this deployment is called MMITSS-Utah.

3.3 Data Description and Processing

3.3.1 Data Description

In this project, assessing TSP performance required various datasets from three distinct sources (DSRC, ATSPM, and UTA), which are shown in Figure 3.2 (Leonard et al., 2019). The figure includes the available field data and describes how they were used to correlate the various datasets. The labels on the arrows indicate the fields that were used to link the table and join records between the datasets. It must be noted that the UTA datasets were used independently of the others. In this study, the four months in 2018 (August, September, November, and December) were selected for evaluation.

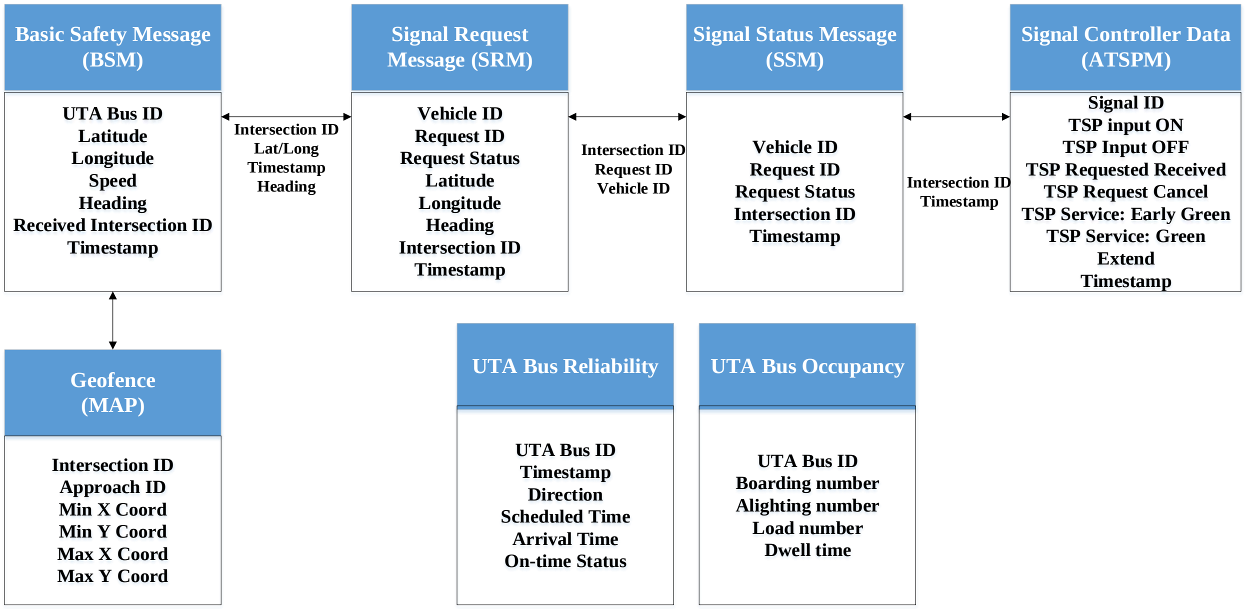


Figure 3.2 Diagram of available datasets *(Leonard et al., 2019).*

DSRC Data

DSRC data were obtained from the system that manages communication between the buses and traffic signals. Four types of messages were broadcast between OBUs and RSUs including MAP, BSM, SRM, and SSM messages. The first type focuses on information about the intersections, such as the street names and the number of lanes, which are used to delineate the “geofence” around each equipped intersection. The OBUs broadcast information about buses, creating a record of BSMs including bus location (longitude, latitude, elevation), motion (speed and direction headed), bus ID#, and the time the messages were sent. A record of an SRM message is created when OBUs send a TSP request to RSUs. Similarly, each SRM includes a randomly generated bus ID, location (longitude, latitude, elevation), bus motion (speed, direction headed), the location of the intersection with which the bus is communicating, and time the message was sent. The SSM message includes a timestamp, the bus ID, and the request status.

UTA Data

This system provides two datasets: the reliability dataset and the occupancy dataset. Each record in the first dataset includes a timestamp, bus ID, direction, the actual and scheduled arrival time to the bus stops, and the bus status ("critically early," "early," "on time," "late," and "critically late"). These statuses are determined via 5-minute and 15-minute differences between the actual and scheduled arrival times, as shown in Table 3.2. The occupancy database records the number of passengers on the bus, the number of passengers that boarded and departed at each bus station, and the dwell time at each bus station.

Table 3.2 Rules to define the bus status at each timepoint.

Actual arrival time – Scheduled arrival time (min)	Bus status
$(-\infty, -15)$	Critical Late
$(-15, 0)$	Late
$(0, 5)$	On-Time
$(5, 15)$	Early
$(15, +\infty)$	Critical Early

ATSPM Data

ATSPM data were obtained from UDOT's traffic signal system. The data included the signal ID, timestamp, event number, and event parameter. The event number and event code were defined according to "Indiana Traffic Signal High-Resolution Data Logger Enumerations."

3.3.2 Data Processing

Before conducting the evaluations, the obtained raw data were processed. Notably, an RSU can only receive a message sent by OBUs within a 1,000-foot range. However, this distance can be increased in the real world. As a result, the message sent by buses to one signal can be received by other signals. In addition, the BSM data are broadcast every one-tenth of a second, which generate much redundant data. To solve this problem, the BSM and MAP data were paired by signal ID and the BSM data were filtered using the maximum and minimum limits set by each geofence per intersection. Then, the limit, time, and direction filters were used to determine the first and last records for each occurrence and to identify the time the bus spent at each signal.

All the DSRC data were reported at Greenwich Mean Time (GMT) instead of local time. Due to the fact that daylight savings occured during the data collection period, adjustments were made to the timestamps depending on the date of data collection. The driving direction was referred to as “direction headed” in both BSM and SRM datasets, and was determined by the compass direction or “northbound,” “southbound,” “westbound,” or “eastbound.” Then, the “westbound” and “eastbound” data were filtered since Route 217 travels from northbound/southbound to southbound/northbound.

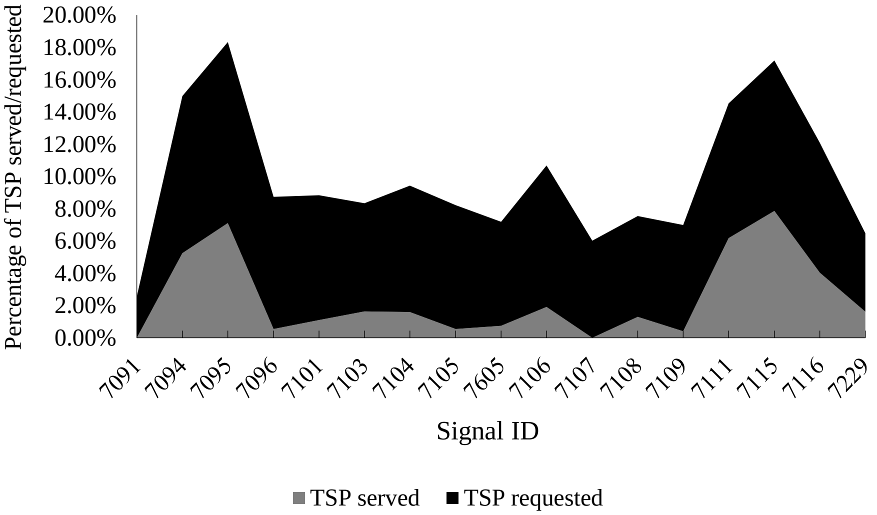
During the data review period, we found that Intelight MaxTime and Econolite Cobalt brands of controllers were utilized to operate traffic signals along this corridor. Each type interpreted the TSP event codes differently. For example, event codes 517 and 518 were used to denote TSP activation by the Intelight Controller; however, TSP activations were denoted as codes 113 and 114 by Econolite. Therefore, these unique event codes needed to be converted to TSP Check In, Check Out, and Granted.

The SRM dataset was used to determine if TSP was requested by bus drivers and whether a requested TSP could be obtained from ATSPM datasets. Hence, these two datasets can be used to determine the percentage of granted TSP for a specific time (e.g., a particular day). However, after these data were reviewed, we found that some were lost, which resulted in different dates for the two datasets. This problem was solved by further analyzing the data to ensure that the dates of the two datasets were the same.

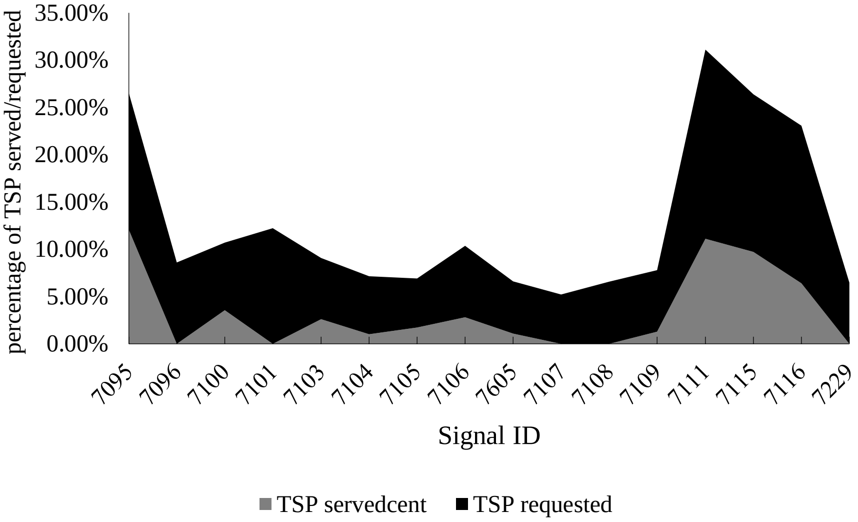
3.4 Analysis of Results

3.4.1 Analysis of TSP Requested and Granted

One key step for evaluating the effectiveness of the TSP system is to determine how often it is requested and granted. This is also critical for understanding changes in bus performance before and after signal retiming. Hence, for the study, the BSM and SRM datasets were utilized to determine the number of buses traveling through intersections and the number of times a TSP was requested. When a bus travels through a DSRC-equipped intersection, it broadcasts multiple messages, which are recorded in the BSM datasets. These multiple records were grouped into a single event per trip, which represents its travels through this intersection. Then, the total number of bus trips at each intersection was calculated by aggregating the grouped bus events. The total number of TSP requests at each intersection was determined from the SRM dataset. Then, the rate of TSP requests was obtained by comparing these two values. The ATSPM dataset was utilized to identify how many TSP requests were actually granted. The signal controller logs an event when it receives a TSP request, which is designated as granted if extra time is offered to buses. Then, the frequency of granted requests can be determined by comparing the events logged by signal controllers to bus events. Figures 3.3 (a) and (b) show the percentage of TSP requests and grants at each intersection before and after signal retiming. The grey area indicates the distribution of the percentage of granted TSP requests and the black area indicates the distribution of the non-granted percentage.



(a) Rate of TSP requests and grants before signal retiming.



(b) Rate of TSP requests and grants after signal retiming.

Figure 3.3 Rate of TSP requests and grants with various signal plans.

According to the data analysis, most TSP requests were not granted under both signal plans. One major reason is that most buses can travel through intersections during the green interval without utilizing TSP, which leads to requests being canceled. At some intersections, the TSP service rate is quite small because the traffic volume on the side streets is low, which causes more green time to be allocated to traffic in the main street. In general, the average rate of granted TSP requests before signal retiming was 33.13%, which is lower than what occurred after signal retiming (35.29%).

3.4.2 Reliability Analysis

One of the most important reasons for building the CV corridor enabled with TSP technology was to improve the reliability of the bus system. UTA's method of calculating reliability was adopted in this research, in which all on-time arrivals were divided by total arrivals for a specific time point. This process resulted in a UTA reliability dataset. Figure 3.4 shows the reliability rates before and after signal retiming for both the northbound and southbound directions. Average reliabilities for these directions before signal retiming were 89.44% and 92.07%, respectively. After signal retiming, they improved to 92.09% and 93.28%, respectively, largely because the TSP granted rate after signal retiming was higher than before the retiming, causing many more buses to run on time.

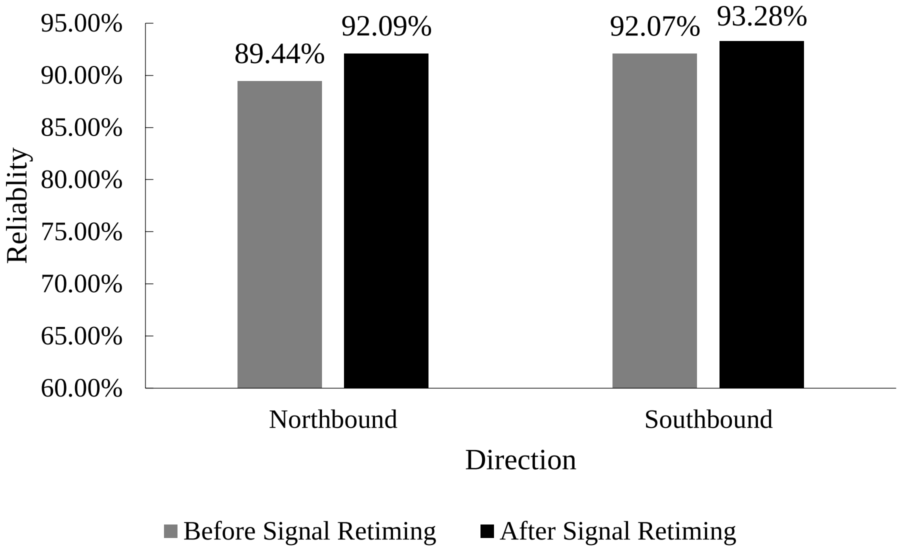


Figure 3.4 Reliability in the northbound and southbound directions of route 217 before and after signal retiming.

Reliability reflects the percentage of buses running on time through each time point. To improve the reliability of transit operations, it is critical to study the average rate of each bus status. As shown in Table 3.3, each rate is calculated by counting the number of bus arrivals that are aligned with each state for each time point and dividing it by the total number of arrivals. We found that the percentage of late arrivals was much higher compared to other statuses, which means the actual arrival times of most buses were between 5 and 15 minutes later than their scheduled times. Therefore, it is still necessary to improve bus reliability by reducing dwell times, increasing travel speeds, or creating a more realistic time schedule.

Table 3.3 Bus status rates in the northbound and southbound directions of Route 217 before and after signal retiming.

Direction	Signal Plan	Bus Status			
		Critical Early	Early	Late	Critical Late
Northbound	Before signal retiming	0.003%	1.82%	8.27%	0.47%
	After signal retiming	0%	1.98%	5.57%	0.38%
Southbound	Before signal retiming	0.02%	0.85%	6.61%	0.45%
	After signal retiming	0.02T	1.03%	5.27%	0.40%

3.4.3 Travel and Running Time Analysis

As previously stated, the bus travel and running time was analysed using UTA's reliability and occupancy datasets. Travel time refers to the period a bus spends from the first point (departure station) to the last point (terminal station). Running time can be calculated by deducting the dwell time from the travel time. Figure 3.5 shows the travel time before and after signal retiming in both the northbound and southbound directions. These travel times before signal retiming were 4,107 seconds and 4,191 seconds, respectively, which were higher than the 3625.06 seconds and 4095.07 seconds after signal retiming. Despite the difference in dwell times at each station under the two signal plans, the reduction of travel time after signal-retiming was mainly due to a decrease in running time, as shown in Figure 3.6. Another reason is that the TSP granted rate after signal retiming was higher than before the retiming occured. More specifically, after signal retiming, TSP service was activated during the red interval, which resulted in less stop time at intersections. Therefore, both travel and running time were reduced after signal retiming.

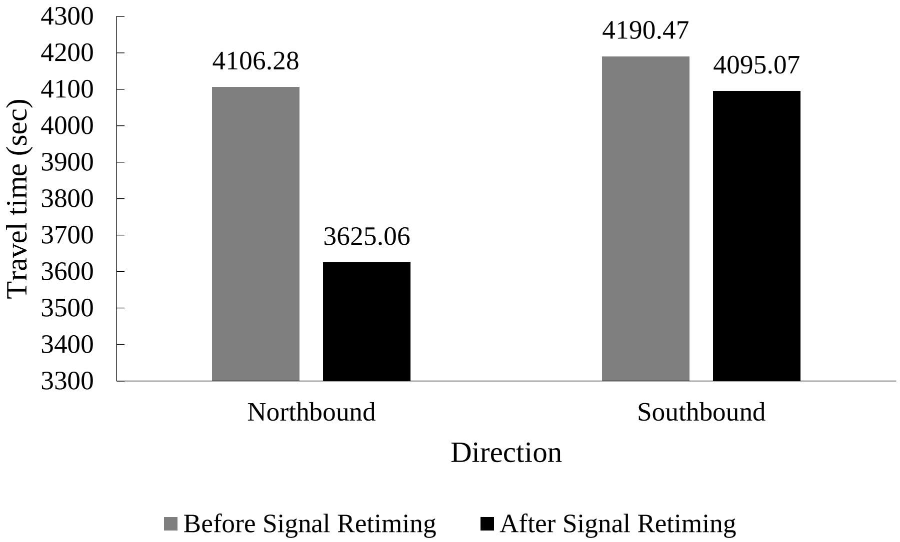


Figure 3.5 Bus travel time for northbound and southbound directions of route 217 before and after signal retiming.

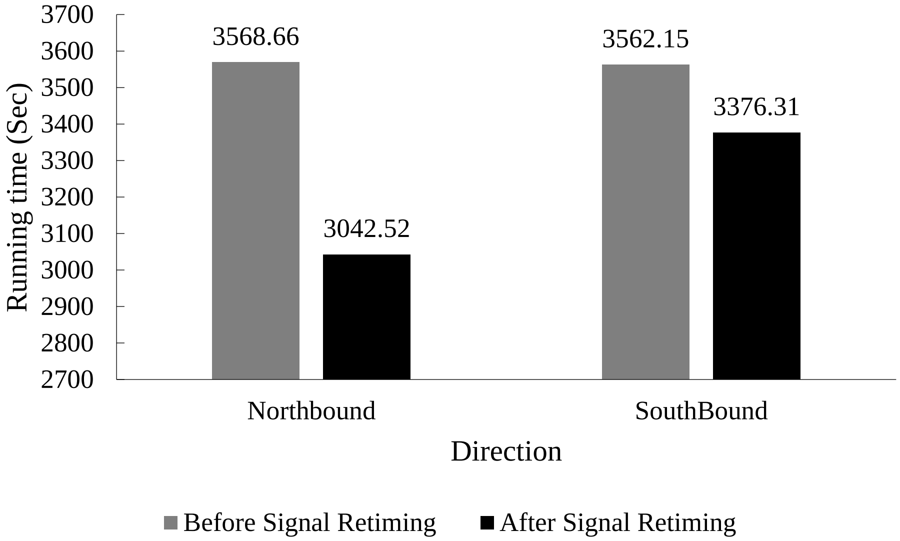


Figure 3.6 Bus running time for northbound and southbound directions of route 217 before and after signal retiming.

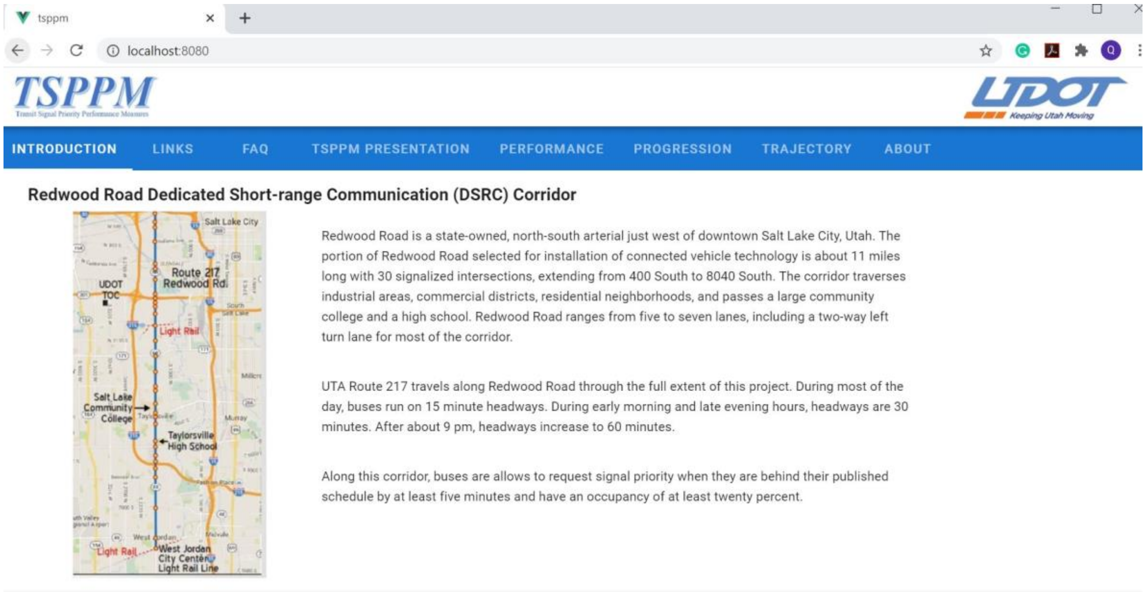
4.0 WEB-BASED TOOL INTRODUCTION

4.1 Overview

This chapter serves as an introduction to the designed web-based tool that will give engineers and researchers a better understanding of CV-based TSP technology. First, each function on the website is explained in detail. Then, detailed instructions for potential users are provided.

4.2 Web-Based Tool Overview

The web-based tool, the Transit Signal Priority Performance Measures (TSPPM), is designed to help traffic engineers and scholars directly measure the performance of TSP logic and the specific signal timing plans of the Redwood Road connected corridor. The interface of this tool is shown in Figure 4.1, which includes the following eight menus: “introduction,” “FAQ,” “links,” “TSPPM presentation,” “performance,” “progression,” “trajectory,” and “about,” which are discussed in detail in the next section.



Redwood Road Dedicated Short-range Communication (DSRC) Corridor

Redwood Road is a state-owned, north-south arterial just west of downtown Salt Lake City, Utah. The portion of Redwood Road selected for installation of connected vehicle technology is about 11 miles long with 30 signalized intersections, extending from 400 South to 8040 South. The corridor traverses industrial areas, commercial districts, residential neighborhoods, and passes a large community college and a high school. Redwood Road ranges from five to seven lanes, including a two-way left turn lane for most of the corridor.

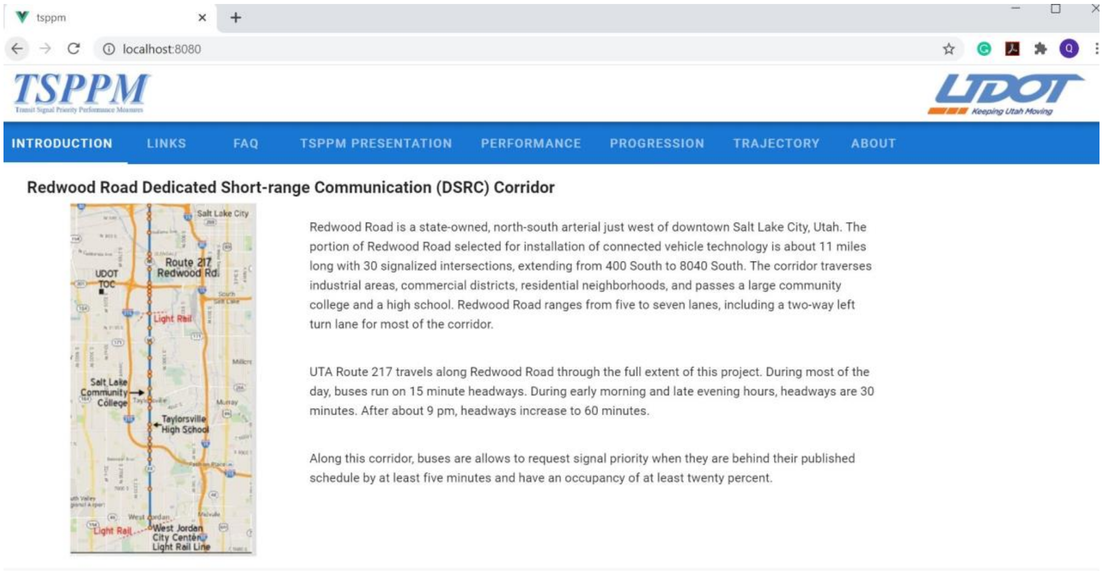
UTA Route 217 travels along Redwood Road through the full extent of this project. During most of the day, buses run on 15 minute headways. During early morning and late evening hours, headways are 30 minutes. After about 9 pm, headways increase to 60 minutes.

Along this corridor, buses are allows to request signal priority when they are behind their published schedule by at least five minutes and have an occupancy of at least twenty percent.

Figure 4.1 Display of the designed website.

(1) Introduction

The purpose of “Introduction” is to give a brief overview of the DSRC corridor along Redwood Road as well as the implementation logic of TSP. The interface is shown in Figure 4.2.



Redwood Road Dedicated Short-range Communication (DSRC) Corridor

Redwood Road is a state-owned, north-south arterial just west of downtown Salt Lake City, Utah. The portion of Redwood Road selected for installation of connected vehicle technology is about 11 miles long with 30 signalized intersections, extending from 400 South to 8040 South. The corridor traverses industrial areas, commercial districts, residential neighborhoods, and passes a large community college and a high school. Redwood Road ranges from five to seven lanes, including a two-way left turn lane for most of the corridor.

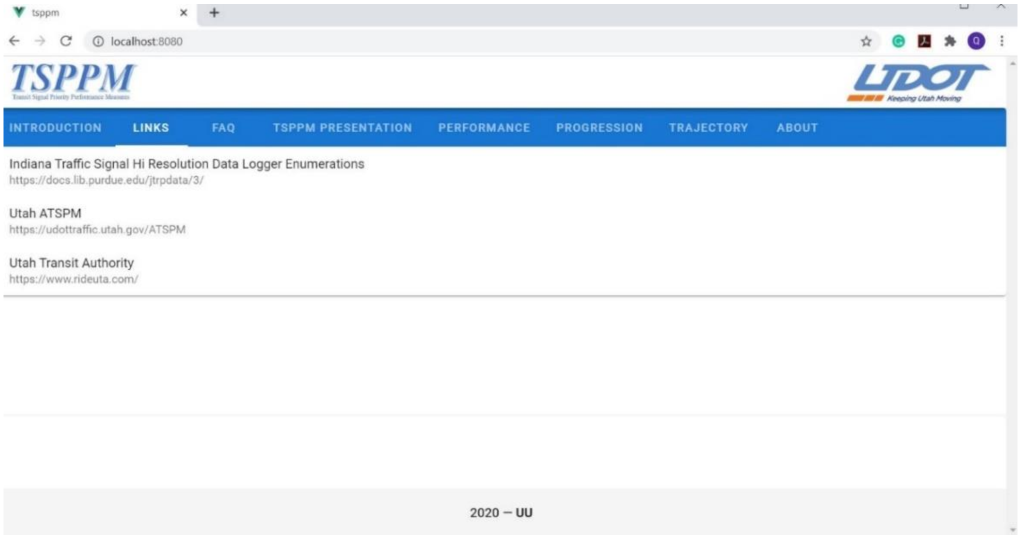
UTA Route 217 travels along Redwood Road through the full extent of this project. During most of the day, buses run on 15 minute headways. During early morning and late evening hours, headways are 30 minutes. After about 9 pm, headways increase to 60 minutes.

Along this corridor, buses are allows to request signal priority when they are behind their published schedule by at least five minutes and have an occupancy of at least twenty percent.

Figure 4.2 The Introduction interface from the designed website.

(2) Links

This menu contains several useful links that clarify several key methods for processing the raw data and evaluating the related performance of this corridor. The interface is shown in Figure 4.3.



Indiana Traffic Signal Hi Resolution Data Logger Enumerations
https://docs.lib.purdue.edu/jtrpdata/3/

Utah ATSPM
https://udottraffic.utah.gov/ATSPM

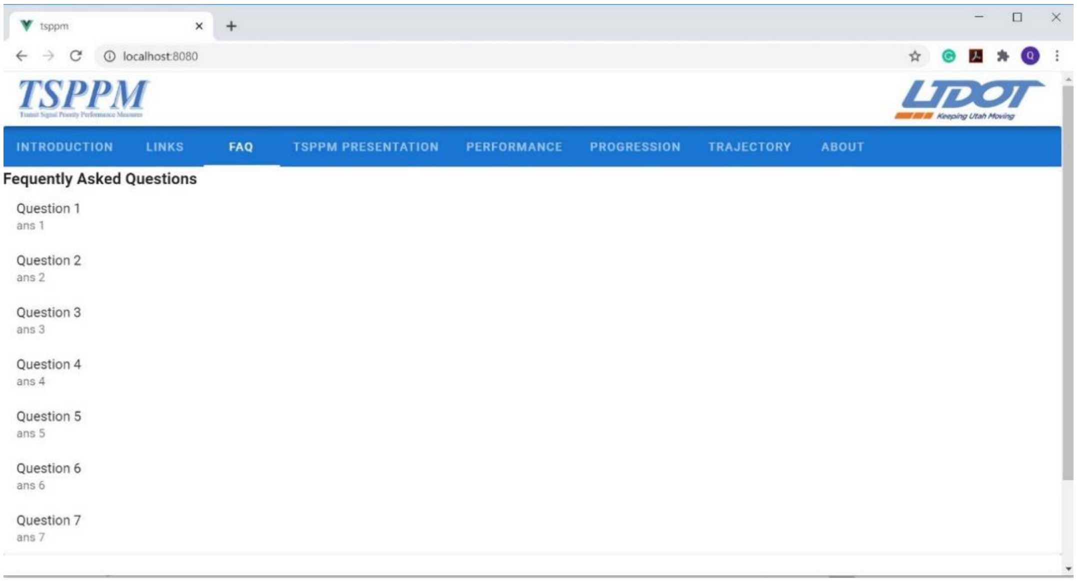
Utah Transit Authority
https://www.rideuta.com/

2020 — UU

Figure 4.3 The Links interface from the designed website.

(3) FAQ

These frequently asked questions (FAQ) will give users a better understanding of the TSPPM technology. The FAQ interface is shown in Figure 4.4.



Fequently Asked Questions

Question 1
ans 1

Question 2
ans 2

Question 3
ans 3

Question 4
ans 4

Question 5
ans 5

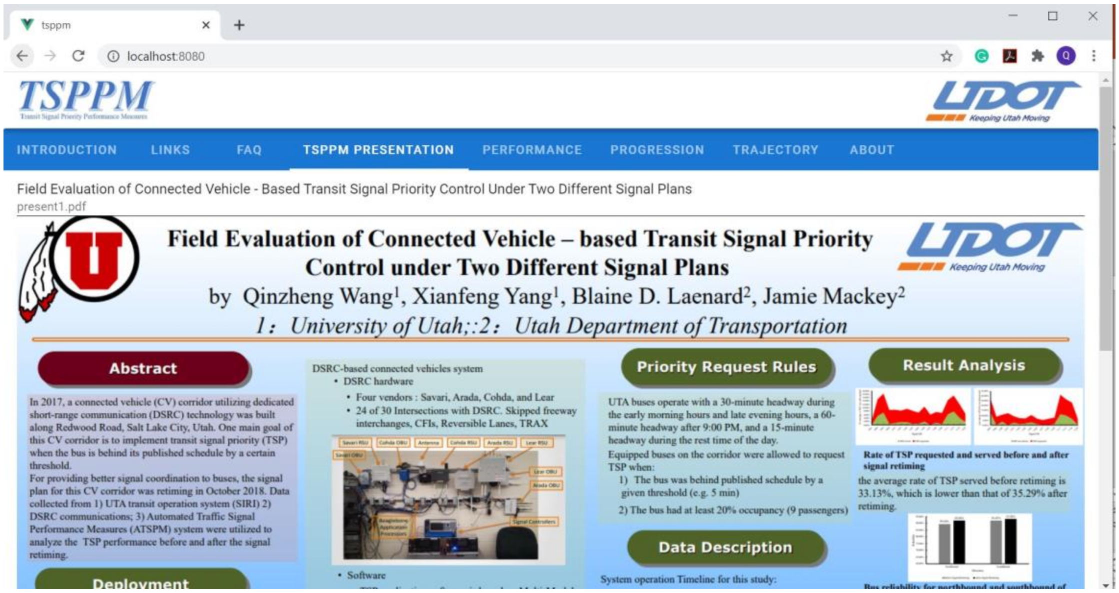
Question 6
ans 6

Question 7
ans 7

Figure 4.4 The FAQ interface from the designed website.

(4) TSPPM Presentation

This menu encompasses how developers have created the TSPPM system, including presentations, papers, and meeting notes, as shown in Figure 4.5.



Field Evaluation of Connected Vehicle - Based Transit Signal Priority Control Under Two Different Signal Plans

Field Evaluation of Connected Vehicle – based Transit Signal Priority Control under Two Different Signal Plans

by Qinzheng Wang[1], Xianfeng Yang[1], Blaine D. Laenard[2], Jamie Mackey[2]

1: University of Utah;:2: Utah Department of Transportation

In 2017, a connected vehicle (CV) corridor utilizing dedicated short-range communication (DSRC) technology was built along Redwood Road, Salt Lake City, Utah. One main goal of this CV corridor is to implement transit signal priority (TSP) when the bus is behind its published schedule by a certain threshold.
For providing better signal coordination to buses, the signal plan for this CV corridor was retiming in October 2018. Data collected from 1) UTA transit operation system (SIRI) 2) DSRC communications; 3) Automated Traffic Signal Performance Measures (ATSPM) system were utilized to analyze the TSP performance before and after the signal retiming.

DSRC-based connected vehicles system
- DSRC hardware
  - Four vendors : Savari, Arada, Cohda, and Lear
  - 24 of 30 Intersections with DSRC. Skipped freeway interchanges, CFIs, Reversible Lanes, TRAX
- Software

UTA buses operate with a 30-minute headway during the early morning hours and late evening hours, a 60-minute headway after 9:00 PM, and a 15-minute headway during the rest time of the day.
Equipped buses on the corridor were allowed to request TSP when:
1) The bus was behind published schedule by a given threshold (e.g. 5 min)
2) The bus had at least 20% occupancy (9 passengers)

System operation Timeline for this study:

Rate of TSP requested and served before and after signal retiming

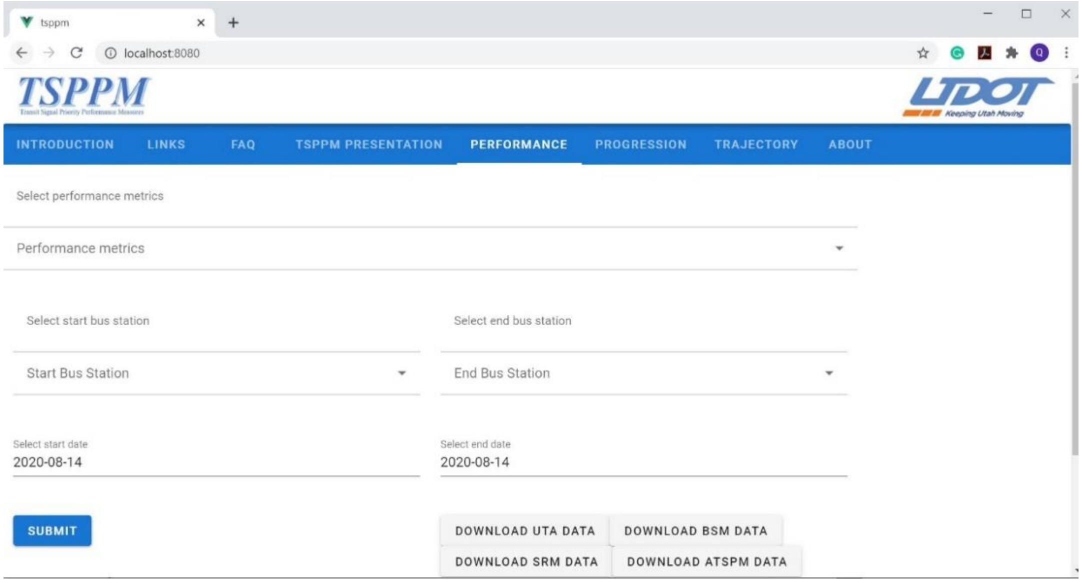
the average rate of TSP served before retiming is 33.13%, which is lower than that of 35.29% after retiming.

Bus reliability for northbound and southbound of

Figure 4.5 The TSPPM Presentations interface from the designed website.

(5) Performance

This element provides users with information about how TSP functions and the signal timing plans along the corridor, including bus travel time, running time, the requested and granted ratios, and bus status performance. The main interface is shown in Figure 4.6. The performance results are shown in Figures 4.7 and 4.8. More specifically, Figure 4.7 shows the statistical results of bus travel time and running time southbound and northbound along the corridor as well as the statistical indicators of bus status (“critically early,” “early,” “on-time,” “late,” and “critically late”). In addition, the requested/granted TSP ratios can be seen in Figure 4.8.



Select performance metrics

Performance metrics

Select start bus station

Start Bus Station

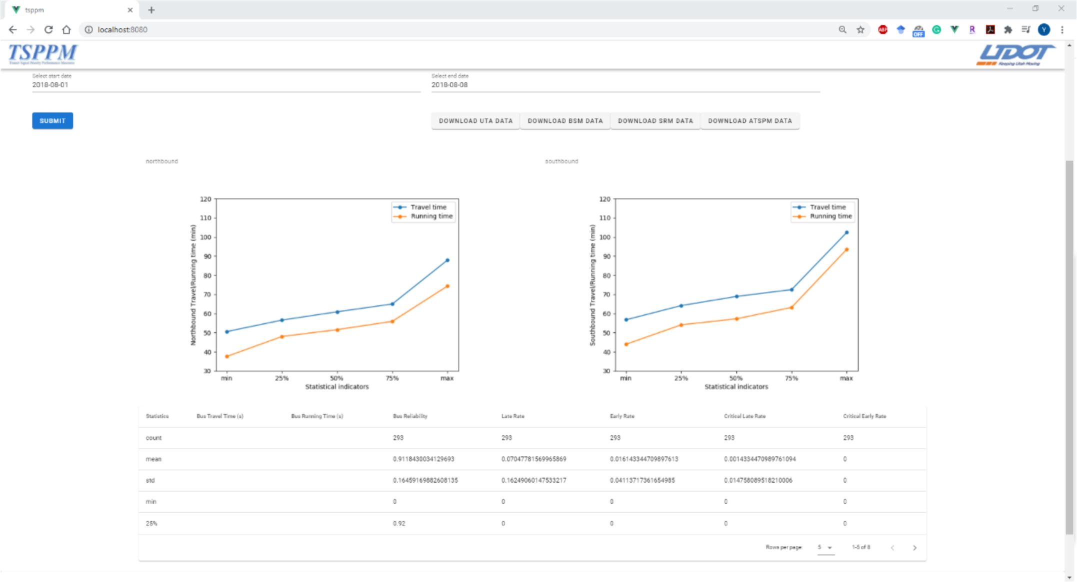
Select end bus station

End Bus Station

Select start date
2020-08-14

Select end date
2020-08-14

Figure 4.6 The Performance interface from the designed website.

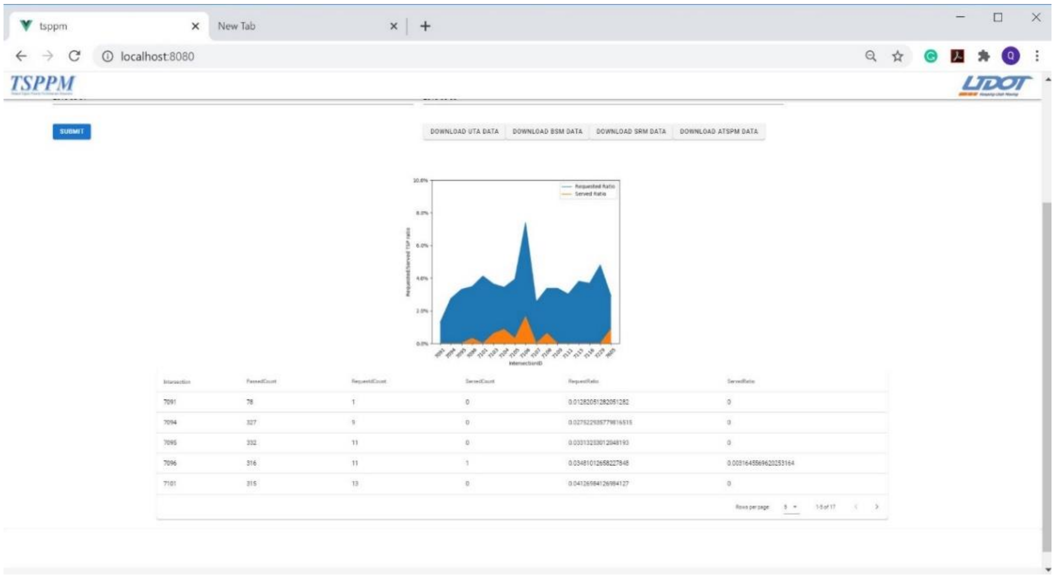


Select start date
2018-08-01

Select end date
2018-08-08

Statistics	Bus Travel Time (s)	Bus Running Time (s)	Bus Reliability	Late Rate	Early Rate	Critical Late Rate	Critical Early Rate
count			293	293	293	293	293
mean			0.9118430034129693	0.07047781569965869	0.016143344709897613	0.0014334470989761094	0
std			0.16459169882608135	0.16249060147533217	0.04113717361654985	0.014758089518210006	0
min			0	0	0	0	0
25%			0.92	0	0	0	0

Figure 4.7 The bus travel display of running time and reliability.

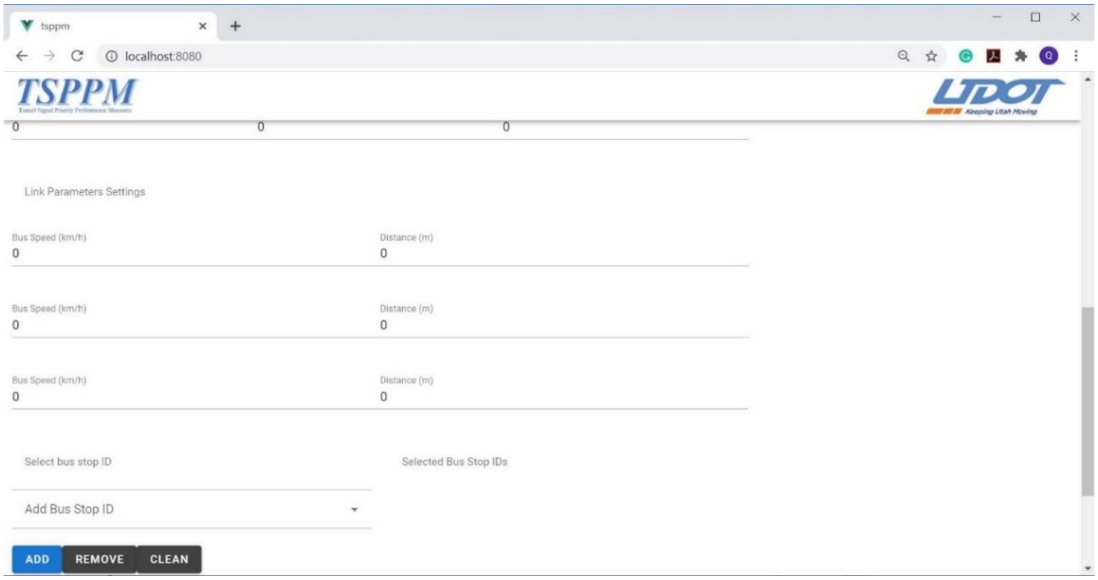


Intersection	PassedCount	RequestCount	ServedCount	RequestRatio	ServedRatio
7091	78	1	0	0.01282051282051282	0
7094	327	9	0	0.027522935779816515	0
7095	332	11	0	0.03313253012048193	0
7096	316	11	1	0.03481012658227848	0.0031645569620253164
7101	315	13	0	0.04126984126984127	0

Figure 4.8 Display of the requested/granted TSP ratio.

(6) Progression

This function will help users visualize the green bandwidth of buses that travel along the corridor guided by specific signal timing plans at each intersection as well as the bus speed. The main visualization interface is shown in Figures 4.9 and 4.10.



0 0 0

Link Parameters Settings

Bus Speed (km/h) 0 | Distance (m) 0

Bus Speed (km/h) 0 | Distance (m) 0

Bus Speed (km/h) 0 | Distance (m) 0

Select bus stop ID

Add Bus Stop ID

Selected Bus Stop IDs

Figure 4.9 The Progression interface shown on the designed website.

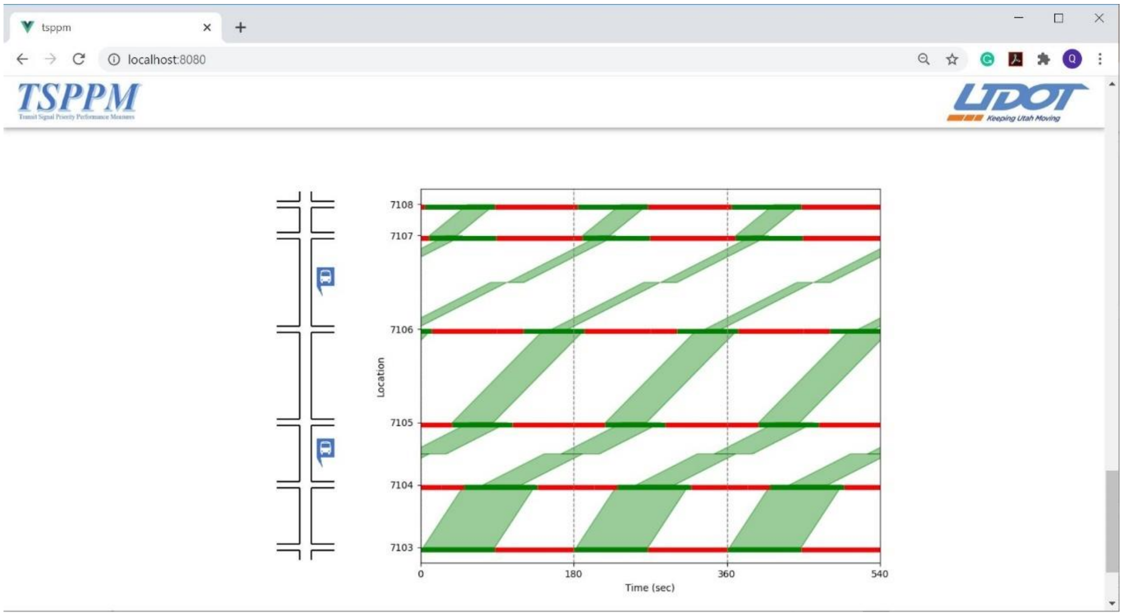
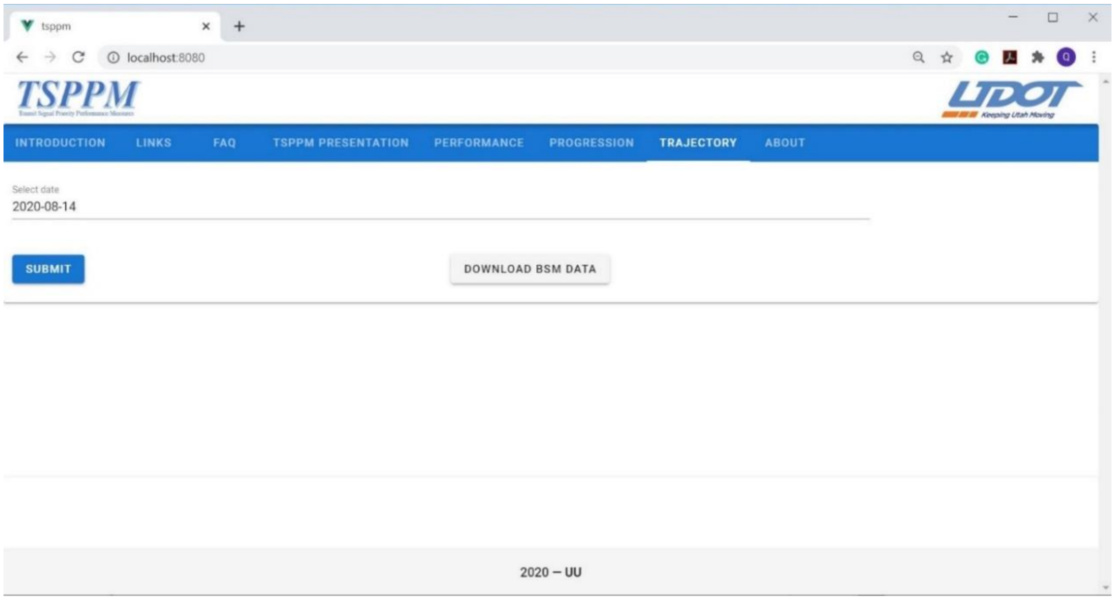


Figure 4.10 A display of the progression of buses.

(7) Trajectory

The trajectory of buses traveling along this corridor is illustrated with this function. The main interfaces and results are shown in Figures 4.11 and 4.12.



Select date
2020-08-14

Figure 4.11 The Trajectory interface from the designed website.

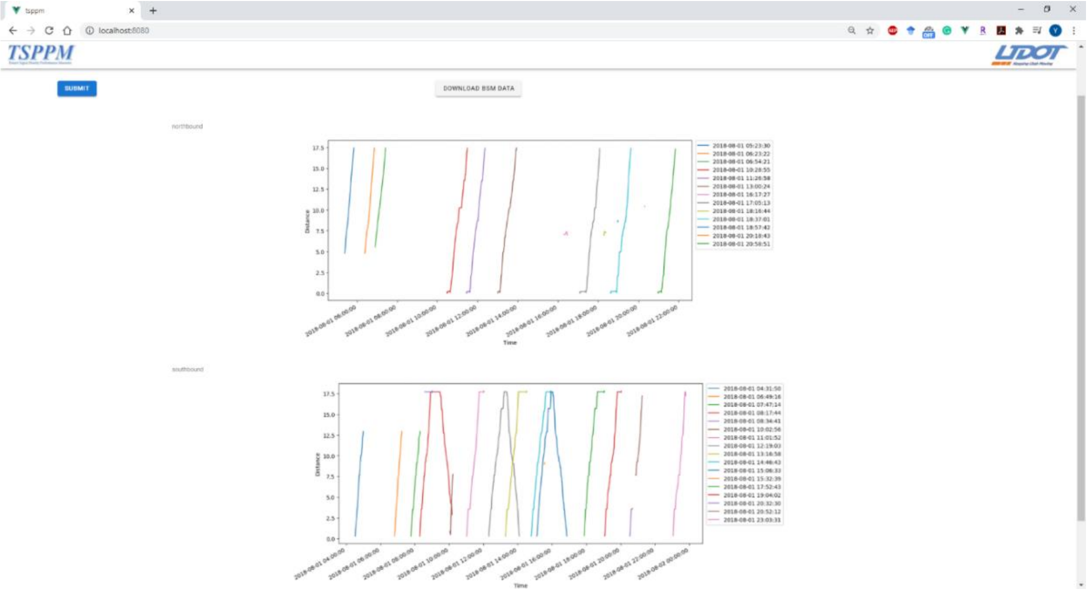
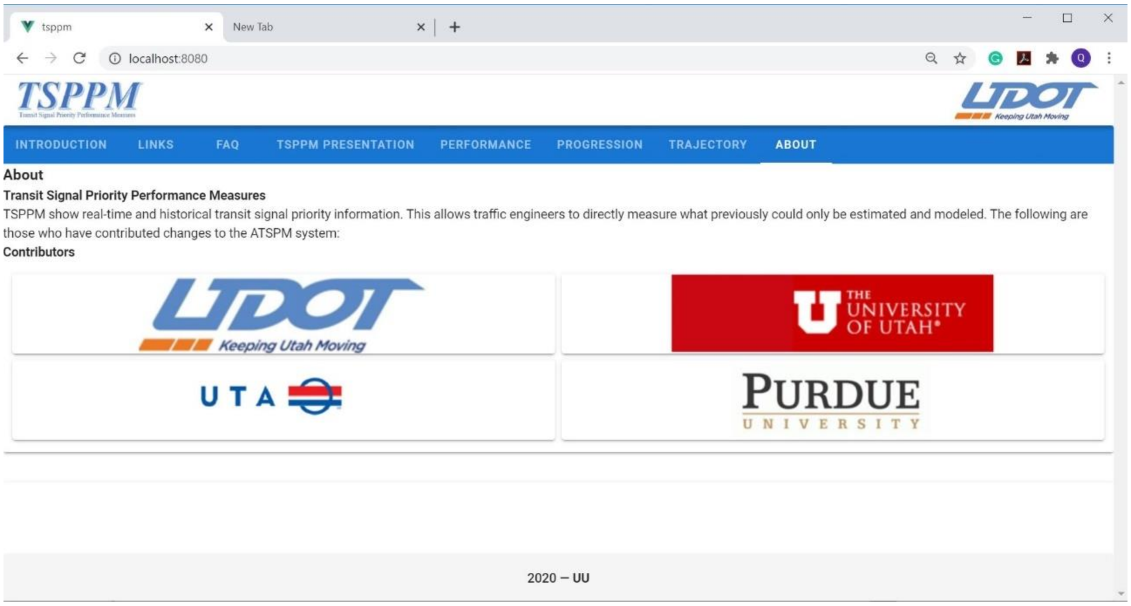


Figure 4.12 The bus trajectory display from the designed website.

(8) About

This menu explains how the TSPPM system functions and includes a list of all contributors who developed this system.



About

Transit Signal Priority Performance Measures

TSPPM show real-time and historical transit signal priority information. This allows traffic engineers to directly measure what previously could only be estimated and modeled. The following are those who have contributed changes to the ATSPM system:

Contributors

2020 — UU

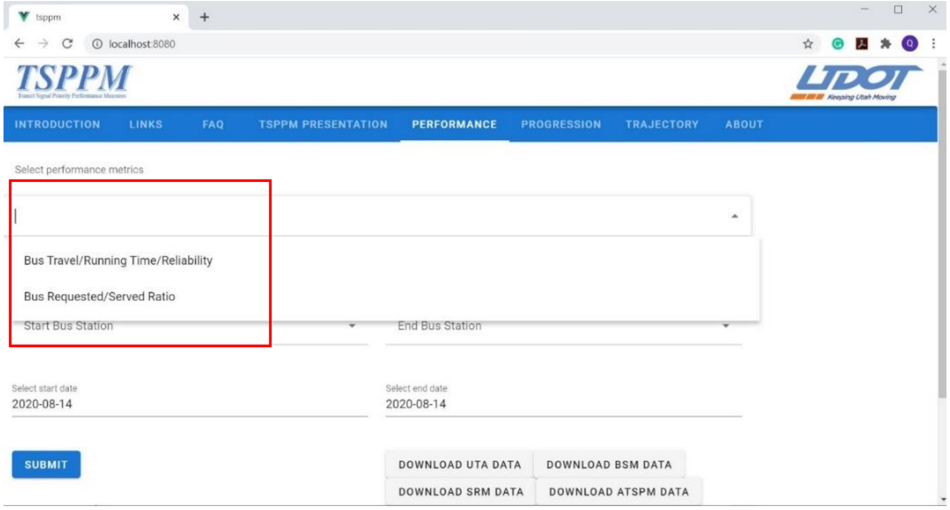
Figure 4.13 The About interface from the designed website.

4.3 User Guide

The most important functions of the TSPPM system are to evaluate the TSP performance as well as to illustrate bus progression and trajectory. Therefore, the main purpose of this guide is to demonstrate the performance of these three functions on this website.

(1) Performance

1. Select the performance metrics, as shown in Figure 4.14.

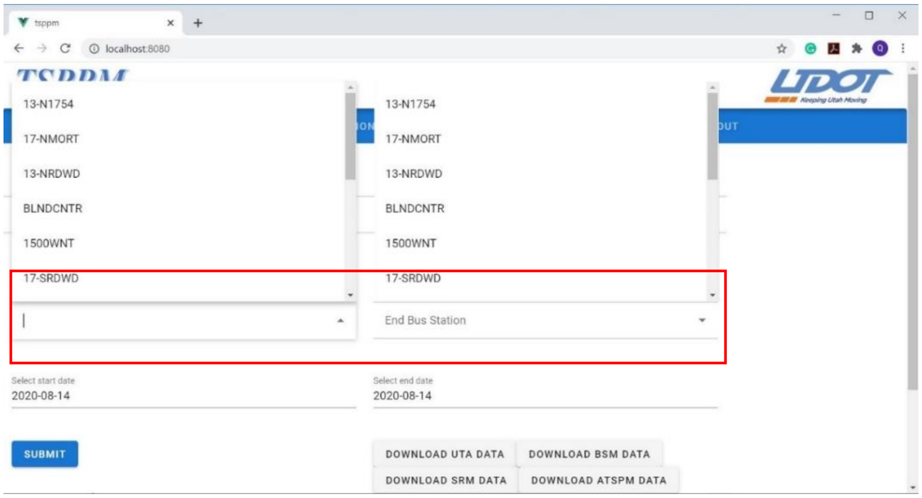


Select start date
2020-08-14

Select end date
2020-08-14

Figure 4.14 Display of performance interface.

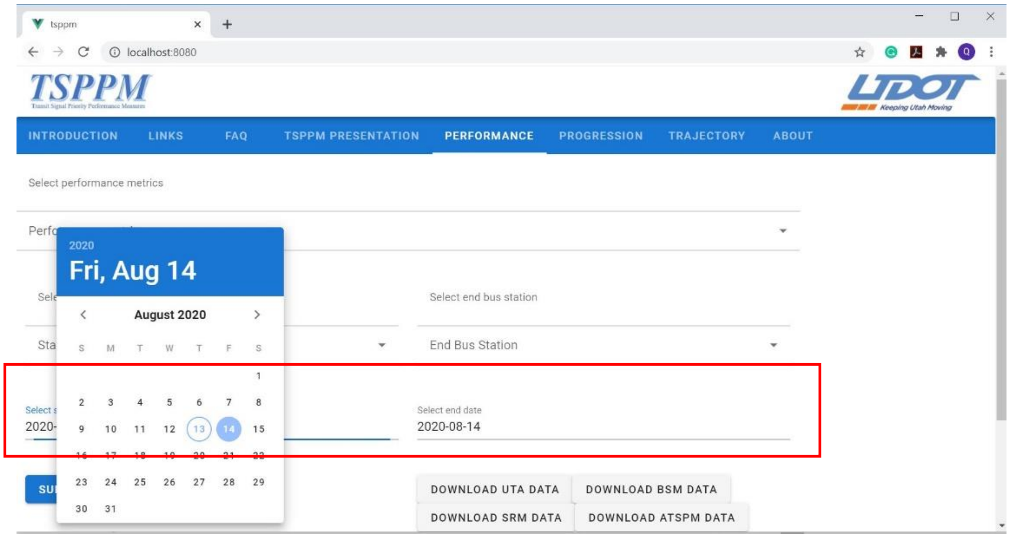
2. Select the start bus station and end bus station options, as shown in Figures 4.15 and 4.16.



Select start date
2020-08-14

Select end date
2020-08-14

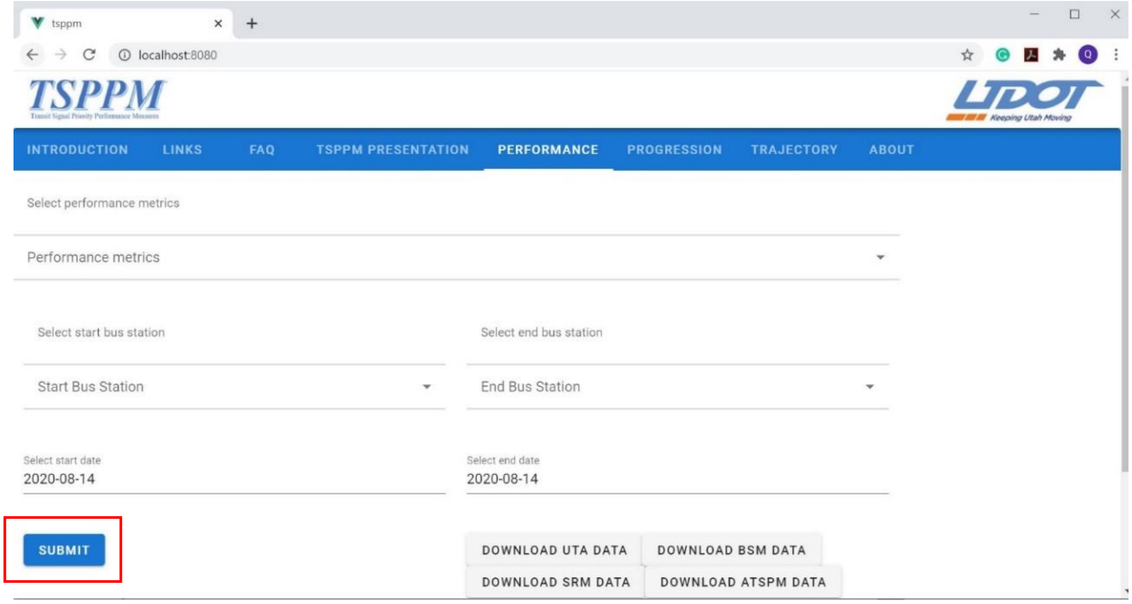
Figure 4.15 The station options of the designed performance interface.



Select end date
2020-08-14

Figure 4.16 The data options of the performance interface.

3. Click “Submit,” as shown in Figure 4.17.



Select start date: 2020-08-14

Select end date: 2020-08-14

Figure 4.17 Display of Submit interface on the designed performance interface.

(2) Progression

1. Select the intersections through which buses will travel, as shown in Figure 4.18.

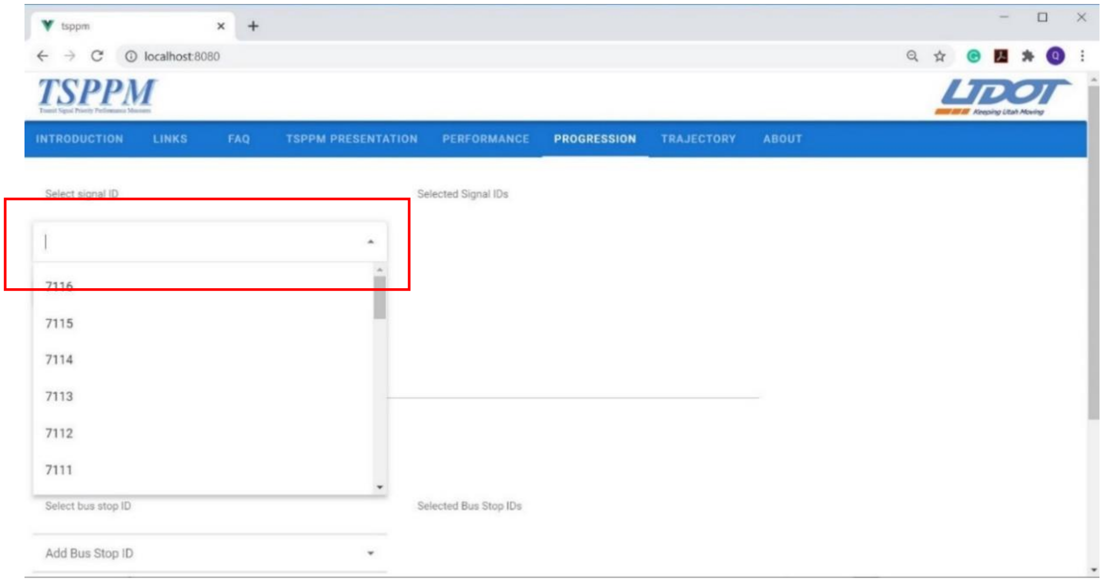
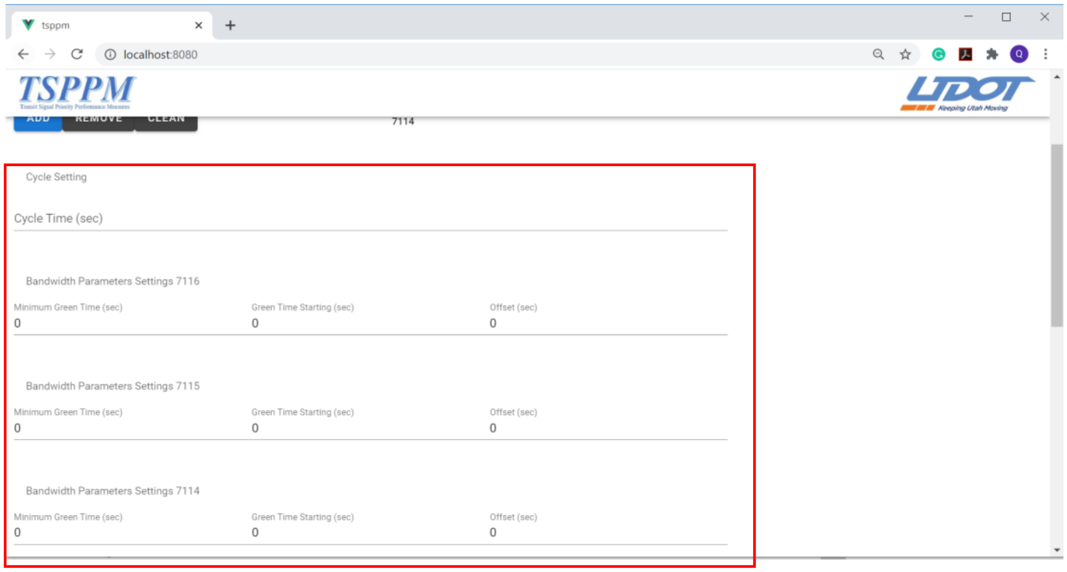


Figure 4.18 Display of progression interface.

2. Set the signal timing schedule for each intersection, including cycle length, green start time, green duration, and offset time, as shown in Figure 4.19.



Cycle Setting

Cycle Time (sec)

Bandwidth Parameters Settings 7116

Minimum Green Time (sec): 0
Green Time Starting (sec): 0
Offset (sec): 0

Bandwidth Parameters Settings 7115

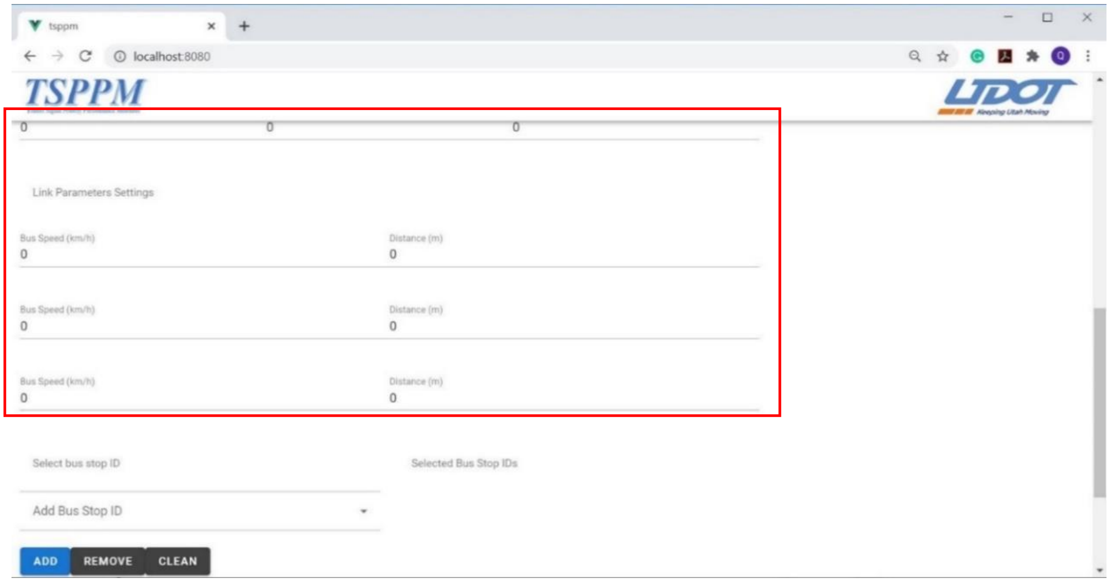
Minimum Green Time (sec): 0
Green Time Starting (sec): 0
Offset (sec): 0

Bandwidth Parameters Settings 7114

Minimum Green Time (sec): 0
Green Time Starting (sec): 0
Offset (sec): 0

Figure 4.19 The signal timing schedule of the designed progression interface.

3. Set the link parameters that consist of the distance between two intersections and the travel speed of the bus, as shown in Figure 4.20.



0 0 0

Link Parameters Settings

Bus Speed (km/h): 0
Distance (m): 0

Bus Speed (km/h): 0
Distance (m): 0

Bus Speed (km/h): 0
Distance (m): 0

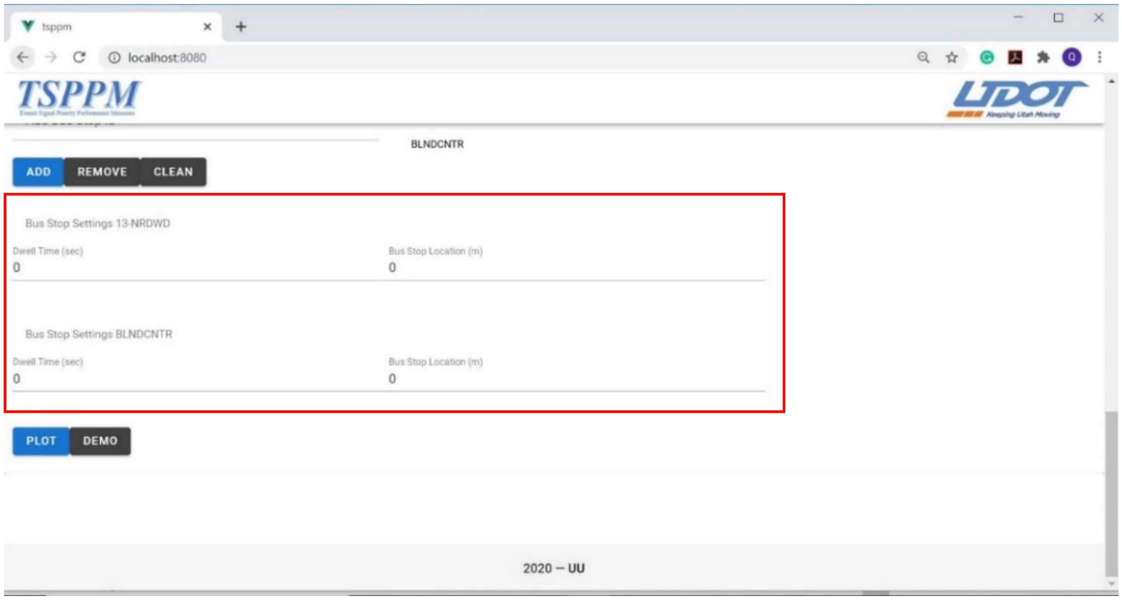
Select bus stop ID

Selected Bus Stop IDs

Add Bus Stop ID

Figure 4.20 The link parameters of the designed progression interface.

4. Set the parameters for the bus stops, including location and average dwell time, as shown in Figure 4.21.



Bus Stop Settings 13-NRDWD

Dwell Time (sec): 0

Bus Stop Location (m): 0

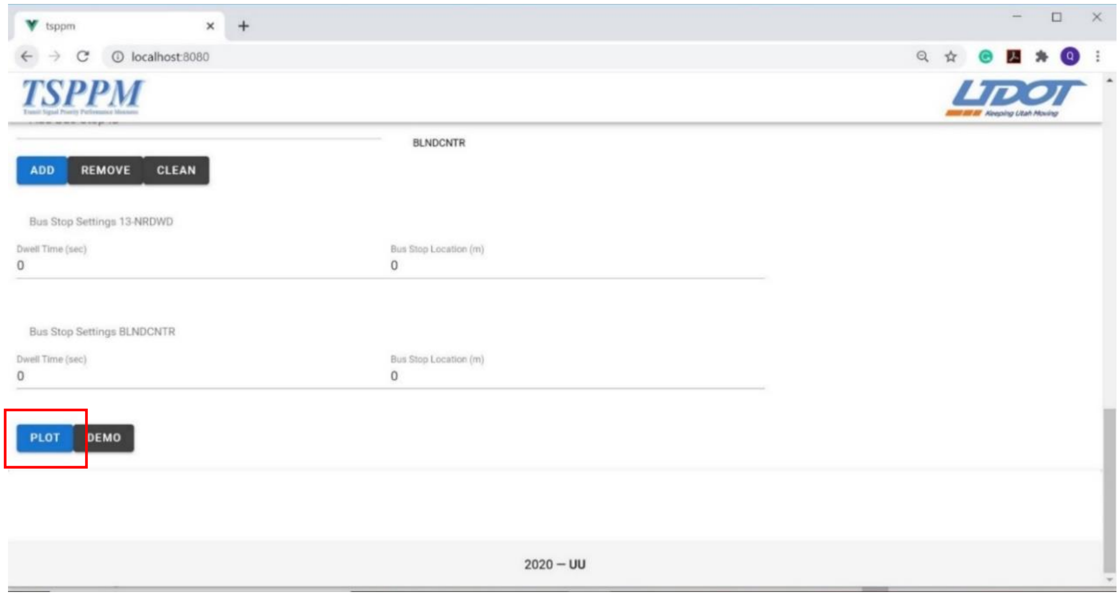
Bus Stop Settings BLNDCNTR

Dwell Time (sec): 0

Bus Stop Location (m): 0

Figure 4.21 The stop parameters of the designed progression interface.

5. Click “Plot,” as shown in Figure 4.22.



Bus Stop Settings 13-NRDWD

Dwell Time (sec): 0

Bus Stop Location (m): 0

Bus Stop Settings BLNDCNTR

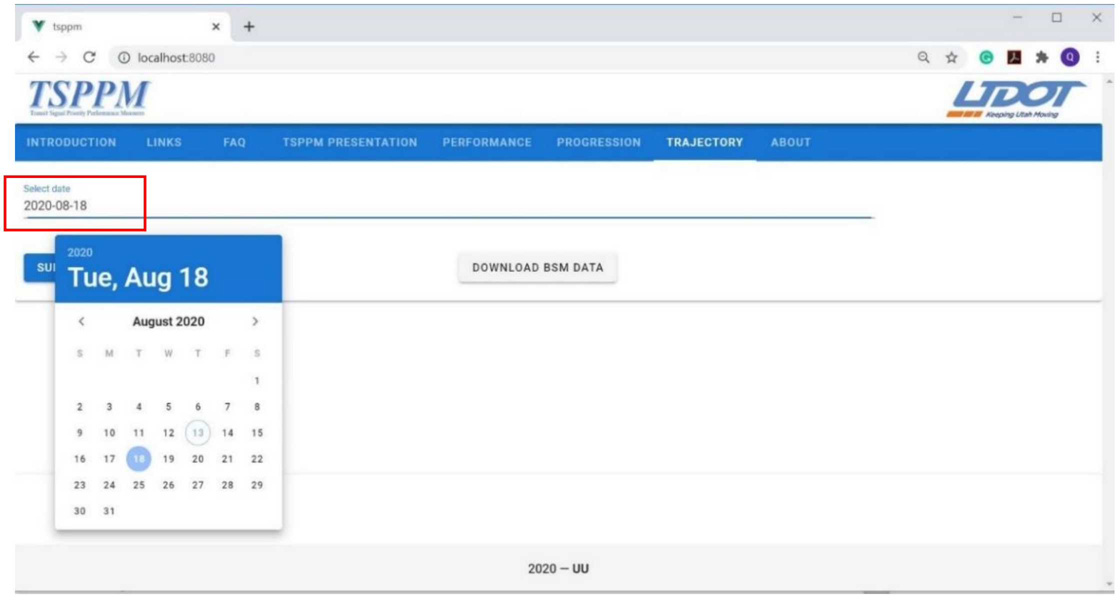
Dwell Time (sec): 0

Bus Stop Location (m): 0

Figure 4.22 Display of plot of the designed progression interface.

(3) Trajectory

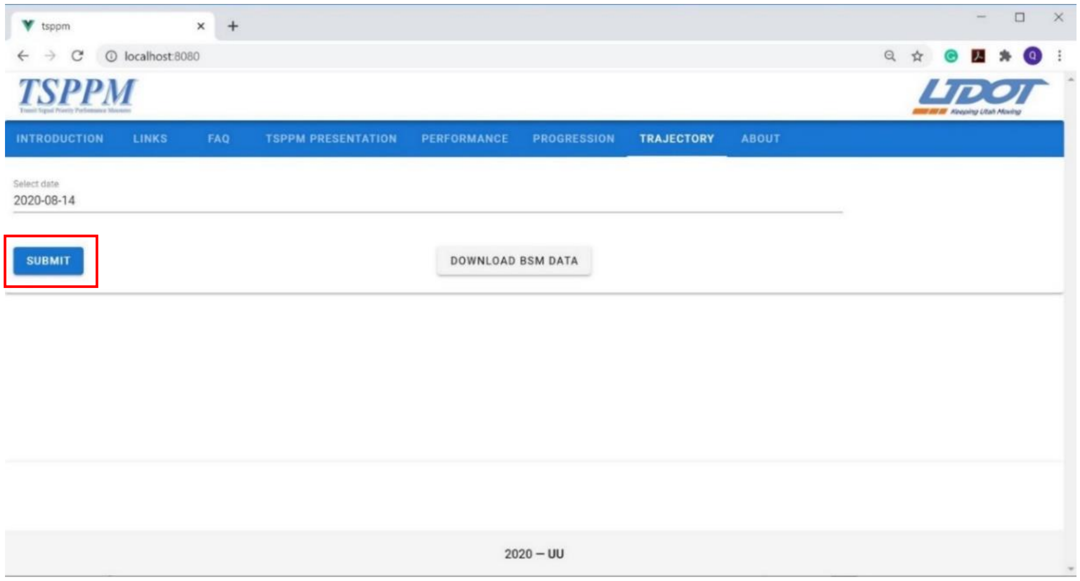
1. Select the specific date you wish to predict, as shown in Figure 4.23.



Select date
2020-08-18

Figure 4.23 The date option of the designed trajectory interface.

2. Click “Submit,” as shown in Figure 4.24.



Select date
2020-08-14

Figure 4.24 Display of Submit interface from the designed trajectory interface.

4.4 Tool Development and Testing

4.4.1 Technical Structure

The TSP analysis modules are incorporated into the web application. This application is based on the browser service framework, which means that the service provider should establish a server for this application and that the users should be able to access service via any web browser or the Internet. Unlike the desktop or the client-service application, the browser service is installation-free, accessible, portable, lightweight, and compatible with various operating systems and environments. This TSP web application supports most mainstream browsers, such as Google Chrome, Microsoft Edge, Apple Safari, and Mozilla Firefox.

The TSP application was developed as a modern two-fold structure: the front end module and the back end module. Both modules are separate, meaning that one module can be altered while the other remains unaffected. Thus, these two modules can be developed and installed in two different programming languages or environments. The front end module was designed to run in the user’s browser, show a modern, user-friendly interface including menus, buttons, and textboxes, and provide an interactive and responsive user experience. The back-end module was developed to be compatible with multiple services involving mathematical calculations, analytical graph plotting, data inquires, and processing.

To set up the web application on the server, the server manager should configure the environment, the TSP application program, and the code by following the instructions in the README file.

4.4.2 Front End Development

The front end was coded in JavaScript language, which is the most accepted programming language in a browser or as a standalone. The front end server was inspired by the NodeJS environment and the JavaScript Package Management System. These necessary elements facilitate its lightweight nature and easy maintenance.

The interface development was based on the Vue framework, Vue.js, an open-source progressive framework for building user interfaces and single-page applications, is capable of dynamic set up in-browser by a click or mouse move to certain functions, such as submitting requests for data downloading and analytical plotting. Compared to the technology of previous generations, the Vue.js framework is more concise, flexible, and maintainable.

A Vue-based user interface library, known as Vuetify, is leveraged in the TSP application. It is an open-source toolkit for creating modern-style web applications without requiring high-level art skills on the part of the user. The TSP application makes use of the Material Design, which is the most popular UI style for website creation. This design language was developed by Google in 2014 and uses more grid-based layouts, responsive animations and transitions, padding, and sophisticated effects such as lighting and shadows.

The UI of the webpage is designed in three sections. The top segment includes the logos and the menu. The bottom includes copyright information. These two sections remain onscreen when navigating to other pages. The middle section, which can be changed by clicking the corresponding index item on the menu, can be customized by adding or removing the corresponding indices in the source code. The content of each middle section can also be customized in the source code.

4.4.3 Back End Development

The back end was coded in Python language, which has the largest user group and the most active open-source community. The open-source web application framework, Flask, was utilized to build the webserver. The back end was designed to provide a web application programming interface (API) for things like data searching and analytical chart plotting. An updated front end module or an additional module can be installed depending on the API regardless of the type of front end module.

The dedicated modules were programmed using open-source packages such as NumPy and Matplotlib for data loading and filtering, bus reliability analysis, travel/running time evaluation, requested/granted analysis, and the plotting of the bus trajectory, including mapping the green band of the bus signal coordination diagram. These modules can be requested from either the web API or the front end module.

The back end of the TSP application, the offline data files in CSV format that include ATSPM, BSM, SRM, bus trajectory and UTA reliability, are stored in the operating system folder and the file system. One data file is created for each day and category of data. The name of the data file is a combination of the category of data and the date it was created. The data files are organized in folders on a monthly basis. For example, the data collected in August are put into a folder entitled “Aug.” The server manager may update these folders by copying the downloaded data into the corresponding folders.

4.4.4 Possible Further Extensions

Currently, all related data are stored in the back end server and can be updated only manually. If the managers at UDOT decide to integrate the TSP application into their system, the data storage and inquires may be moved into a comprehensive database. The planned database server acts as a data warehouse for the internal data centers of UDOT and UTA and the web-based applications (i.e., the TSP application). The database application is programmed to automatically extract updated data from multiple internal databases at UDOT and UTA. When a great deal of data has been transferred, the database runs much faster than the file system. However, the connection between the databases can be improved with the web interface.

5.0 CONCLUSIONS

5.1 Summary

TSP has great potential to reduce bus delays at intersections, improve operational transit reliability, and consequently increase transit ridership due to improved service. With the emerging CV technology, high-resolution data can be easily obtained and used to evaluate TSP performance. This research evaluated the efficiency of bus TSP requests and grants, reliability, travel time, and running time at the Redwood CV corridor in Salt Lake County, Utah. The signal plan for this corridor underwent retiming in October 2018.

The purpose of this study was to analyze the TSP performance before and after signal retiming by utilizing data from three different sources: DSRC, ATSPM, and UTA. The first dataset was used to identify the total number of bus trips and TSP requests at each intersection. The total number of granted TSP requests was determined from the ATSPM dataset. Then the rates of TSP requests and grants were identified. The UTA dataset was used to determine bus reliability, travel time, and running time. Results revealed that the TSP granted rate after signal retiming was 35.29%, which is higher that the 33.12% before this occurred. As a result, the bus reliability for the northbound and southbound corridor improved by 2.65% and 1.21%, respectively, after signal retiming. In addition, travel time and running time were also reduced after signal retiming. Moreover, in order to assist UDOT in designing signal progression and evaluating TSP performance, a website was developed to display the related performance index (i.e., bus travel time, running time, status performance, bus requested/granted ratio), bus progression, and trajectory.

5.2 Limitations and Challenges

Although TSP has resulted in many benefits, an activated TSP control may also negatively impact intersection traffic due to changes in signal timings (e.g., green extension, red truncation). Therefore, the impacts on other traffic of granting signal priority for both signal plans must be explored. In addition, more studies must be conducted to determine the benefits of granting TSP to buses and the potential negative impacts of this technology on other types of traffic.

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