RESEARCH

Keeping Utah Moving

Utah Department of Transportation - Research Division
4501 South 2700 West - P.O. Box 148410 - SLC,UT 84114-8410

Report No. UT-20.08

EVALUATING THE QUALITY OF SIGNAL OPERATIONS USING SIGNAL PERFORMANCE MEASURES

Prepared For:

Utah Department of Transportation
Research & Innovation Division

Submitted By:

Brigham Young University
Dept. of Civil and Environmental Engineering

Authored By:

Grant G. Schultz, Ph.D., P.E., PTOE
Professor

Gregory S. Macfarlane, Ph.D., P.E.
Assistant Professor

Bangyu Wang, EIT
Graduate Research Assistant

Sabrina McCuen
Undergraduate Research Assistant

Final Report
July 2020

DISCLAIMER

ACKNOWLEDGMENTS

The authors acknowledge the Utah Department of Transportation (UDOT) for funding this research. The following individuals from the UDOT Technical Advisory Committee and from Brigham Young University (BYU) helped to guide this research and contribute to the final product:

- Mark Taylor – UDOT Traffic Operations
- Jamie Mackey – UDOT Freeway Operations
- Brian Philips – UDOT Region 3 Traffic Operations
- Travis Jensen – WCEC Engineers/UDOT Research
- Jesse Sweeten – UDOT Traffic & Safety
- Adam Lough – UDOT Traffic & Safety
- Emily Andrus – BYU Civil & Environmental Engineering

TECHNICAL REPORT ABSTRACT

1. Report No. UT-20.08	2. Government Accession No. N/A	3. Recipient's Catalog No. N/A
4. Title and Subtitle EVALUATING THE QUALITY OF SIGNAL OPERATIONS USING SIGNAL PERFORMANCE MEASURES		5. Report Date July 2020 6. Performing Organization Code R0402329
7. Author(s) Grant G. Schultz, Ph.D., P.E., PTOE; Gregory S. Macfarlane, Ph.D., P.E.; Bangyu Wang, EIT; and Sabrina McCuen		8. Performing Organization Report No. N/A
9. Performing Organization Name and Address Brigham Young University Department of Civil and Environmental Engineering 430 Engineering Building Provo, Utah 84602		10. Work Unit No. 5H080 40H 11. Contract or Grant No. 19-8766
12. Sponsoring Agency Name and Address Utah Department of Transportation 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410		13. Type of Report & Period Covered Final Report Jan 2019 to July 2020 14. Sponsoring Agency Code UT18.303

15. Supplementary Notes

Prepared in cooperation with the Utah Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The Utah Department of Transportation (UDOT) has taken an active role in evaluating and monitoring traffic signal performance throughout the state of Utah. Automated traffic signal performance measures (ATSPM) have been adopted to collect data concerning the current and historical performance of signalized intersections to optimize mobility and manage traffic signal timing and maintenance to reduce congestion, save fuel costs, and improve safety. The collected and aggregated data that are continuously generated yields approximately 1 TB of data per month. The purpose of this research was to provide a method that can evaluate intersection-level and corridor-level performance using the ATSPM data. The method described in this paper analyzed three signalized corridors in Utah, consisting of 22 total intersections. Four ATSPM were used to develop threshold values. These performance measures include Platoon Ratio, Split Failures, Arrivals on Green, and Red-Light Actuation. These four performance measures are scaled and classified using k-means cluster analysis. The k-means cluster analysis is a broad set of techniques for finding subgroups of observations within a data set. The results of this analysis produced a score for each intersection and corridor determined from the weighted average of the four measures. The methodology can be developed with more performance types and more extensive corridors for future studies.

17. Key Words Traffic signal, performance measures, ATSPM, UDOT		18. Distribution Statement Not restricted. Available through: UDOT Research Division 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410 www.udot.utah.gov/go/research	23. Registrant's Seal N/A
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 107	22. Price N/A

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ATSPM	Automated Traffic Signal Performance Measures
BYU	Brigham Young University
DOT	Department of Transportation
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
HCM	Highway Capacity Manual
IPA	Importance-Performance Analysis
MAU	Multi-Attribute Utility
MOE	Measures of Effectiveness
NCHRP	National Cooperative Highway Research Program
PCD	Purdue Coordination Diagram
PSF	Purdue Split Failure
PPT	Purdue Phase Termination
SPUI	Single-Point Urban Interchange
SQL	Structured Query Language
TAC	Technical Advisory Committee
UDOT	Utah Department of Transportation
VC	Volume to Capacity

EXECUTIVE SUMMARY

The Utah Department of Transportation (UDOT) has taken an active role in evaluating and monitoring traffic signal performance throughout the state of Utah since 2012. The Automated Traffic Signal Performance Measures (ATSPM) data use traffic-signal detection data to illustrate the actual and historical performance of signalized intersections. ATSPM use high-resolution data capability added to existing infrastructure to evaluate the quality of progression of traffic along a corridor. In Utah, the measured data help to inform UDOT of vehicle and pedestrian detector malfunctions, while also measuring vehicle delay and recording volume, speed, and travel time of vehicles. UDOT uses the data to optimize mobility and manage traffic signal timing and maintenance to reduce congestion, save fuel costs, and improve safety (UDOT, 2019a). The majority of existing ATSPM research is focused on the performance of individual movements or intersections, but Day et al. (2018) used a method of evaluating corridor performance at the system level using high-resolution data to provide a corridor-level analysis.

The purpose of this research is to evaluate real-time data collected through the UDOT ATSPM database and determine which performance measures are useful for ranking intersections and corridors. These intersections and corridors are ranked according to scores assigned based on threshold values which must be identified for each performance measure chosen. A score is assigned for both intersection-level and corridor-level analyses.

Once the ranking method is established, it is possible to efficiently identify poorly performing intersections and corridors. The research team created a data visualizer that calculates and displays scores for the intersections by taking all the data from all signals into account. Scores for intersections can then be ranked on a corridor basis or on a system-wide basis. Using this ranking system can enable a more cost-effective and timely maintenance of signals for the state of Utah. It will also be feasible to use the methodology established in this research to determine how the performance of intersections and corridors varies over time.

1.0 INTRODUCTION

1.1 Problem Statement

The Utah Department of Transportation (UDOT) has taken an active role in evaluating and monitoring traffic signal performance throughout the state of Utah since 2012. The Automated Traffic Signal Performance Measures (ATSPM) are a series of visual aids that display the high-resolution data from traffic signal controllers. ATSPM are a valuable asset management tool, aiding technicians and managers in the control of both traffic signal hardware and traffic signal timing and coordination. They allow analysis of data collected 24 hours a day, 7 days a week, improving the accuracy, flexibility, and performance of signal equipment and the system as a whole (Bullock et al., 2014). In Utah, the measured data help to inform UDOT of vehicle and pedestrian detector malfunctions, while also measuring vehicle delay and recording volume, speed, and travel time of vehicles. UDOT uses the data to optimize mobility and manage traffic signal timing and maintenance to reduce congestion, save fuel costs, and improve safety (UDOT, 2019a).

The use of ATSPM data has been adopted by many agencies and state departments of transportation (DOTs) to help optimize signal operations. The UDOT system generates a large quantity of data, about 1 TB of data per month in the state of Utah; however, the data are currently not being utilized to their full extent, although a recent Federal Highway Administration (FHWA) publication estimates that UDOT's ATSPM system has saved the taxpayers over $107 million in 10 years (Day et al., 2020). One need that has not been met with the ATSPM data is to provide context for performance measures data and to provide a history of this context over time. Even though a large amount of data has been generated for different performance measures, users still must generally rely on their own experience and expertise to provide context to the quality of operations across the system.

The majority of existing ATSPM research is focused on the performance of individual movements or intersections. Day et al. (2018), however, used a method of evaluating corridor performance at the system level using high-resolution data to provide a system-level analysis. The analysis method was built based on the results from five sub-scores for the areas of communication, detection, safety, capacity allocation, and progression. The performance measures to be considered must be adapted to available data, while the time period for analysis varies depending on local conditions.

The purpose of this research is to evaluate real-time data collected through the UDOT ATSPM database and to determine the measures that can be aggregated into higher level metrics for detailed evaluation in an intersection-level, corridor-level, and system-wide level of analysis. Thresholds will be identified for each performance measure suitable for detailed evaluation and a ranked score will be assigned for each level of the analysis.

1.2 Objectives

The first objective of the research was to evaluate performance measurement data collected through the ATSPM database and determine which performance measures could be used for evaluation of maintenance and operations. The second objective was to develop threshold values for each selected performance measure so that the intersections could be evaluated on multiple dimensions. The final objective was to provide a process that could be used for an overall evaluation of the historic quality of signal system operations across the state.

1.3 Organization

The body of the report is organized into the following chapters:

- Chapter 1 includes an introduction to the research, project objectives, and the organization of the report.
- Chapter 2 includes a literature review of ATSPM including current practices for using ATSPM, current ATSPM used in Utah, effects of ATSPM, and methods for ATSPM evaluation.
- Chapter 3 includes a discussion of the methodology used for this research including data selection, performance measures selection, and intersection scoring.
- Chapter 4 includes a general discussion on the ATSPM data collection and aggregation process.
- Chapter 5 includes a discussion on the refinement of the corridors and measures based on the collected data.

- Chapter 6 includes a discussion of the ATSPM data analysis, evaluation, and a field data comparison.
- Chapter 7 includes the conclusion for the research project and recommendations for future research.

2.0 LITERATURE REVIEW

2.1 Overview

A literature review was performed to gain insight and understanding on ATSPM evaluation as well as methods utilized in other industries for evaluating performance measures. This chapter contains a summary of the literature review with discussion provided on several key topics. First, ATSPM will be defined and current practices for using ATSPM and the effects of using ATSPM will be explained. Second, each performance measure and evaluation tool currently used by UDOT and the website used to display them will be described. Finally, potential methods for selecting and evaluating ATSPM to be used for analysis will be explained.

2.2 Automated Traffic Signal Performance Measures

Detector technology exists at intersections to improve signal operations. This detector technology can be used to collect data. The purpose of ATSPM is taking a large input of data from detector technology and identifying the most important measures to rank signals. This will allow for a focused time-effective and cost-effective maintenance schedule. This section will cover the detection used to collect data, the way DOTs are implementing ATSPM, the effects of using ATSPM, and the support ATSPM have received from federal agencies.

2.2.1 ATSPM Data Collection Methods

ATSPM use detector data to show actual and historical performance of signalized intersections. They use high-resolution data capability added to existing infrastructure to evaluate the quality of traffic progression along a corridor. Although ATSPM are a relatively new technology, the idea for automated performance measures has existed since the 1970s. The methods used then were based on analog systems and were relatively expensive (Lavrenz et al., 2017). In Utah, the measured data are summarized and evaluated to inform UDOT of detector malfunctions and provide insight into vehicle delay from volume, speed, and travel time detection. UDOT uses the ATSPM data to optimize mobility and manage traffic signal timing and maintenance to reduce congestion, save fuel costs, and improve safety (UDOT, 2019b).

ATSPM data are collected using additions to existing signal infrastructure. In addition to the typical equipment required for a traffic signal, a high-resolution controller, data collection engine, and communication system or reporting engine are required for ATSPM analysis. An operator interface is also required so the analyst can access the data (Day et al., 2014). Different detection types may be added to an intersection to collect various performance metrics. Figure 2.1 shows the types of detection used by UDOT and the metrics they measure. Detection at each intersection allows traffic engineers to evaluate the intersection performance. At UDOT, "System Health Alerts" are sent daily to identify signals with communication issues such as having no performance data, or having too many max-outs, force-offs, or pedestrian calls.

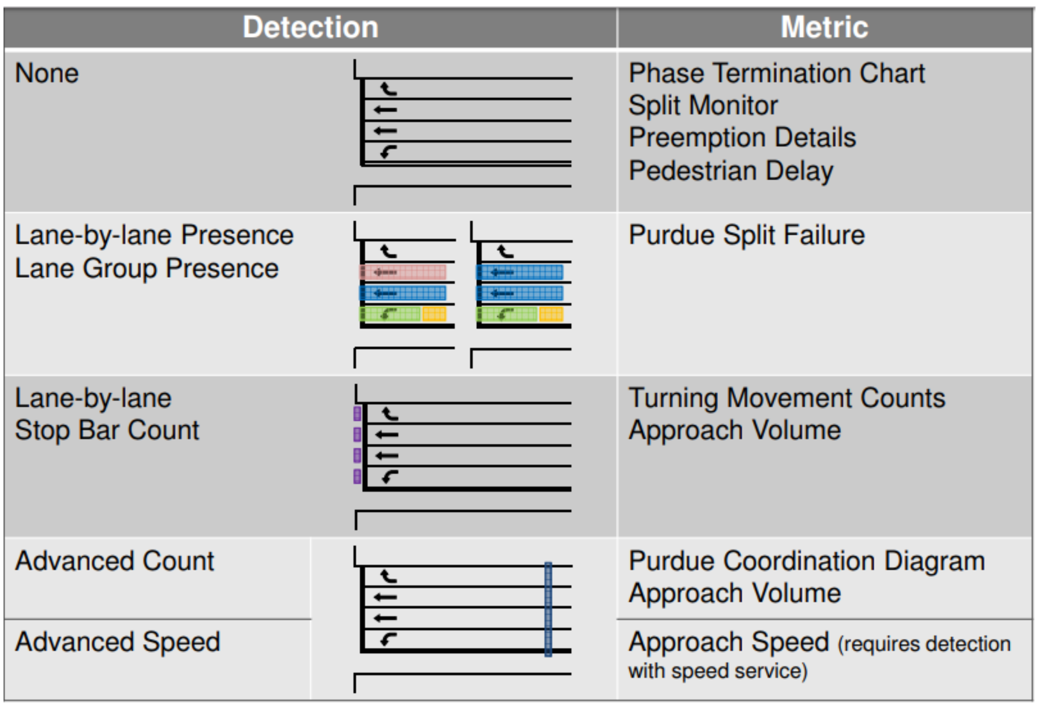

Figure 2.1. UDOT detection and metrics (Mackey, 2017).

<u>2.2.2 Implementation of ATSPM from Various Departments of Transportation</u>

In 2017 the National Cooperative Highway Research Program (NCHRP) published Project 03-122: "Performance-Based Management of Traffic Signals." In this research, staff from 16 public agencies were interviewed and asked to take written surveys regarding their use of ATSPM data. The results of the interviews and surveys showed that agencies often use ATSPM for the following activities: identifying and prioritizing short-term maintenance needs, identifying and prioritizing long-term equipment replacement, identifying and prioritizing signal retiming locations, determining adjustments to signal timing, evaluating operational changes, evaluating operations to report to external groups, and sharing data with other groups (Kittelson & Associates and Purdue University, 2017).

In Minneapolis, MN, an ATSPM system (called SMART-SIGNAL) is being used to collect “event-based” traffic data from multiple intersections, interpret the data, and measure arterial performance at the same time. SMART-SIGNAL was tested on an 11-intersection corridor on France Avenue in Minneapolis (Liu et al., 2008). The ATSPM data were collected then averaged over several months, with emphasis on travel time and queue length. When necessary, signal timing improvements were made using field observations and time-space diagrams. Then, the ATSPM were used to monitor improvements at individual intersections and over a corridor to ensure efficiency. Finally, a comparison was made of the conditions before and after the signal improvements (ITE, 2014). The data flow for the ATSPM in Minneapolis is shown in Figure 2.2.

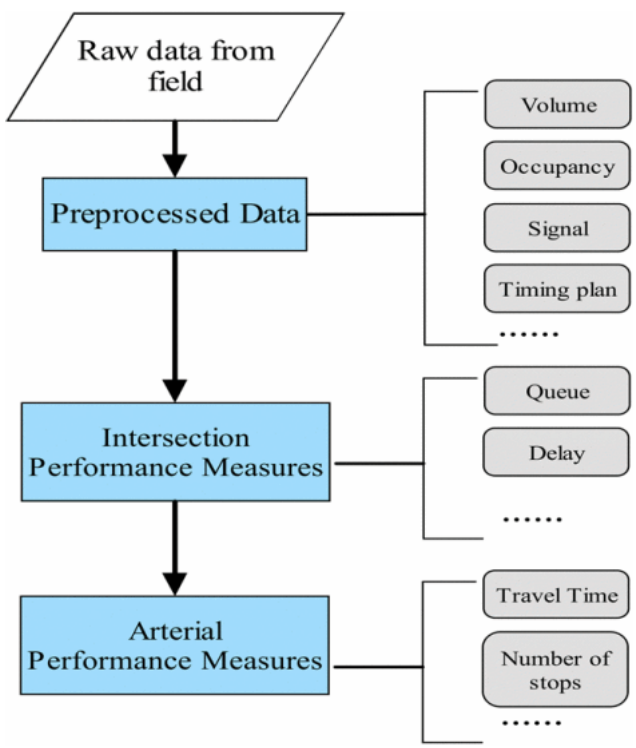

Figure 2.2. Data flow of the ATSPM system in Minneapolis, MN (Liu et al., 2008).

In Indiana, one of the major focuses regarding ATSPM is on performance measures related to corridor coordination. These measures are collected using automated detector data. An example of using the coordination performance measures to improve corridor progression is given in a study done by Lavrenz et al. (2017) where US 421 in Indiana was evaluated using these measures. This study emphasized visualizing detector failures relative to signal timing. When detection issues were found in the signals, changes were made, and the progression of vehicles in the corridor improved significantly.

Seminole County, FL has also begun to introduce ATSPM in their signal network. Seminole County uses ATSPM to supplement its traffic counting program by identifying fluctuations in detected volumes, then using that evaluation to retime signals where necessary. One of the main purposes of the implementation in Seminole County is to decrease the cost of manually collecting traffic counts. With the ATSPM data, continuous traffic counts are available in most urban areas (Wetzel, 2016).

One of the perceived leaders in ATSPM use is the Georgia Department of Transportation (GDOT). “With more than 88 percent of its signals reporting high-quality data, GDOT uses ATSPM as its primary tool to improve operations and manage maintenance of its traffic signal network” (CTI, 2018). GDOT also uses ATSPM to remotely survey traffic situations in real-time and then to adjust signal timing as needed. ATSPM enable the agency to make decisions on a corridor basis instead of intersection by intersection and to manage incidents and planned events (GDOT, 2019).

All these agencies (Minneapolis, Indiana, Seminole County, and GDOT) use ATSPM data to improve intersection and corridor movement. Minneapolis has their own system to collect performance measures and evaluate corridor performance. Indiana uses primarily the Purdue Coordination Diagram (PCD) to evaluate detector failure and signal timing. Seminole County uses ATSPM data to collect continuous traffic counts and then uses those counts to retime signals when necessary. GDOT uses ATSPM data to evaluate corridor performance during large events and for incident management.

The growth of interest in and development of ATSPM tools was accelerated and adopted in many state agencies across the U.S. The ATSPM technology has been implemented by at least

39 state DOTs at a demonstration stage or higher, and 4 state DOTs at the institutionalized stage. Figure 2.3 shows a map representing the status of ATSPM implementation adoption in the United States as of December 2018. Most of these systems were still in the development and demonstration stage, with many systems that only have a few intersections or corridors with ATSPM available. Over time, however, the number of intersections has been growing (Day et al., 2020).

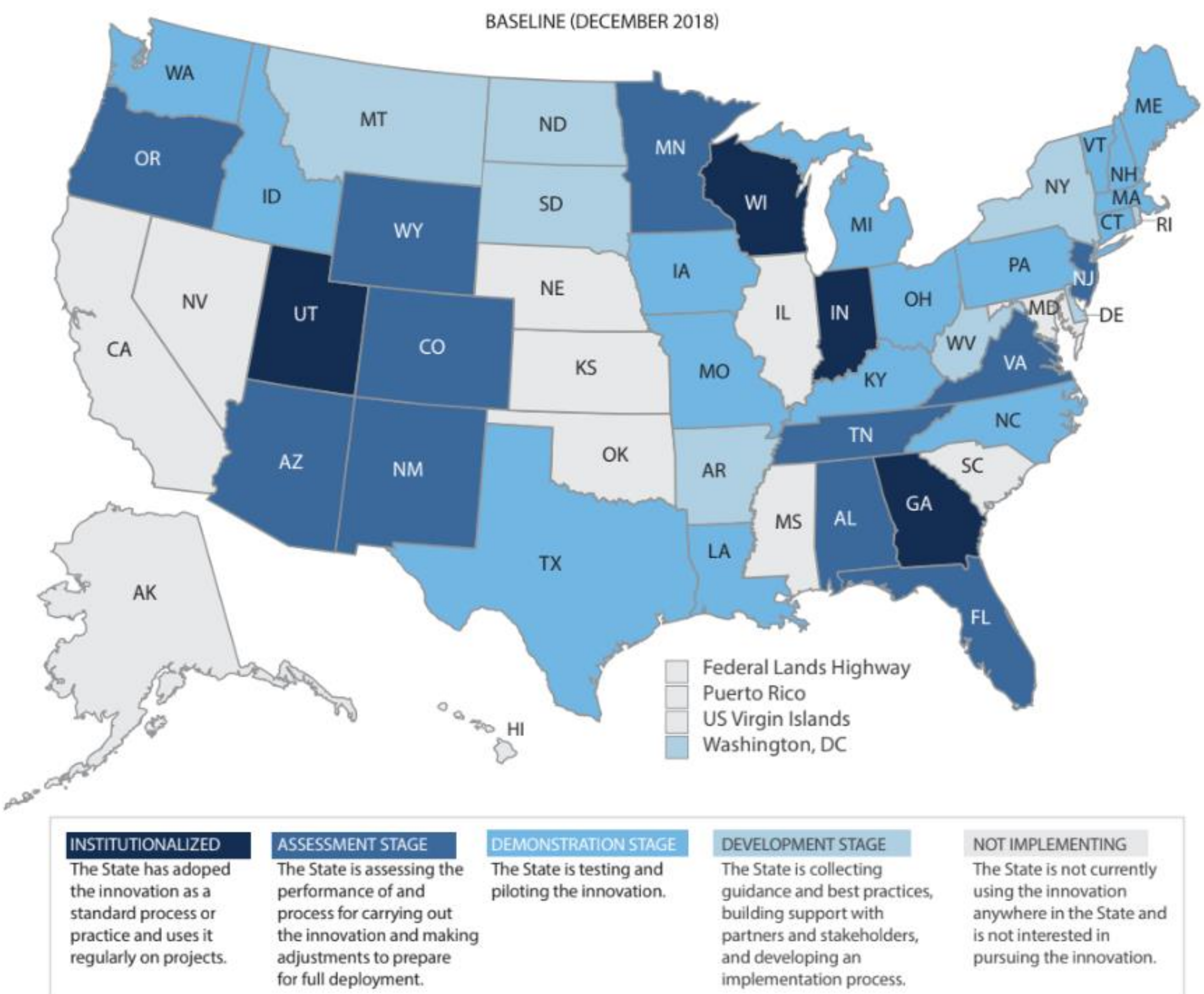

Figure 2.3. Map of ATSPM implementation adoption in December 2018 (Day et al., 2020)

2.2.3 Effects of Automated Traffic Signal Performance Measures

ATSPM data can be used to optimize mobility and manage traffic signal timing and maintenance to reduce congestion, save fuel costs, and improve safety (UDOT, 2019b). Benefits of ATSPM data have been seen in multiple studies, discussed in the following paragraphs.

In a study by Day et al. (2010), PCDs were used to visualize existing offsets of coordinated signals, and then optimize the offsets accordingly. The statistical comparison showed a 28 percent reduction in mean northbound travel time, and although southbound travel times did not decrease, they were not negatively affected by the offset changes.

Lavrenz et al. (2017) performed a study on how detector maintenance affected vehicle progression along a corridor. PCDs were used to evaluate various intersections along US 421 in Indiana using arrival-on-green percentage as the major indicator of progression. The percentage of vehicles arriving on green before the detection repairs was 56.1 percent, and after the detector repairs was 83.7 percent (Lavrenz et al., 2017). Similarly, a study done by Day et al. (2018) found that "making repairs to vehicle loop detectors not only provides benefit to drivers on the corresponding intersection approaches but can also substantially improve performance for drivers on other approaches" (Day et al., 2018).

A study by Kittelson & Associates and Purdue University for the NCHRP identifies another positive effect of ATSPM: "ATSPM enable a more rapid comprehensive evaluation of incident management measures" (Kittelson & Associates and Purdue University, 2017). This principle has had multiple applications for GDOT. GDOT has used their ATSPM data to improve traffic in emergencies and during special events. For example, in 2017, a fire was set underneath a bridge on I-85 in Atlanta, GA. The fire led to the collapse of the bridge and subsequently, required a plan to reroute traffic during reconstruction (NTSB, 2017). ATSPM were used to redirect traffic and adjust signal timing along the detours by monitoring volumes in real time (Davis, 2017). GDOT also used ATSPM data to manage hosting the Super Bowl in February 2019. ATSPM allowed GDOT to remotely survey traffic and adjust signal timing as needed. They also provided insight on a corridor level, not just intersection by intersection. ATSPM allowed Atlanta to keep traffic moving even with the addition of 75,000 vehicles per day (GDOT, 2019).

ATSPM provide useful information to improve signal and corridor performance, however, there are some limitations in using ATPSM including difficulty sharing information between agencies, updating and adding features, analyzing corridors, and knowing how long to store data (Wetzel, 2016). Even with these limitations, the variety of performance measures and the tools used to analyze them allow for analysis of intersections and corridors that is custom to each signal and that cannot easily be accomplished in any other way.

2.2.4 Endorsement of ATSPM from the Federal Highway Administration

The FHWA encourages the use of ATSPM to improve safety, target maintenance, and improve operations by providing continuous performance monitoring capability. One of the greatest benefits of ATSPM data is that "signal retiming efforts can be based directly on actual performance without dependence on software modeling or expensive, manually collected data" (FHWA, 2019). In addition, ATSPM allow for signals to be maintained as needed, not on an arbitrarily set schedule, which greatly reduces the money spent on maintenance (FHWA, 2019). ATSPM were created through a collaboration between the FHWA, the American Association of State Highway and Transportation Officials (AASHTO), state DOTs, and academic research teams. A Transportation Pooled Fund study, "Traffic Signal Systems Operations and Management," was led by the Indiana DOT with participation from the FHWA, 11 state DOTs, and the City of Chicago. As a result of this study, an open source software was created that allowed for the implementation of ATSPM in multiple state DOTs. The FHWA approximates that "…26 transportation agencies at both state and local levels are currently involved in implementing ATSPM. The AASHTO Innovation Initiative led by the Utah DOT has resulted in early implementation of the technology in 12 states and a community of peers ready to share implementation experience" (FHWA, 2019).

2.3 Performance Measures Used Currently by UDOT

UDOT currently uses a website to allow agency partners access to the ATSPM data in Utah. This website and its capabilities will be explained in this section followed by a summary of the performance measures and tools for visualizing and evaluating performance metrics that UDOT currently uses in their ATSPM system including the Purdue Phase Termination (PPT) diagram, Split Monitor, Pedestrian Delay, Preemption Details, Purdue Split Failure (PSF), Yellow and Red Actuations, Turning Movement Counts, Approach Volume, Approach Delay, Arrivals on Red, PCD, and Approach Speed. All figures for performance metrics display data at the intersection of State Street and Center Street in Orem, UT on June 12, 2019 between 7:00 AM and 10:00 AM.

2.3.1 UDOT ATSPM Website

UDOT has developed a website that displays several metrics developed using data collected by detection across the state of Utah. The website is configured to request the data for the signal, performance metric, and time period requested. Figure 2.4 shows the data selection menu found on the home page of the ATSPM website (UDOT, 2019c). The code for the ATSPM website was provided by UDOT. This code is open sourced on GitHub allowing agencies across the world to use it for free.

On the UDOT ATSPM website, by selecting the signal ID of an intersection, a list of metrics appears in the chart selection portion of the screen. This list is determined by the types of detection at an intersection. The intersection used as an example for this section, State Street and Center Street in Orem, UT, has all types of detection available. The types of detection that each metric require were referenced and summarized previously in Figure 2.1. Each metric has a list of options particular to that metric that are displayed to the right of the chart selection section. A date and time range can then be selected from the menu below the chart selection menu for use in summarizing the data.

The goal of developing ATSPM is to be able to identify poorly performing intersections quickly and reliably. With the website's current capabilities, it is not possible to identify which signals are performing poorly. To identify poorly performing signals using the website, each individual intersection would need to be queried. This is impractical and time consuming, especially considering this process would need to be completed for each metric. However, the goal of developing comparative performance indicators from ATSPM data could be accomplished using the raw data stored in the UDOT database. The metrics displayed through the website will be explained individually in the remaining subsections.

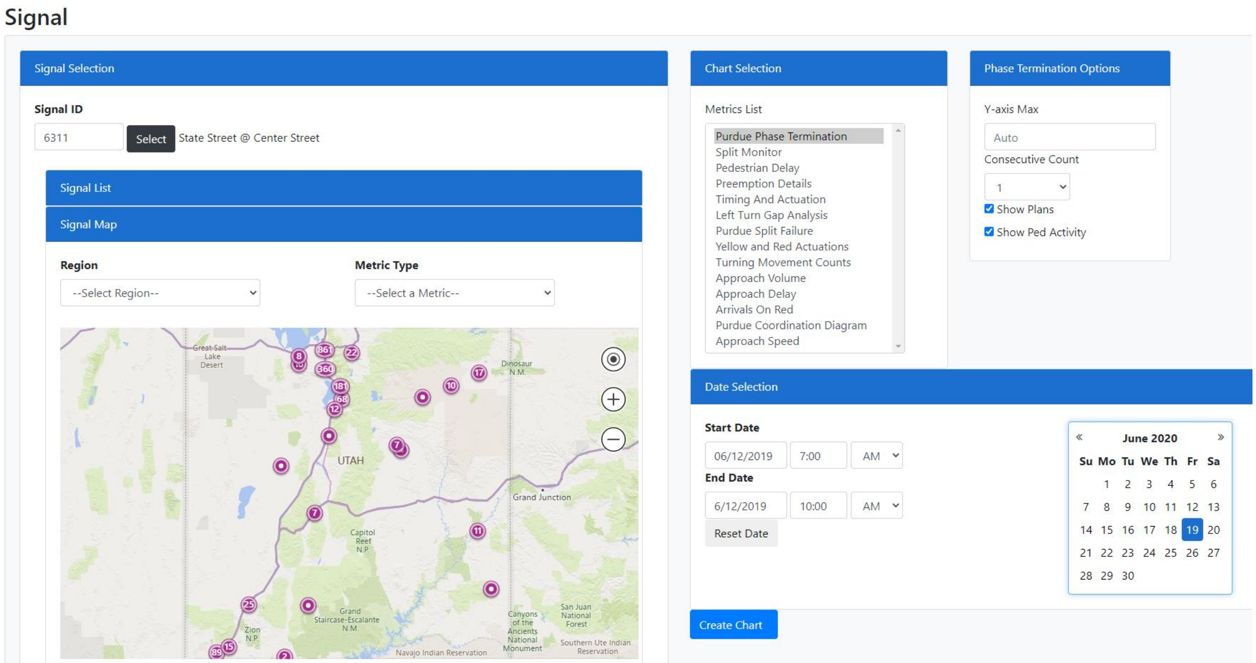

Figure 2.4. UDOT ATSPM website data selection display.

2.3.2 Purdue Phase Termination

The PPT diagram is a tool for evaluating performance measures by plotting the controller's phases and the reason the phase terminated. It does not require detection because this performance metric is based on information obtained from the signal controller. The metric plots phase termination due to force-off, gap out, or max out and identifies where split time may need to be added or subtracted from a phase (UDOT, 2019a). Figure 2.5 shows an example of a PPT diagram.

2.3.3 Split Monitor

The Split Monitor chart generates separate plots for each phase on the controller indicating how much split time is being used for each phase. Each plot depicts the length of the phase in seconds and the reason the phase terminated. There is no detection needed for this performance metric (UDOT, 2019a) because this chart is also populated using data from the signal controller. Figure 2.6 provides an example of a Split Monitor chart.

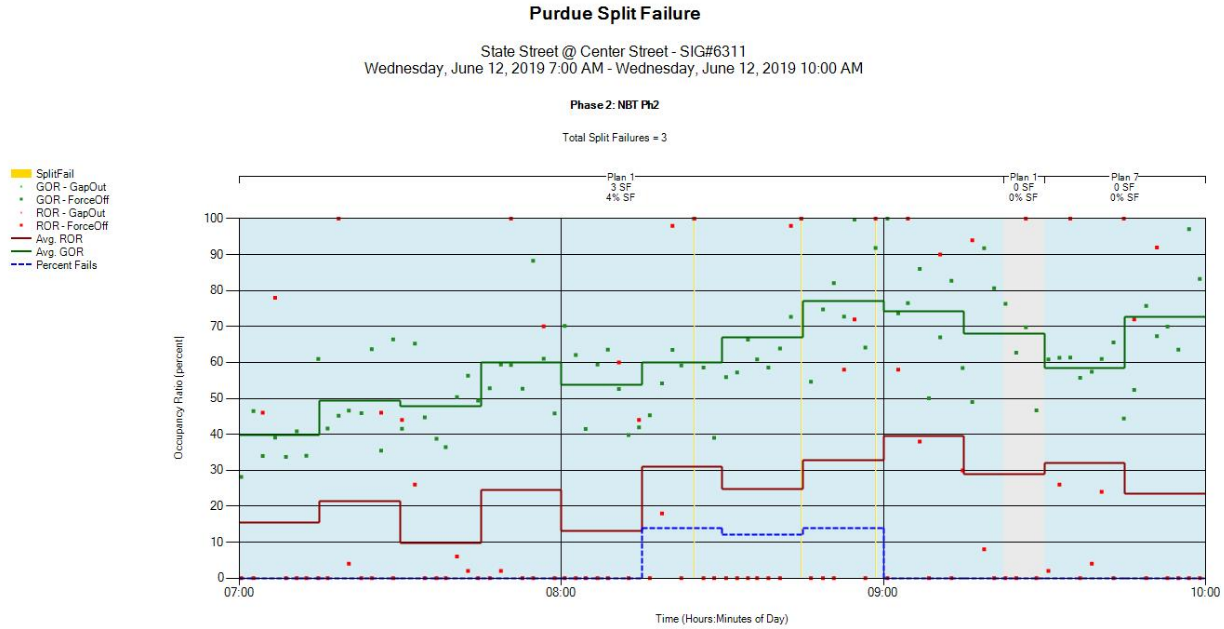

Figure 2.5. Purdue Phase Termination diagram for Phase 2 at State Street and Center Street in Orem, Utah (UDOT, 2019c).

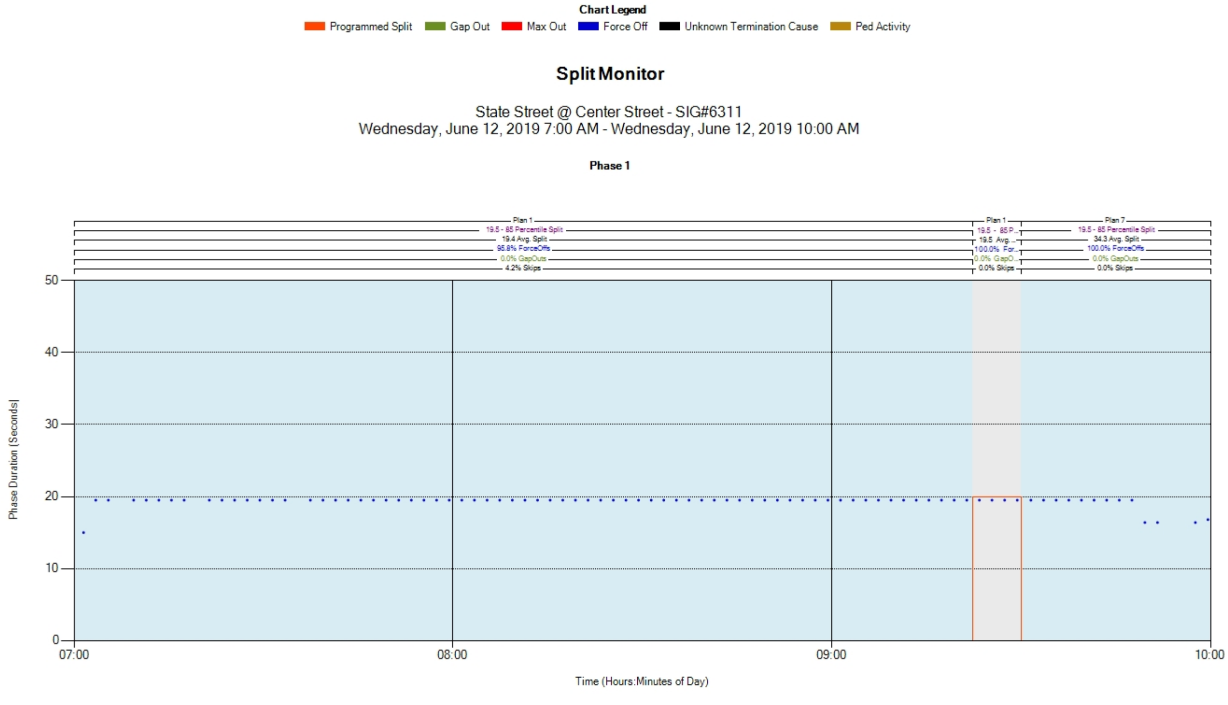

Figure 2.6. Split Monitor chart for Phase 1 at State Street and Center Street in Orem, Utah (UDOT, 2019c).

2.3.4 Pedestrian Delay

Pedestrian Delay is a time-of-day metric that depicts the delay, in minutes, associated with each pedestrian actuation. It also provides a summary of the minimum, maximum and average delay for each phase. A pedestrian actuation button is required to measure pedestrian delay (UDOT, 2019a). The data are reported by the signal controller. Figure 2.7 gives an example of a pedestrian delay graph.

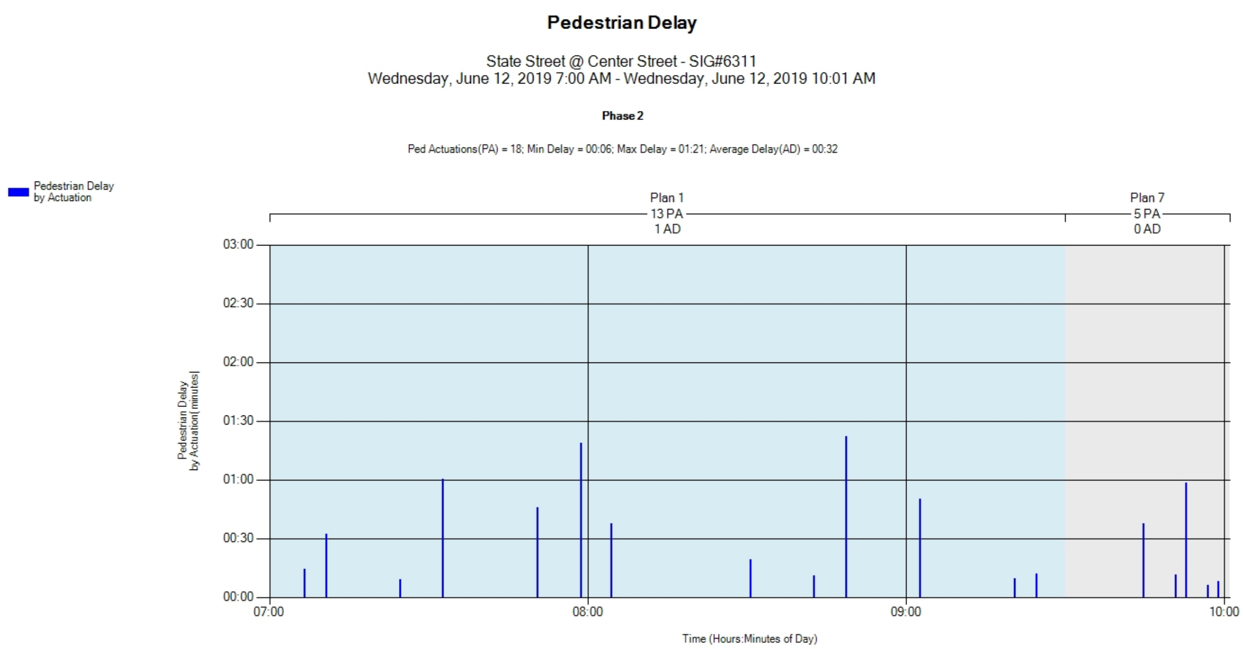

Figure 2.7. Pedestrian Delay for Phase 2 at State Street and Center Street in Orem, Utah (UDOT, 2019c).

2.3.5 Preemption Details

Preemption Details identify preemption events that might occur at a signal. For example, railroad crossings or emergency vehicles may preempt normal signal operation. This metric does not require any detection or provide any options to configure the output, it only provides information on when and why preemption occurred at a signal (UDOT, 2019c).

2.3.6 Purdue Split Failure

Split failure occurs when a traffic queue at a signal is not cleared during the green phase. The PSF diagram relies on stop bar presence detection, either by lane group or lane by lane. This tool calculates the percent of time that stop bar detectors are occupied during the green phase and then during the first five seconds of red. The calculated values are the green occupancy ratio and red occupancy ratio. They measure how often a vehicle does not make it through an intersection on the first green light given. PSF is arguably the most useful tool to traffic analysts because it shows where delay is most prevalent (UDOT, 2019a). Figure 2.8 shows an example of a PSF diagram.

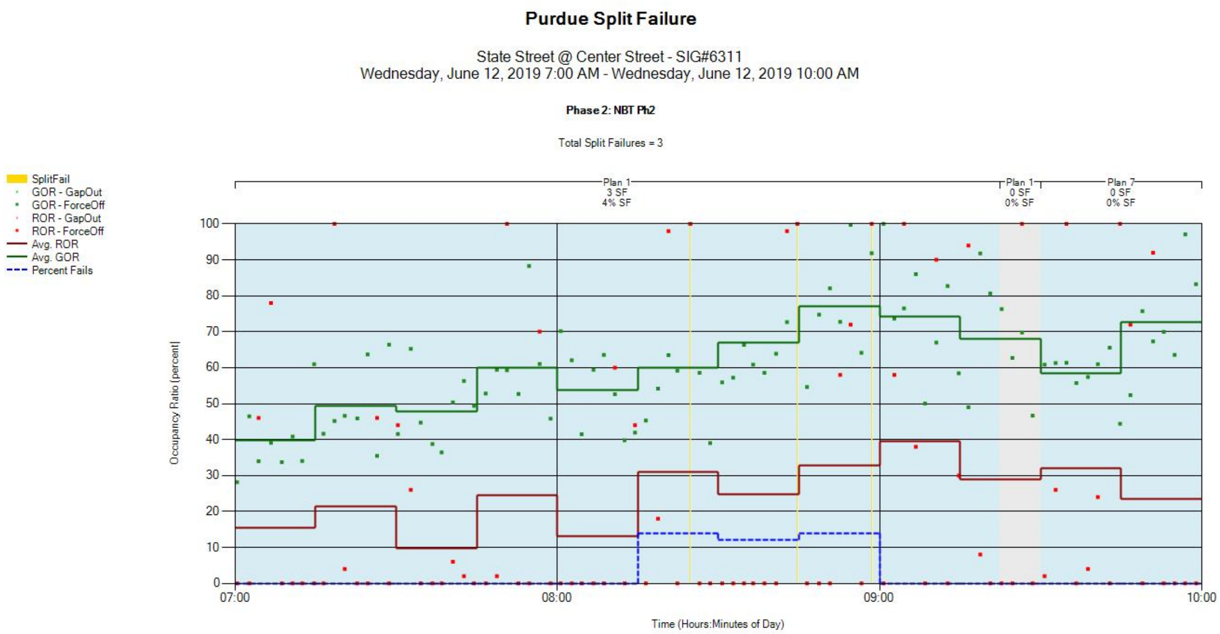

Figure 2.8. Purdue Split Failure diagram for State Street and Center Street in Orem, Utah (UDOT, 2019c).

2.3.7 Yellow and Red Actuations

The Yellow and Red Actuations metric plots vehicle arrivals during the yellow and red portions of an intersection's movements where the speed of the vehicle is interpreted to be too fast to stop before entering the intersection. It provides users with a visual indication of occurrences, violations, and several related statistics. Yellow and red actuations require a stop bar count with speed detection included (UDOT, 2019a). Figure 2.9 shows an example of yellow and red actuations for an intersection. The purpose of this chart is to identify engineering countermeasures to address red-light running.

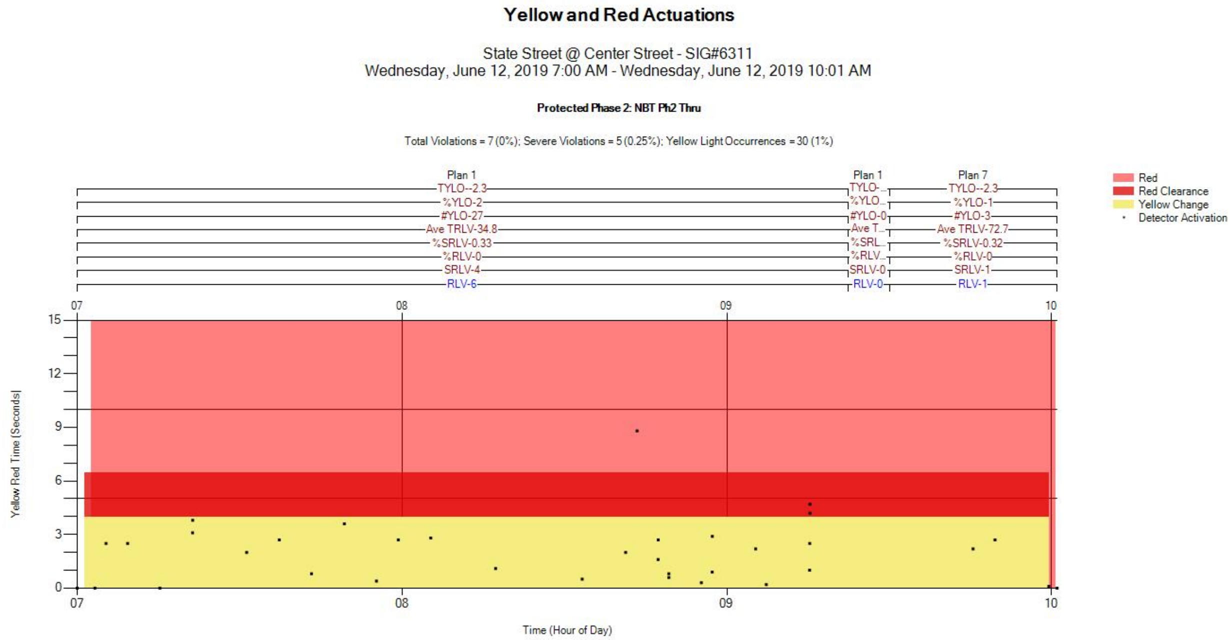

Figure 2.9. Yellow and Red Actuations for Protected Phase 2 at State Street and Center Street in Orem, Utah (UDOT, 2019c).

<u>2.3.8 Turning Movement Counts</u>

The Turning Movement Counts metric generates traffic volume for each lane on an approach. Turning movement counts provide useful metrics that include volume, peak hour, peak hour factor, and lane utilization factor. These counts require a stop bar presence detector in each lane (UDOT, 2019a). Figure 2.10 shows a sample of turning movement counts.

Figure 2.10. Eastbound Through Turning Movement Counts at State Street and Center Street in Orem, Utah (UDOT, 2019c).

2.3.9 Approach Volume

The Approach Volume metric differs from the Turning Movement Counts by using advanced detection that is normally located 300 feet to 500 feet upstream of the stop bar and counts vehicles for the approach. Approach volumes are useful in traffic modeling, identifying directional splits, and identifying the least disruptive times for maintenance and other traffic disruptions. If detection exists at both the stop bar and in advance of the intersection, there is an option to view the approach volume data using one or the other detector device. Figure 2.11 shows a sample graph of approach volumes in an intersection.

This plot also displays directional factors, or D-factors. A D-factor is a measure of the percentage of total volume in a specified direction. For example, if the volume of vehicles in opposing directions is equal, the D-factor would be 0.5 for both directions (FHWA, 2018). Stop bar count detection is required to measure approach volume, while advanced presence detection is required to measure approach volume upstream from the stop bar (UDOT, 2019a). This graph displays data from 425 feet upstream of the stop bar.

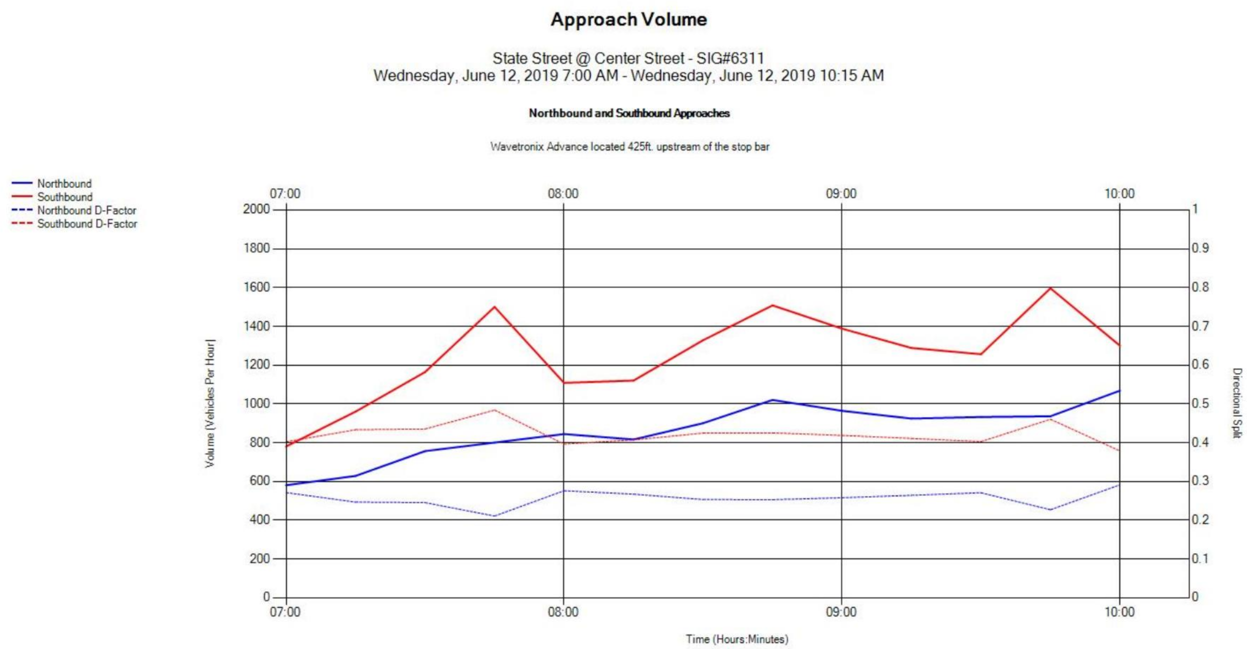

Figure 2.11. Approach Volumes for Northbound and Southbound Approaches at State Street and Center Street in Orem, Utah (UDOT, 2019c).

2.3.10 Approach Delay

The Approach Delay metric plots a simplified approach delay experienced by vehicles approaching and entering the intersection. The delay per vehicle and total delay are both available. Delay in this case is defined as the time between detector activation during red phase and green phase and requires stop bar detection (UDOT, 2019a). Figure 2.12 gives an example of approach delay at an intersection.

2.3.11 Arrivals on Red

The Arrivals on Red metric plots both the volume and percentage of vehicles arriving on red for those phases where data are available. The Arrivals on Red metric is usually used in identifying poor progression in a corridor and requires an advance count detection system (UDOT, 2019a). Figure 2.13 presents the plot of arrivals on red for an intersection.

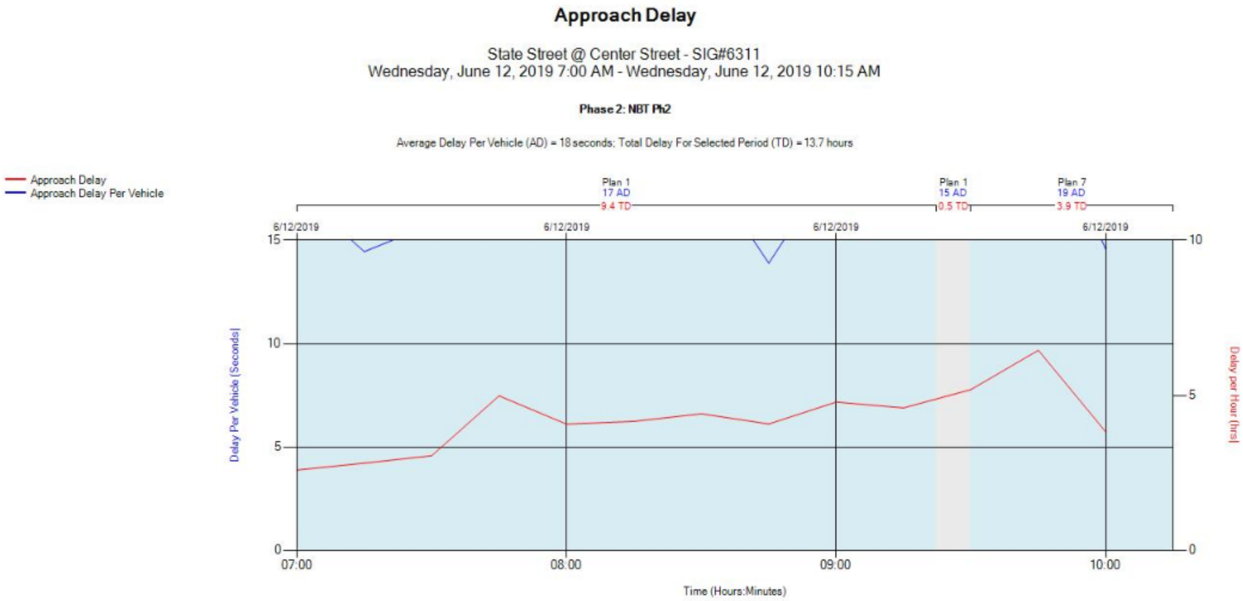

Figure 2.12. Approach Delay for Phase 2 at State Street and Center Street in Orem, Utah (UDOT, 2019c).

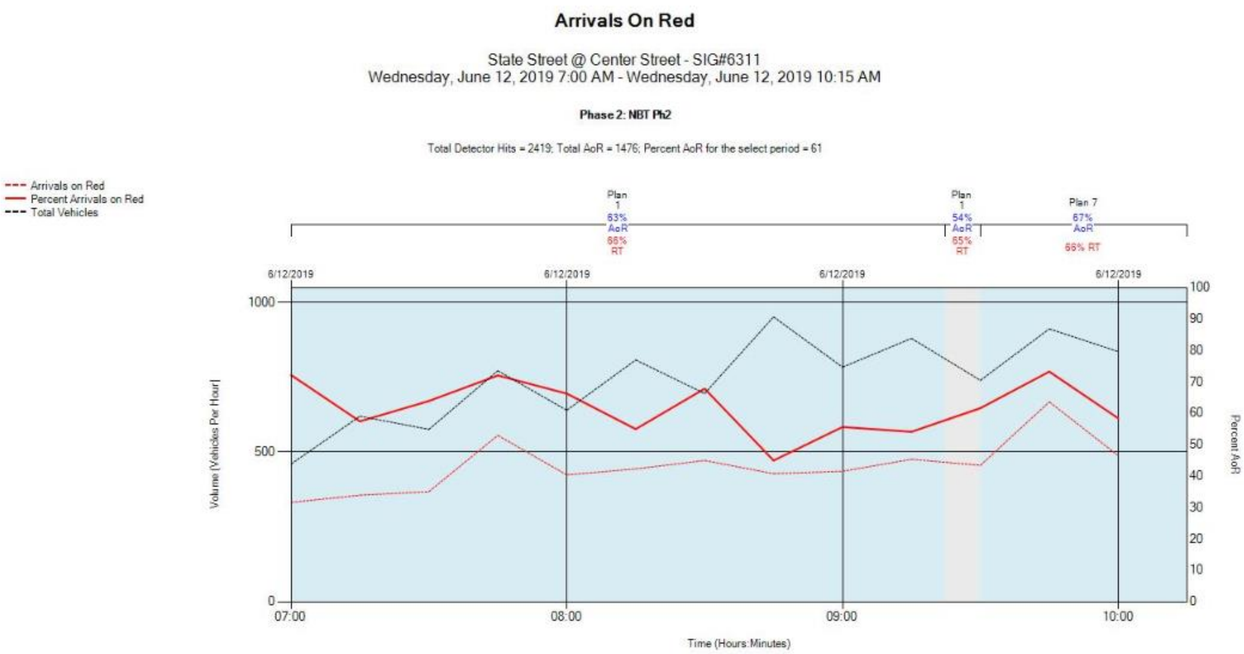

Figure 2.13. Arrivals on Red for Phase 2 at State Street and Center Street in Orem, Utah (UDOT, 2019c).

2.3.12 Purdue Coordination Diagram

The PCD is a powerful tool to analyze multiple performance measures related to intersection delay and performance. The PCD plots vehicle arrivals against the current movement (green, yellow, red) and traffic flow in vehicles per hour using the percentage of vehicles that arrive on green and the platoon ratios. This metric allows the analyst to optimize the offsets, identify over- or under-saturated splits, and visualize the impacts of queuing and different phase actuations. In general, it provides an idea of progression quality in a corridor (UDOT, 2019a). Figure 2.14 shows an example of a PCD. Advance count detection is required to create PCDs.

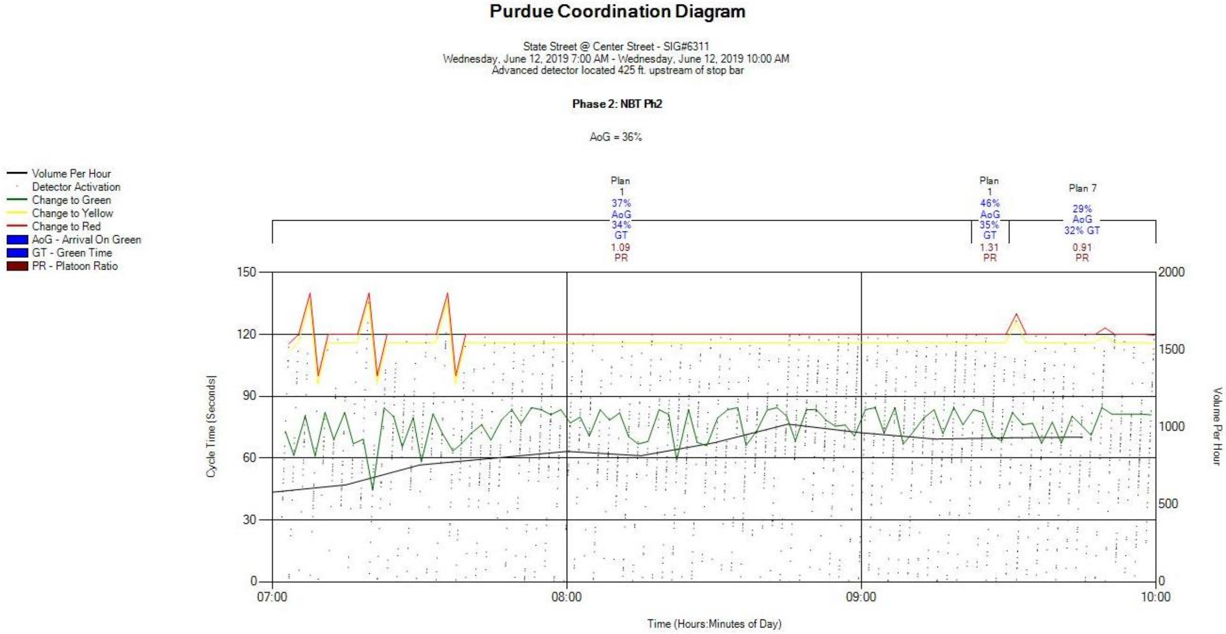

Figure 2.14. Purdue Coordination Diagram for Phase 2 at State Street and Center Street in Orem, Utah (UDOT, 2019c).

2.3.13 Approach Speed

The Approach Speed metric tracks the speed of vehicles approaching a signalized intersection for those phases where the data are available. This metric requires detection set back from the stop bar that can detect speed. Currently the only supported product is the Wavetronix SmartSensor^{TM} Advance (UDOT, 2019a). Figure 2.15 gives a sample graph of the approach speed of an intersection.

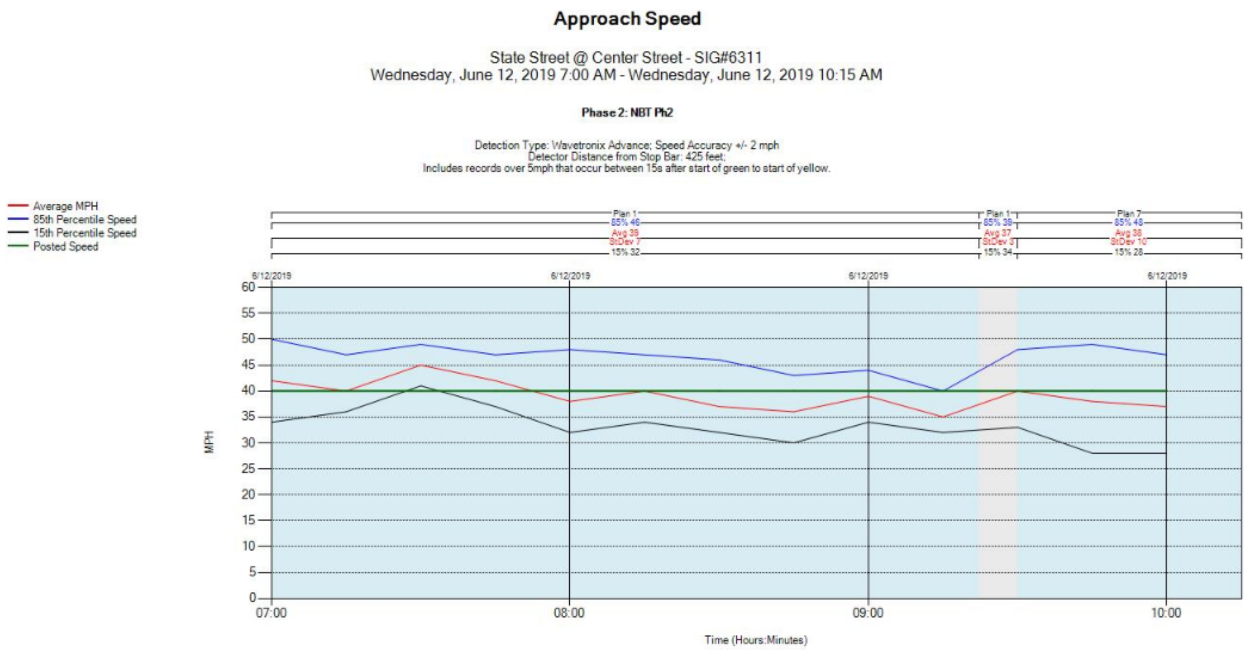

Figure 2.15. Approach Speed for Phase 2 at State Street and Center Street in Orem, Utah (UDOT, 2019c).

2.4 Methods for Identifying Relevant Performance Measures

One of the difficulties of using ATSPM data is the large amounts of data collected daily, increasing by approximately 1 TB of data every month (UDOT, 2019a). With such large amounts of data, it is important to identify which measures have the greatest effects on intersections, corridors, and the system. This section will discuss several potential methods of determining the most important measures to be used in analysis for this research. Specifically, the Delphi approach, a data-driven approach, and approaches used in other industries to evaluate and rank performance measures will be discussed.

2.4.1 Delphi Approach

The Delphi approach to decision making is "a qualitative, long-range forecasting technique, that elicits, refines, and draws upon the collective opinion and expertise of a panel of experts" (Gupta and Clarke, 1996). Experts on the panel rely on past experiences similar to the topic being studied and on their own knowledge of the subject (Cavalli-Sforza and Ortolano, 1984). According to Linstone and Turoff (1975), there are four effective phases to a Delphi approach:

- Phase 1 – Each member of the panel of experts supplies information they think is useful/pertinent
- Phase 2 – Reach a consensus on relative terms and what those terms mean
- Phase 3 – If there is disagreement, evaluate differences to find reasons for it
- Phase 4 – Analyze initial evaluations and receive feedback

There have been many studies in the transportation field that have used a Delphi approach to develop scoring systems, rank factors or qualities, and predict future impacts. For example, Cavalli-Sforza and Ortolano (1984) used the Delphi method to forecast land use and predict impacts of alternative transportation programs in San Jose, CA. A preliminary survey was sent to the panel of experts, evaluated, adjusted, and re-sent as the "Delphi questionnaire." A similar approach could be useful to identifying the performance measures with the highest impacts and the effects of any changes or adjustments. However, similar assessments could be made based on historical data, especially using measures like congestion and safety (Hendren and Niemeier, 2006).

Hirschhorn et al. (2017) use a Delphi approach to rate core performance indicators in a public transportation system. They declare their purpose as "defining what organizational features drive strategic performance outcomes, and what performance metrics are more suitable to measure these impacts" (Hirschhorn et al., 2017).

The Delphi approach in the case of Hirschhorn et al. (2017) was done in three stages on more than 400 indicators:

- Stage 1 – Brainstorming
    - Panel could propose any relevant elements to the subject
    - Major themes are identified, grouped, and redundancies are eliminated
- Stage 2 – Narrowing down
    - Panel chooses most relevant elements from those brainstormed in the first stage
- Stage 3 – Rating
    - Panel ranks elements on the short list from the second stage

Schultz and Jensen (2009) developed a scoring system for advanced warning signal systems in Salt Lake City, UT, using a Delphi approach. The Linstone and Turoff phases, outlined previously, were implemented to analyze and rank the signal conditions to determine if an advanced system should be installed. “A scoring system was developed to provide a basis for the prioritization process. The sensitivity of the scoring system was evaluated through multiple scenarios and reviewed with the Technical Advisory Committee according to the Policy Delphi process” (Schultz and Jensen, 2009).

2.4.2 Data-Driven Approach

The general data-driven approach means that progress in an activity is compelled by data, rather than by intuition or personal experience. In other words, the decision is made with hard empirical evidence and not speculation or “gut feel.” This method is used in many technology and business fields.

In recent years, the concept of a data-driven approach has been gaining popularity for traffic management. In the transportation field a data-driven approach to ranking, scoring, and evaluating the data performance has been used. For example, Day et al. (2018) use a data-driven approach to rank a coordinated traffic signal system for maintenance and retiming. The authors propose a method of evaluating corridor performance at the system level using high-resolution data from ATSPM. Their method develops five sub-scores based on the collected data for the areas of:

- Communication
- Detection
- Safety
- Capacity allocation
- Progression

Liu and Chen (2017) use the data-driven approach to incorporate the performance monitoring and planning processes for freeway performance evaluation and decision making. The data-driven performance-based approach presented in their study is effective in quantitatively evaluating the freeway mobility/reliability, and the impact of incidents and adverse weather.

Wang et al. (2018) developed a method to analyze the probability of pedestrian flow congestion. This method uses a data-driven approach based on Kernel Density Estimation. Walking speed, crowd density, and flow rate when pedestrians walk towards possible bottlenecks are considered.

2.4.3 Approaches Used in Other Industries

Other industries outside of transportation engineering use different approaches to evaluate performance measures. Some of the principles used in these methods can be applied to evaluating ATSPM.

Jansen et al. (2011) wrote about the Multi-Attribute Utility (MAU) Theory, which allows a decision maker to choose between various alternatives that have multiple attributes to consider. The example used in this study is of buying a house where "…the decision-maker has to consider multiple attributes of the available alternatives at the same time, such as the preferred dwelling type, number of rooms, and costs. Thus, the decision problem has multiple value dimensions, which may be in conflict" (Jansen et al., 2011). This can be related to ATSPM data; there are multiple measures, but the most important ones must be identified based on certain attributes. Jansen et al. (2011) provides five steps to use MAU Theory in decision-making based on attributes:

- Defining alternatives and value-relevant attributes
- Evaluating each alternative separately on each attribute
- Assigning relative weights to the attributes
- Aggregating the weights of attributes and the single-attribute evaluations of alternatives to obtain an overall evaluation of alternatives
- Perform sensitivity analyses and make recommendations

These five steps are similar to the Delphi method, where the "decision-maker" is instead a panel of experts on the attributes and metrics being measured.

A study performed in supply chain management by Gunasekaran et al. (2001) focused on developing performance measures, specifically for supply chain operations. Some of the principles used in this study are useful when considering ATSPM evaluation. Each step in the supply chain process is considered, and the most important one or two measures are chosen for each step. Emphasis is placed on eliminating waste (e.g. extra green time) and reducing cost (e.g. travel time).

The American Heart Association used a method like the Delphi method in determining new and revised performance measures for evaluating heart failure in a patient. A writing committee was created, consisting of experts from both medicine and performance management. The committee made decisions about which measures to change or include, reviewed them, reached a consensus, and then submitted the measures for peer and public review. Then, the suggestions resulting from those reviews were also reviewed and changes were made as necessary (Bonow et al., 2012).

An additional method used by Abalo et al. (2007) gives further recommendation on ranking performance measures. A method called Importance-Performance Analysis (IPA) which ranks measures based on their importance to the rater was used. Nine attributes for assessing patient-perceived quality of primary health care were ranked and a mathematical method was used to place the measures on a matrix that related importance and performance. It was found that absolute rating (rating measures individually on a scale of 1-10) was not as effective as a relative rating, which ranked measures in relation to each other. Relative ranking provided a better assessment of what measures needed to be prioritized (Abalo et al., 2007).

These studies, though not related to signal performance, could provide additional methods to identify and rank the most important signal performance measures.

2.5 Chapter Summary

The purpose of this literature review is to provide valuable background on the current use of ATSPM across the nation and in the state of Utah using the various types of detection at each intersection. ATSPM data also have the potential to be used for data collection and analysis. This idea built the foundation for using ATSPM. With ATSPM, data are collected from intersection detection and information provided by the signal controller. ATSPM are already being used in several states. Utah has begun using ATSPM to increase the efficiency and economy of maintaining signals. UDOT has developed a website to display the performance measures in the form of metrics that are currently being used as ATSPM.

Although ATSPM are already proving useful in improving intersection and corridor progression, there is no current method in the state to rank and compare intersections to each other or to their historical performance. This research aims to create a method for ranking intersections and corridors to identify those performing poorly. The following chapters in this report will outline a method to rank intersection and corridor performance using ATSPM in the state of Utah.

3.0 METHODOLOGY

3.1 Overview

The methodology for this research will be explained in this chapter. The methodology for identifying performance measures for this research project is largely based on the Delphi and data-driven performance-based methods, mentioned in Section 2.4. The key component of the Delphi method is to make decisions based on feedback from an expert panel. In this research the members of the Technical Advisory Committee (TAC) represent the expert panel described in the Delphi method. In addition, the decisions on how to analyze the data are limited by the available data. As such, the methodology is also a data-driven performance-based approach.

As stated in Chapter 1, one of the goals of this research project is to outline a method to rank intersection performance using ATSPM. To accomplish this goal, there are three necessary steps that will be discussed in this chapter. First, the process for selecting performance measures to be analyzed will be discussed. Second, the selection of signals and time periods for analysis will be discussed. Finally, the method for providing scores for individual intersections and entire corridors will be presented.

3.2 Selecting Performance Measures

This section will discuss the initial selection of performance measures to be analyzed. This selection was based on discussion with the TAC and on research conducted by Day et al. (2018). After collecting data for these performance measures, it was determined that some should be omitted from the final analysis. The final selection and the process to determine these performance measures will be presented in Section 5.3.

3.2.1 Force-Offs and Max-Outs

The TAC suggested that force-offs and max-outs would be useful performance measures for analysis. Force-offs and max-outs both measure when a phase is forced off. The max out term is derived from the signal controller reaching a predetermined maximum amount of time. If the number of force-offs or max-outs is high, it means that the signal is not operating optimally. It was also determined that to better compare force-offs and max-outs between signals, values for the percentage of cycles that end in a force-off and the percentage of cycles that end in a max-out should be used for analysis. This required obtaining data for the number of cycles in a given time period. If number of force-offs and number of cycles are collected for a specific period of time, a value can be obtained for the percentage of cycles that end in a force-off. The same calculation method can be used for max-outs.

Force-offs and max-outs are particularly useful because they are available at every signal and do not require any additional configuration to obtain, as it is logged automatically in the high-resolution data. Other performance measures are based on detection that is not available at every signal; however, the defined enumerations in the high-resolution data are always available as long as the signal controller is logging the data. The tool that displays force-offs and max-outs is the PPT diagram.

3.2.2 Arrivals on Green and Arrivals on Red

Arrivals on green and arrivals on red were identified as performance measures that would be useful for this research. A high number of vehicles arriving on green is preferred because these vehicles experience lower delay. A low number of vehicles arriving on red is likewise preferred. To effectively compare results between different signals, it was determined that these measures should be presented as percent arrivals on green and red. Calculating the percent arrivals on a signal phase requires an additional data element: the total volume of the movement.

Arrivals on green and red are obtained using advanced presence detection available at many signals. The tool that displays these performance measures is the PCD.

3.2.3 Split Failures

Another useful performance measure for consideration was split failures. Vehicles that fail to pass an intersection on the first green light they are given experience higher delay. As with arrivals on green and red, to effectively compare results between different signals, it was determined that this measure should be presented as a percentage. This also requires the total volume of the movement in addition to the number of split failures.

Split failures are obtained using stop-bar presence detection, either by lane group or lane by lane, which is available at many signals. The tool that displays this performance measure is the PSF.

3.2.4 Platoon Ratio

The TAC suggested that the platoon-ratio performance measure would be useful for this research. The platoon ratio is a measure of how effectively an intersection is utilizing the green portion of a cycle. Equation 3.1 displays how to calculate the platoon ratio.

$$f_p = \frac{PVG}{g/C} \tag{3.1}$$

where, f_p = platoon ratio,

PVG = percentage of vehicles arriving during the effective green,

g = effective green time,

C = cycle length.

Platoon ratio is also a measure of how well the corridor is progressing. UDOT places great importance on this measure because it can quickly display whether a signal is performing well or poorly. A high platoon ratio signifies good performance and a low platoon ratio signifies poor performance. Although there is no maximum value for a platoon ratio, any value higher than 1.5 is exceptional and any value lower than a 0.5 is considered poor (TRB, 2010).

Platoon ratio is obtained using advanced presence detection available at many signals. The tool that displays this performance measure is the PCD.

3.2.5 Red-Light Violations

There was some discussion amongst TAC members about how useful red-light violations would be for analysis. The TAC noted that there are some inconsistencies in the calculation of red-light violations. For example, the latency required to determine a red-light violation is inconsistent between signals. In other words, the radar sensors used for this metric are not consistent. Because of the latency, there will be missing counts of the red-light violation. Although the red-light violation performance measure has some inconsistencies when comparing across intersections, it will still be possible to determine if signal performance is worsening, staying the same, or improving over time using this performance measure by comparing the same intersections longitudinally. The red-light violation performance measure is also the only measure related to safety. As such, it was decided to consider red-light violations in the analysis.

Red-light violation data are obtained using lane by lane with speed restriction detection, which is available at many signals. The tool that displays this performance measure is the Yellow and Red Actuations diagram.

3.2.6 Volume-to-Capacity Ratio

Day et al. (2018) use the volume-to-capacity ratio as a performance measure for consideration. Favorable progression is more difficult to achieve as an intersection approaches saturation. To account for this, the volume-to-capacity ratio measures how saturated an intersection is. A volume-to-capacity ratio of 1.0 shows that an intersection is at capacity. The study used a volume-to-capacity ratio in conjunction with platoon ratio to allow intersections with higher saturation to receive higher scores. For example, if an intersection had a platoon ratio of 0.9 and a volume-to-capacity ratio of 0.2, it would receive a letter grade of D. However, if an intersection had a platoon ratio of 0.9 and a volume-to-capacity ratio of 0.8, it would receive a letter grade of C (Day et al. 2018). The research team decided to consider this performance measure for intersection analysis.

Volume-to-capacity ratio is calculated using three data points: volume, saturation flow rate, and total green time.

3.2.7 Performance Measure Summary

Discussion with the TAC, data availability, and reference to literature determined the performance measures to be considered. Table 3-1 shows the performance measures the research team initially decided to consider for analysis. All the performance measures can be found on the UDOT ATSPM website except platoon ratio, which can be calculated independent of a PCD.

Table 3-1. Performance Measures by Tool and Detection Type

Tool	Detection Type	Performance Measure(s)
Purdue Phase Termination (PPT)	Signal Controller	Percent Max-Outs per Cycle, Percent Force-Offs per Cycle
Purdue Coordination Diagram (PCD)	Advanced Presence Detection	Percent Arrivals on Green, Percent Arrivals on Red, Platoon Ratio
Purdue Split Failure	Stop Bar Detection (lane by lane)	Percent Split Failure
Yellow and Red Actuations	Lane by lane with speed restriction	Red-Light Violations
N/A	Stop Bar Detection	Volume-to-Capacity Ratio

3.3 Selecting Time Periods and Signals for Analysis

The selection of time periods for this research was primarily based on obtaining an ample amount of data for analysis. This section will describe the process followed for selecting time periods and signal data.

3.3.1 Selecting Time Periods

The research team chose to focus on the split-failure performance measure first in analysis. Because this was the first selected performance measure, the time period selection was primarily influenced by this performance measure. A large number of split failures typically occur during the PM peak due to a large number of cars on the road at this time. This is to be expected and may not be an accurate reflection of poor performance. As a result, the AM peak time period was investigated instead of the PM peak. If many split failures occur during this time period, it is more likely that the signal is not performing well. An afternoon time period was also chosen to provide a "control" time period. The chosen time periods were from 7:00 AM to 9:00 AM and from 12:00 PM to 2:00 PM on Tuesdays and Wednesdays in March, July, and October in 2018. Tuesdays and Wednesdays were chosen as they are historically very similar regarding traffic. Two days were chosen to provide more data points. This differs from the literature by using only two weekdays as opposed to five (Day et al. 2018). The motivation behind this is that the days closer to the weekend are anticipated to have different traffic patterns than those closer to the middle of the week. Three separate months were chosen to account for changes in weather and traffic demand. The year 2018 was chosen because it was the most recent full year of data available at the time the research team began aggregating the data (summer of 2019). Figure 3.1 shows a visual representation of the selected days for the chosen signals.

Figure 3.1. Visual representation of chosen study dates.

<u>3.3.2 Selecting Signals and Approaches</u>

This section will cover the process for selecting signals and approaches.

3.3.2.1 Selecting Signals

The amount of performance measure data available at a given signal is determined by the type of detection available as was explained in greater detail in Sections 2.2 and 3.2. The goal for selecting signals was to select intersections that had enough data available to perform an analysis. The TAC provided the research team with a summary of the detection types and tools available at each intersection overseen by UDOT. This UDOT signal summary assisted in the selection of signals.

Originally, the research team chose corridors that were near the location of the Brigham Young University (BYU) campus to be able to observe these corridors in person if the need arose. This led to choosing the University Avenue corridor in Provo and the 800 North and State

Street corridors in Orem. Signals along these corridors had ample data in the UDOT signal summary. Originally, eight signals were chosen from each corridor. Table 3-2 shows the intersections selected on State Street, 800 North, and University Avenue including the signal numbers and cross streets associated with each intersection. Figure 3.2 shows a visual representation of the initially selected corridors.

3.3.2.2 Selecting Approaches

The research team decided to evaluate only the through movements for each signal to simplify the interpretation of performance measures such as platoon ratio, force-offs, max-outs, and split failures, which can become complicated in permitted and protected left-turn phases. The phases investigated were typically 2 and 6, but sometimes phases 4 and 8 were used. The through movements chosen were those in the same direction as the corridor being investigated. When this was in the direction of the primary route for a signal, the phases used were 2 and 6, otherwise phases 4 and 8 were used.

Table 3-2. Original Selection of Intersections on the State Street, 800 North, and University Avenue Corridors

Primary Route	Cross Street	Primary Route	Cross Street	Primary Route	Cross Street
800 North	Geneva Road	State Street	University Pkwy.	University Ave.	100 North
	I-15 SPUI[1]		1200 South		200 North
	1200 West		800 South		500 North
	980 West		400 South		700 North
	State Street		Center Street		800 North
	Main Street		400 North		960 North
	400 East		800 North		Canyon Road
	800 East		1600 North		1230 North (Cougar Blvd.)

[1]SPUI: Single Point Urban Interchange

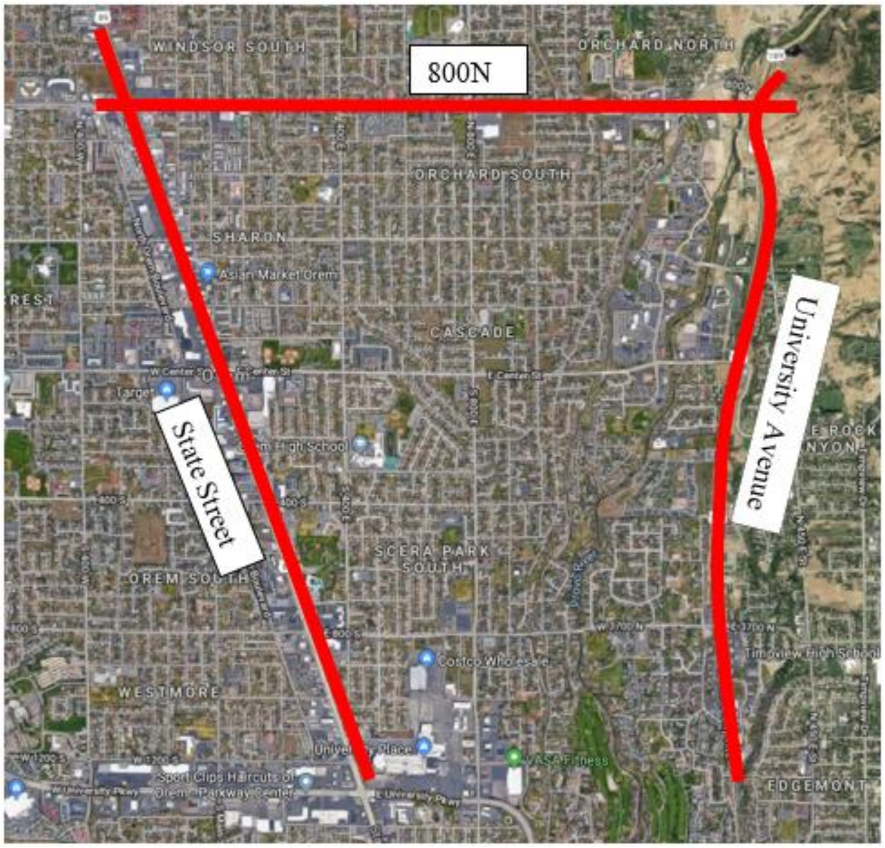

Figure 3.2. Map of corridors included in the sample network.

3.4 Scoring Methodology

Once the data were collected for the chosen signals, the intersections and corridors were scored based on the performance measures identified previously. The general process for scoring is described in this section. First, threshold values were determined for each performance measure using cluster analysis supplemented by expert opinion. These threshold values enabled the research team to assign scores for each performance measure. Then, the intersection was given an overall score based on the scores of the individual performance measures. Finally, each corridor was given an overall score based on the scores of the intersections in that corridor. To aid in completing each of these steps, the research team developed an interactive data visualizer using the Shiny application framework for the statistical analysis program R (Chang et al., 2020)

3.4.1 Threshold Values

Determining threshold values is one of the most essential portions of providing intersection scoring. Threshold values were determined for each of the performance measures selected for analysis. The research team created threshold values based on various sources including a k-means cluster analysis, the Highway Capacity Manual (HCM), and through consultation with the TAC. The specific threshold values determined by the research team will be discussed in Section 6.3.

Clustering, in general, is a non-parametric machine-learning technique used to classify data across multiple attributes. The specific k-means algorithm can be used when all attributes $x_1, x_2, \ldots x_n$ of a particular data point p_i are continuous variables (i.e., there are no categorical or logical values). The k-means algorithm works as follows:

1. Select k random points in n-dimensional space as initial "mean points."
2. Calculate the distance between each data point and each mean point.
3. Calculate a new mean point as the average $\bar{x}_1, \bar{x}_2, \ldots, \bar{x}_n$ of the points closest to each existing mean.
4. Calculate the mean squared error for points associated with each new mean.
5. Iterate steps 2 through 4 until the change in mean squared error between iterations drops below a specified tolerance level.

The result of this algorithm is a set of "clusters" defining groups of points that are more alike to each other than those points in other clusters. One important note is that all attribute x_i must be on effectively the same scale or variables with wider ranges will exert more influence on the definition of the clusters. It is thus common practice to rescale all attributes on the [0,1] range. More details on this process are available from the University of Cincinnati (UC, 2016) and multiple machine-learning textbooks. This research uses the `kmeans` function for R (R Core Team, 2020). In this project, the `kmeans` process informs a search for threshold values that can effectively distinguish intersections showing different performance characteristics across a wide variety of numeric performance measures. The research team created an interactive data visualizer to apply the cluster analysis and visually verify the threshold values. The visualizer was developed by the research team using the “Shiny” application interface for R (Chang et al., 2020).

3.4.2 Providing Scores

Once an intersection has been given a score for each performance measure, an overall score can be calculated. The method used to calculate the overall score was a weighted average. Greater emphasis can be given to individual performance measures by increasing the weights associated with these measures, depending on how the analyst might perceive the relative importance of each performance measure. The method for calculating overall scores will be discussed in greater detail in Section 6.5.

Once each intersection has been scored, the corridor can be scored. Day et al. (2018) calculated the corridor score as the minimum score for any single intersection on the corridor. The research team investigated the sensitivity of the overall score to several different scoring schemes. These potential scoring schemes include using the minimum, average, or maximum score for the corridor.

3.5 Chapter Summary

The purpose for this chapter was to describe the methodology for this research project. In this chapter, an initial set of performance measures and signals were selected based on the Delphi approach. The research team chose to focus on through movements for each selected signal to simplify the collection and interpretation of data. The data were collected for several Tuesdays and Wednesdays throughout the year 2018. After the data were collected, the research team determined threshold values to be used to assign scores to intersections and rank them to identify poorly performing intersections. Scores were assigned on the corridor level and corridors were ranked. Once the general methodology for the research was established, the research team was prepared to collect analysis data.

4.0 DATA COLLECTION

4.1 Overview

The data for this project were the same being used for the ATSPM website. The location of this raw data is a UDOT database located on a server housed in the Traffic Operations Center. Specifically, the data are stored on a Microsoft Structured Query Language (SQL) Server database, the name of which is Measures of Effectiveness (MOE), within this server. The official name of the server is srwtcmoe, but for the purposes of this report it will be referred to as the UDOT server. The MOE database on the UDOT server was copied to a server in the BYU Transportation Lab and aggregated from the raw data. This database transection allowed the research team to aggregate data from the BYU server without any changes on the UDOT server. To aggregate this raw data on the BYU server, the same aggregation code used to produce aggregation for the UDOT server was utilized. This code was added to and adjusted to meet the needs of the research team.

This chapter will summarize research data collection. First the UDOT ATSPM website and its connection to data collection will be discussed. Then, the characteristics of the UDOT server will be explained. The process of creating the BYU server will then be described. Next, the adjustments made to the aggregation code by the research team will be explained. The data aggregation process will then be described. Finally, a verification of the aggregated data will be shown.

4.2 UDOT ATSPM Website

The preceding literature review contains a description of the ATSPM used by UDOT. The tools that display each performance measure can be accessed through the public UDOT ATSPM website (UDOT, 2019c). This website organizes data by Signal ID, start date (with time field), end date (with time field), and a selection of characteristics depending on the performance measure. The website provides a user-friendly method of determining how a single intersection may be performing regarding specific performance measures. This section will discuss the website limitations and website aggregation code. The limitations of the current ATSPM website show the necessity for this research.

4.2.1 Website Limitations

There are a few limitations to the ATSPM website that were identified through this research. One is the limited number of dates that can be queried. When the website was accessed in July 2019, information for any dates before December 2018 could not be found. This impaired the ability of the analyst to perform a longitudinal analysis and to determine whether the signal is improving, getting worse, or staying the same over time. However, when the website was accessed in June 2020, the website displayed data back to November 2017 in many cases. Because UDOT is working backwards in time to aggregate data, the capabilities of the website are improving. In addition, one location where data for split failures weren't available previously, the intersection of 980 West and 800 North, now has split failures. This is likely due to the addition of stop-bar presence detection. Table 4-1 displays the signals investigated in July of 2019 and the comparative availability of data between the original investigated date and secondary investigated date of June 2020. All data presented in the table is in relation to split failures. The originally selected signals on University Avenue were also inspected in July 2019. However, since they were not included in the final analysis, they have been left out of the June 2020 verification.

Another limitation is the inability to look at multiple signals simultaneously. While the ATSPM website is useful for looking at individual intersections, it cannot analyze how well a corridor is performing.

As mentioned in Section 2.3.1, it is also not possible to identify which signals are performing poorly directly from the information contained on the website. To do so, each individual intersection would need to be queried. This is impractical and time consuming, especially considering this would need to be completed for every tool displayed on the ATSPM website as discussed previously in Section 2.3.

The user is also unable to compare intersections based on multiple performance measures directly from the website output. Taking multiple performance measures into account would allow intersections to be compared more holistically.

Table 4-1. Data Availability for Split Failures

Signal ID	Primary Name	Secondary Name	Earliest date with data available (July 2019 verification)	Earliest date with data available (June 2020 verification)
6303	State Street	800 North	12/30/2018	11/12/2017
6304	Main Street	800 North	12/30/2018	6/12/2018
6305	400 East	800 North	12/30/2018	8/30/2018
6306	800 East	800 North	12/30/2018	11/12/2017
6308	State Street	400 North	12/30/2018	11/12/2017
6311	State Street	Center Street	12/30/2018	11/12/2017
6313	State Street	400 South	2/25/2019	2/25/2019
6314	State Street	800 South	12/30/2018	11/12/2017
6323	State Street	1200 South	No PSF	No PSF
6324	State Street	University Pkwy	12/30/2018	11/2/2018
6393	State Street	1600 North	12/30/2018	11/12/2017
6395	Geneva Road	800 North	12/30/2018	11/12/2017
6397	800 North	I-15 SPUI	No PSF	No PSF
6398	1200 West	800 North	12/30/2018	11/12/2017
6399	980 West	800 North	No PSF	11/12/2017

This research aims to create a method that can take multiple performance measures into account and assign scores for individual intersections and corridors.

4.2.2 Website Aggregation Code

The UDOT ATSPM website does not display raw data. Rather, the website displays tools or metrics that utilize the raw data, some of which are directly connected to the raw data. The tools not connected to raw data are connected to data that have been aggregated from the raw data but are still stored in the UDOT server. This aggregated data takes the raw data collected from different types of detection such as lane-by-lane presence, stop-bar count, and advanced count and places it in 15-minute bins. The code used to perform the ATSPM website data aggregation is located on an open source website (UDOT, 2020).

4.3 UDOT Server

The UDOT Server collects and stores raw detector and signal data. These data are stored in the MOE database of this server. The MOE database in the UDOT server contains a controller event log table where the raw data aggregated by the ATSPM website are stored. This table is continuously updated with real-time data that contains information regarding all the signals in Utah. Figure 4.1 shows what this controller-event log table looks like in the SQL server. Each event code and event parameter corresponds to data being recorded for different performance measures. The aggregation code uses this data to report values such as arrivals on green, split failures, and red-light violations. Data are collected every second of every day.

Results | Messages

	SignalID	Timestamp	EventCode	EventParam
1	1001	2020-01-29 08:30:25.900	3	2
2	1001	2020-01-29 08:30:25.900	3	2
3	1001	2020-01-29 08:30:25.900	3	6
4	1001	2020-01-29 08:30:25.900	3	6
5	1001	2020-01-29 08:30:44.800	2	8
6	1001	2020-01-29 08:30:44.800	2	8
7	1001	2020-01-29 08:30:44.800	4	2
8	1001	2020-01-29 08:30:44.800	4	2
9	1001	2020-01-29 08:30:44.800	4	6
10	1001	2020-01-29 08:30:44.800	4	6
11	1001	2020-01-29 08:30:44.800	7	2
12	1001	2020-01-29 08:30:44.800	7	2
13	1001	2020-01-29 08:30:44.800	7	6
14	1001	2020-01-29 08:30:44.800	7	6
15	1001	2020-01-29 08:30:44.800	8	2
16	1001	2020-01-29 08:30:44.800	8	2
17	1001	2020-01-29 08:30:44.800	8	6
18	1001	2020-01-29 08:30:44.800	8	6
19	1001	2020-01-29 08:30:44.800	43	8
20	1001	2020-01-29 08:30:44.800	43	8
21	1001	2020-01-29 08:30:44.800	82	3
22	1001	2020-01-29 08:30:44.800	82	3
23	1001	2020-01-29 08:30:44.900	43	2
24	1001	2020-01-29 08:30:44.900	43	2
25	1001	2020-01-29 08:30:44.900	43	6
26	1001	2020-01-29 08:30:44.900	43	6
27	1001	2020-01-29 08:30:48.900	9	2

Figure 4.1. Controller-event log table in SQL server.

The MOE database contains many other tables in addition to the controller-event log table. Figure 4.2 shows some of the names for these tables and how they look in the SQL server.

Some are aggregation tables and contain data aggregations, or 15-minute bins of data, from various signals over a relatively small period of time. This time period is only a few months in the year 2015. These tables contain aggregations for cycles, event counts, PCDs, speed, split failures, yellow and red activations, detector event counts, preemption, priority, signal event counts, and pedestrian actuations. An example of an aggregation table can be seen in Figure 4.3, which shows yellow and red activations including severe red-light violations occurring in 15-minute bins. The “is protected” column displays a “1” if the data in that bin are for a protected phase and a “0” if the data are not for a protected phase. Although these aggregations contain useful information, the limited and outdated time period found in the UDOT server made using them for analysis impractical. The research team determined that it would be useful to investigate dates closer to the present time. A copy of the database with current controller-event log data was used to accomplish this goal.

4.4 BYU Server

The enormous amount of information found in the controller-event log table made it impractical to copy the entire table from the UDOT server to the BYU server. This necessitated requesting the set of signals and dates that were to be used for analysis, and for UDOT staff to manually transfer data into the BYU database. This form of obtaining raw data can create delays in the aggregation process if the requested signals and date-times are continuously requiring amendments and adaptations. In the future it would be helpful to provide direct read access to the UDOT-event log tables from the BYU Transportation Lab. A priority request system could prevent BYU research from interfering with UDOT operations. One solution to the limitations of the UDOT server was to create a copy of the MOE database and store it locally on the BYU campus. This allowed for aggregation of any set of signals during any chosen time period.

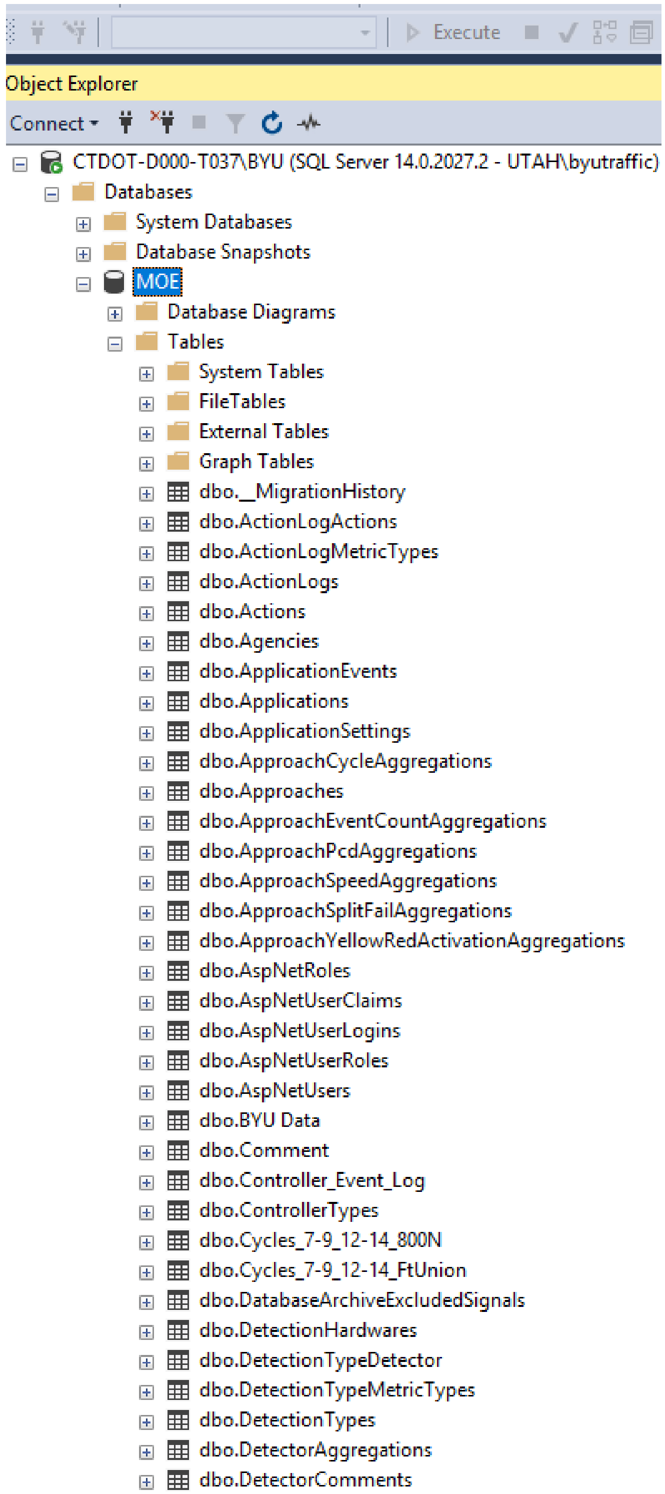

Figure 4.2. Names of tables in the MOE database.

Results Messages

	Id	BinStartTime	ApproachId	SevereRedLightViolations	TotalRedLightViolations	IsProtectedPhase
1	118141	2018-03-06 07:00:00.000	2051	0	1	1
2	118169	2018-03-06 07:15:00.000	2140	0	1	1
3	118182	2018-03-06 07:15:00.000	2051	0	1	1
4	118210	2018-03-06 07:30:00.000	2141	0	2	1
5	118214	2018-03-06 07:30:00.000	2144	9	9	1
6	118215	2018-03-06 07:30:00.000	2145	2	3	1
7	118218	2018-03-06 07:30:00.000	2145	2	3	0
8	118219	2018-03-06 07:30:00.000	2144	9	9	0
9	118225	2018-03-06 07:30:00.000	2055	0	5	1
10	118227	2018-03-06 07:30:00.000	6470	1	1	1
11	118228	2018-03-06 07:30:00.000	6470	1	1	0
12	118254	2018-03-06 07:45:00.000	2141	0	3	1
13	118258	2018-03-06 07:45:00.000	2145	7	8	1
14	118259	2018-03-06 07:45:00.000	2145	7	8	0
15	118267	2018-03-06 07:45:00.000	6470	2	5	1
16	118268	2018-03-06 07:45:00.000	6470	2	5	0
17	118293	2018-03-06 08:00:00.000	2142	0	2	1
18	118296	2018-03-06 08:00:00.000	2144	2	2	1
19	118297	2018-03-06 08:00:00.000	2145	5	5	1
20	118298	2018-03-06 08:00:00.000	2144	2	2	0
21	118299	2018-03-06 08:00:00.000	2145	5	5	0
22	118332	2018-03-06 08:15:00.000	2141	0	1	1
23	118334	2018-03-06 08:15:00.000	2145	5	5	1
24	118335	2018-03-06 08:15:00.000	2144	8	8	1
25	118338	2018-03-06 08:15:00.000	2145	5	5	0

Figure 4.3. Aggregated red and yellow activations table from SQL.

A technical expert from UDOT assisted the research team in creating a copy of the MOE database accessible from the Transportation Lab at the BYU campus. Although there was not enough space for the entire controller-event log table in the BYU server, specific portions were requested and placed in the BYU server. To successfully and accurately aggregate all the data, several lookup tables needed to be copied to the BYU server as well. For the first few weeks of aggregating data through the BYU copy of the MOE database, approximately half of the data aggregations were not running. The problem causing this issue was eventually discovered to be the absence of a necessary lookup table in the local database. When setting up a local database, it is imperative that all required tables are copied over. The tables copied to the BYU server can be seen in Table 4-2. Table 4-3 shows the resulting aggregations that are available with the combination of tables copied from the UDOT server shown in Table 4-2.

Table 4-2. Names of Tables Copied from the MOE Database to the BYU Server

Table Names	
Actions	DetectionTypes
Agencies	Detectors
Applications	DirectionTypes
ApplicationSettings	LaneTypes
Approaches	MetricFilterTypes
AspNetRoles	MovementTypes
AspNetUserRoles	Region
AspNetUsers	Signals
ControllerTypes	ToBeProcessededTables
DetectionHardwares	ToBeProcessedTableIndexes
DetectionTypeDetector	VersionActions
DetectionTypeMetricTypes	

Table 4-3. Available Aggregation Tables on the BYU Server

Aggregation Table	Data Available
SignalEventCountAggregations	X
PhaseTerminationAggregations	X
PhasePedAggregations	
DetectorEventCountAggregations	
DetectorAggregations	X
ApproachYellowRedActivationAggregations	X
ApproachSplitFailAggregations	X
ApproachSpeedAggregations	X
ApproachPcdAggregations	X
ApproachEventCountAggregations	X
ApproachCycleAggregations	X
PreemptionAggregations	X

4.5 Adjustments to Aggregation Code

The UDOT ATSPM website uses raw detector data that has been aggregated into 15-minute bins. Because the specific bins for the periods used in this analysis had not been aggregated at the commencement of the research, the BYU team needed to reconstruct the software environment and repurpose the existing code to function on the selected times and signals in the BYU server. To do this, the research team cloned the C# code developed by UDOT and hosted publicly on GitHub (UDOT, 2020) and modified it locally to meet this purpose. The changes to the code were recorded and pushed to a fork of the original GitHub repository (BYU Transportation Lab, 2020). This section will discuss the adjustments to the code for platoon ratio, date and times, and signals. To clarify the names of the files mentioned in this section, a "cs" file is a source file written in C#, the coding language used in the UDOT aggregation code.

4.5.1 Adjusting Code for Platoon Ratio

Although the code for the ATSPM website is currently set up to display the platoon ratio values on the PCD diagram, there was no value present when the PCD aggregation table was populated in the BYU SQL Server. This required adjusting the code to aggregate a value for platoon ratio to the PCD aggregation table as well. In the ApproachPcdAggregation.cs file, several lines of code were added to display certain metrics that were not previously displayed. The main metric required by the research team was the platoon ratio. However, other metrics such as total cycle time, total green time, and total volume were also output to verify intermediate calculations in case they became necessary later for research. It was also necessary to make changes to the DataAggregation.cs file in multiple locations. The functions that required adjustment were the BulkSaveApproachPCDData function and the SetApproachPCDData function. The adjustments in both files caused the output to the SQL table to be altered.

The code in the DataAggregation.cs file specifies what performance measures will be aggregated for each of the aggregation tables in the SQL server. Making the changes to the code required to aggregate the platoon ratio added several performance measures to the PCD aggregation table, including the platoon ratio. Each performance measure is represented by a column; therefore, it was necessary to add columns to the PCD aggregation table in SQL so the data could successfully be aggregated.

Choosing a character datatype for the platoon ratio ensured that no data would get lost converting values to an integer (int) datatype. For example, choosing integer for the platoon ratio datatype would render this value useless considering that there is a large difference between a platoon ratio value of 1.1 and 1.2, yet both these values would be reported as a 1 if an integer datatype was used. The datatype doubles could have been used but would take up more storage space. Figure 4.4 shows the process for adding a column to a table in the SQL database. It requires naming the column, choosing the datatype, and determining whether the column can allow null values. Figure 4.5 shows the example of an aggregated PCD with all the performance measures added by the research team.

Column Name	Data Type	Allow Nulls
Id	bigint	☐
BinStartTime	datetime	☐
ApproachId	int	☐
ArrivalsOnGreen	int	☐
ArrivalsOnRed	int	☐
ArrivalsOnYellow	int	☐
IsProtectedPhase	bit	☐
Volume	int	☐
TotalVolume	nchar(10)	☑
PlatoonRatio	nchar(10)	☑
PercentGreen	nchar(10)	☑
TotalTime	nchar(10)	☑
TotalGreenTime	nchar(10)	☑
TotalYellowTime	nchar(10)	☑
TotalRedTime	nchar(10)	☑
		☐

Figure 4.4. SQL table creation.

Id	BinStartTime	ApproachId	ArrivalsOnGreen	ArrivalsOnRed	ArrivalsOnYellow	IsProtectedPhase	Volume	TotalVolume	PlatoonRatio	PercentGreen	TotalTime	TotalGreenTime	TotalYellowTime	TotalRedTime
119125	2020-01-28 07:00:00.000	2075	57	67	1	1	1	125	1.21	38	840	322.7	28	489.3
119126	2020-01-28 07:00:00.000	5253	113	84	2	1	1	199	1.36	42	840	348.7	28	463.3
119127	2020-01-28 07:00:00.000	2051	59	44	4	1	1	107	1	55	840	461.8	35	343.2
119128	2020-01-28 07:00:00.000	2052	370	282	24	1	1	676	0.95	58	840	484	35	321
119129	2020-01-28 07:15:00.000	2075	58	109	3	1	1	170	0.87	39	840	324.5	28	487.5
119130	2020-01-28 07:15:00.000	5253	129	106	3	1	1	238	1.38	39	840	323.5	28	488.5
119131	2020-01-28 07:15:00.000	2051	58	51	7	1	1	116	0.98	51	720	364.3	30	325.7
119132	2020-01-28 07:15:00.000	2052	285	295	18	1	1	598	0.92	52	840	435.3	35	369.7
119133	2020-01-28 07:30:00.000	2075	106	119	2	1	1	227	1.31	36	840	300.2	28	511.8
119134	2020-01-28 07:30:00.000	5253	154	161	6	1	1	321	1.33	36	720	260.7	24	435.3
119135	2020-01-28 07:30:00.000	2052	263	321	28	1	1	612	0.93	46	840	389.2	35	415.8
119136	2020-01-28 07:30:00.000	2051	66	125	1	1	1	192	0.87	39	840	324.6	35	480.4

Figure 4.5. Aggregated PCD table displaying additional performance measures.

4.5.2 Adjusting Code for Dates and Times

To increase the ease and efficiency of setting start and end dates and times, a new function called `SetStartEndDateAggregation` was written. Prior to writing this function, a new date or time had to be input for every iteration of executing the code in the Visual Studio solution used by the research team. Now, data only needs to be input one time and the code can be run for a wide set of dates and corresponding times. The function is primarily intended for aggregating a large set of dates for one or more specified time periods. The function is less useful for a large set of dates with different desired time periods on each day. The function can still be used for this purpose, but it would require more time for aggregation.

The reorganization of the functions in the code required rewriting the main function. Prior to writing the new function, the `StartAggregation` function was called directly from the main function. Now the code initially calls the `SetStartEndDateAggregation` function, which in turn calls the `StartAggregation` function. This allows the aggregation to be run for each date and time period combination input by the user. This change also required changing the `StartAggregation` function from public to private. This code is found in the `AggregateAtspmData.cs` file.

4.5.3 Adjusting Code for Signals

The code was initially set up to aggregate one signal at a time. The code was later modified and now allows aggregation of multiple signals simultaneously. This code is found in the `StartAggregation` function mentioned in Section 4.5.2.

4.6 Data Aggregation and Verification

Once the BYU server was set up, the data were aggregated for the signals and times selected in Chapter 3. Once the data were aggregated, it was necessary to organize the data in such a way that it could be analyzed easily using R. The following subsections will discuss the organization of the data followed by a description of the combined aggregation table including the performance measures calculated by the research team for this combined table.

4.6.1 Data Organization

It was necessary to combine the tables for cycle, PCD, red-light violation, and split failure aggregations into one table. This allowed the research team to see multiple performance measure values for one time period. The tables were joined based on the common data of approach ID and bin start time.

Initially, the research team included force-offs in the analysis. This proved to be somewhat problematic considering some tables had approach ID values and other tables only had phase numbers. SQL join capabilities were used to add an approach ID column to the phase termination aggregations. This was performed by inner joining the phase termination aggregations with the approaches table based on the phase number and signal ID values. Figure 4.6 shows a sample of the approaches table for the intersection of State Street and Center Street in Orem (signal ID 6311). This table tells the user what phase number and signal each approach is associated with.

	ApproachID	SignalID	DirectionTypeID	Description	MPH	ProtectedPhaseNumber	IsProtectedPhaseOverlap	PermissivePhaseNumber	VersionID	IsPermissivePhaseOverlap
1	2075	6311	1	NBT Ph2	40	2	0	NULL	88	0
2	5248	6311	4	WBT Ph8	NULL	8	0	NULL	88	0
3	5249	6311	4	WBL Ph3	NULL	3	0	NULL	88	0
4	5250	6311	3	EBT Ph4	NULL	4	0	NULL	88	0
5	5251	6311	3	EBL Ph7	NULL	7	0	NULL	88	0
6	5252	6311	1	NBL Ph5	NULL	5	0	NULL	88	0
7	5253	6311	2	SBT Ph6	40	6	0	NULL	88	0
8	5254	6311	2	SBL Ph1	NULL	1	0	NULL	88	0

Figure 4.6. Sample from approaches table in SQL database.

4.6.2 Aggregation Table

Four aggregated tables were downloaded from the BYU server. These include the PCD, split fail, red-light violation, and cycles table. Bin start time, signal ID, and approach ID are the common variables from each table. Those variables enable combining the four tables into one dataset. Table 4-4 shows the unique variables selected and used from the four downloaded tables.

Table 4-4. Unique Variables from Each Aggregation Table

PCD	Split Fail	Red-Light Violation	Cycles
ArrivalsOnGreen ArrivalsOnYellow TotalVolume PlatoonRatio	SplitFailures	TotalRedLightViolation	TotalCycles

To simplify the aggregation tables and increase the ease of analyzing data, a combined table was created in R and the percent arrivals on green and percent split failures per 15-minute bin performance measures were calculated using the originally collected performance measures. This combined table displays the data from each 15-minute bin. The combined table is a convenient way to see all the data for each 15-minute bin in one row of data. Figure 4.7 shows what this combined table looked like in R. Some of the intersections were missing one or more performance measures because these intersections either did not have the required detection for a certain measure or simply did not have data. The combined table was filled with N/A values if a performance measure was missing from a signal or approach. The percentage of arrivals on green and the percent split failures per 15-minute bin were calculated as specified in Equations 4.1 and 4.2, respectively.

$$Percent\ AOG = \frac{AOG+AOY}{Total\ Volume} \tag{4.1}$$

where, Percent AOG = percent of vehicle arrivals on green in 15-minute bin
AOG = number of vehicle arrivals on green in 15-minute bin
AOY = number of vehicle arrivals on yellow in 15-minute bin
Total Volume = Total number of vehicle arrivals in 15-minute bin

$$Split\ Failures\ per\ Cycle = \frac{Split\ Failures}{Total\ Cycles} \tag{4.2}$$

where, Split Failures per Cycle = number of vehicles that failed to pass the intersection in each cycle
Split Failures = number of vehicles that failed to pass the intersection in 15-minute bin
Total Cycles = number of signal cycles in 15-minute bin

Figure 4.7 contains all the performance measures required for analysis. There is a column for percent split failures per 15-minute bin (SFPerCycle), percent arrivals on green (PercentAOG), platoon ratio, and total red-light violations. There are also columns that show if the bin belongs to the AM peak or the mid-day time period, what corridor the approach is a part of, and which cluster the bin was assigned to from the k-means cluster analysis. This combined aggregation table enables the research team to evaluate the data efficiently.

As a summary of the steps leading to creating the aggregation table, Figure 4.8 shows the workflow for creating a comprehensive aggregation table.

	BinStartTime	SignalId	ApproachId	TotalVolume	SFPerCycle	PercentAOG	PlatoonRatio	TotalRedLightViolations	AMPeak	Corrdior	cluster
1	2018-03-06 07:00:00	4024	5838	82	0.0000000	0.25609756	0.50	0	TRUE	FtUnion	3
2	2018-03-06 07:15:00	4024	5838	114	0.0000000	0.23684211	0.47	0	TRUE	FtUnion	3
3	2018-03-06 07:30:00	4024	5838	120	0.0000000	0.31666667	0.65	1	TRUE	FtUnion	3
4	2018-03-06 07:45:00	4024	5838	128	0.0000000	0.40625000	0.71	1	TRUE	FtUnion	3
5	2018-03-06 08:00:00	4024	5838	140	0.0000000	0.48571429	0.82	0	TRUE	FtUnion	3
6	2018-03-06 08:15:00	4024	5838	146	0.0000000	0.41095890	0.80	0	TRUE	FtUnion	3
7	2018-03-06 08:30:00	4024	5838	153	0.0000000	0.48366013	0.81	0	TRUE	FtUnion	3
8	2018-03-06 08:45:00	4024	5838	181	0.0000000	0.56353591	0.96	0	TRUE	FtUnion	4
9	2018-03-07 07:00:00	4024	5838	61	0.0000000	0.26229508	0.36	0	TRUE	FtUnion	3
10	2018-03-07 07:15:00	4024	5838	103	0.0000000	0.31067961	0.48	0	TRUE	FtUnion	3
11	2018-03-07 07:30:00	4024	5838	95	0.1250000	0.26315789	0.51	0	TRUE	FtUnion	3
12	2018-03-07 07:45:00	4024	5838	142	0.0000000	0.33802817	0.62	0	TRUE	FtUnion	3
13	2018-03-07 08:00:00	4024	5838	113	0.0000000	0.52212389	0.95	0	TRUE	FtUnion	3
14	2018-03-07 08:15:00	4024	5838	168	0.0000000	0.33928571	0.58	0	TRUE	FtUnion	3
15	2018-03-07 08:30:00	4024	5838	143	0.0000000	0.47552448	0.87	1	TRUE	FtUnion	3
16	2018-03-07 08:45:00	4024	5838	179	0.0000000	0.41340782	0.39	0	TRUE	FtUnion	3
17	2018-03-13 07:00:00	4024	5838	77	0.0000000	0.37662338	0.59	0	TRUE	FtUnion	3
18	2018-03-13 07:15:00	4024	5838	99	0.0000000	0.51515152	0.73	0	TRUE	FtUnion	3
19	2018-03-13 07:30:00	4024	5838	119	0.0000000	0.52100840	0.84	0	TRUE	FtUnion	3
20	2018-03-13 07:45:00	4024	5838	135	0.0000000	0.48148148	0.81	0	TRUE	FtUnion	3

Figure 4.7. Combined aggregation table.

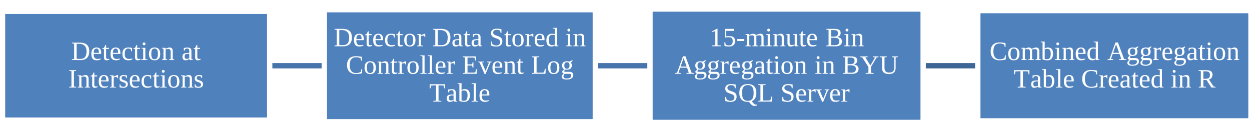

Figure 4.8. Workflow for creating a comprehensive aggregated dataset.

4.7 Aggregation Verification

A time period and signal with available data on the ATSPM website were used to test that the data were aggregating accurately. The State Street and University Parkway intersection (Signal ID 6324) was used for the test case. Using the ATSPM website, it was discovered that this signal did not have PSF data before 2019. As such, April 9, 2019 between 7:00 AM and 7:15 AM was selected as the test period. This time period had split failures recorded for multiple phases according to the ATSPM website. Figure 4.9 displays the results for this time period as found on the ATSPM website. These results are for Phase 1 of the southbound through movement. Figure 4.10 shows a sample of the Split Fail Aggregation table found in the BYU server. Approach ID 9552 corresponds with Phase 1 of this intersection.

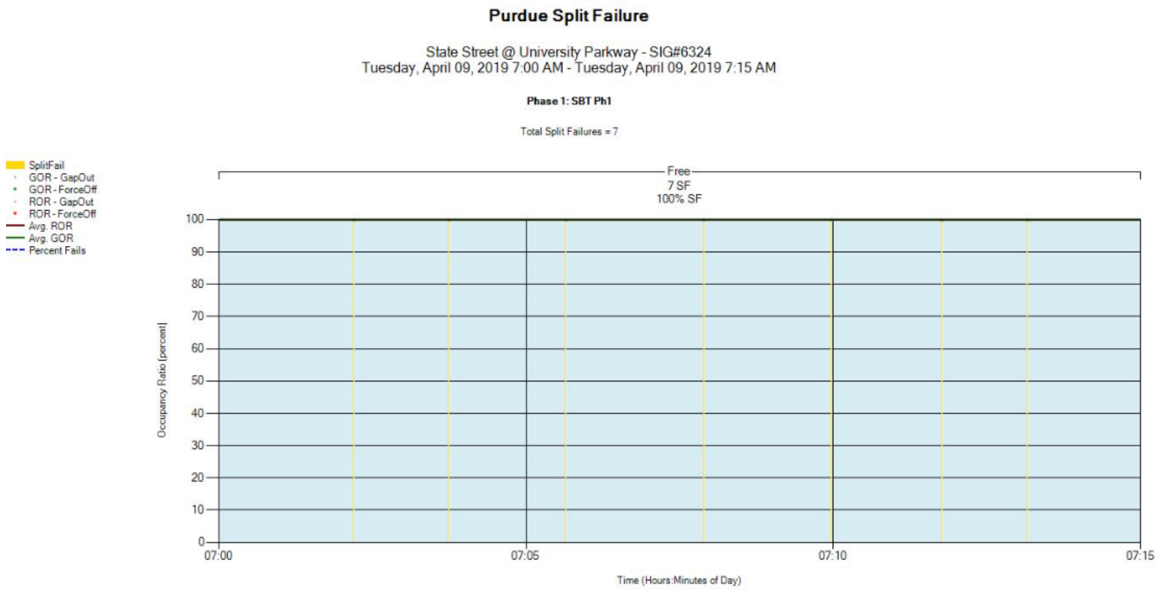

Figure 4.9. Split failures on UDOT ATSPM website.

```sql
SELECT TOP (1000) [Id]
      ,[BinStartTime]
      ,[ApproachId]
      ,[SplitFailures]
      ,[IsProtectedPhase]
  FROM [MOE].[dbo].[ApproachSplitFailAggregations]
  order by BinStartTime desc
```

100 %

Results | Messages

	Id	BinStartTime	ApproachId	SplitFailures	IsProtectedPhase
1	67005	2019-04-09 07:00:00.000	9550	0	1
2	67006	2019-04-09 07:00:00.000	9547	1	1
3	67007	2019-04-09 07:00:00.000	9553	0	1
4	67008	2019-04-09 07:00:00.000	9551	1	1
5	67009	2019-04-09 07:00:00.000	9546	1	1
6	67010	2019-04-09 07:00:00.000	9552	7	1
7	67011	2019-04-09 07:00:00.000	9549	0	1
8	67012	2019-04-09 07:00:00.000	9548	0	1
9	67013	2019-04-09 07:00:00.000	9555	0	1
10	67014	2019-04-09 07:00:00.000	9554	1	1

Figure 4.10. Controller event logs for intersection of State Street and University Parkway.

The ATSPM website and the aggregation table in the BYU server display the same data. It seems that data available on the ATSPM website and the aggregation code reflect the same information. In this case, the website displayed seven split failures for the selected 15-minute bin while the aggregated code displayed seven split failures as well, thus confirming that the data were aggregating correctly.

4.8 Chapter Summary

The research team used code created by UDOT for the ATSPM website as a base for the aggregation of data. To accomplish this, the research team created their own copy of the UDOT server located on a computer in the BYU Transportation Lab. This enabled the research team to have a wider selection of dates for analysis. The research team adjusted the code to obtain the necessary information for aggregation and analysis. Once the data were aggregated, they were organized and prepared for analysis using the R statistical analysis tool. The data were verified by comparing aggregated data with that from the ATSPM website (UDOT, 2019c).

After collecting the data, it was necessary to refine the originally selected signals and performance measures. These adjustments will be summarized in the next chapter.

5.0 REFINEMENTS TO CORRIDORS AND MEASURES

5.1 Overview

After collecting data for the research, it was determined that some of the signals and performance measures should be omitted from the final analysis. Some signals did not contain as much data as expected or it was determined that they would not be useful for analysis. It was also determined to not use some performance measures due to redundancy or issues in calculating the measure. This section will first cover the adjustments to the signal selection and will then describe the adjustments made to the performance measure selection.

5.2 Corridor Signal Selection Adjustment

After collecting the signal data, it was determined that there was not enough useful information on the University Avenue corridor to use it in the final analysis. It was therefore determined that adding another corridor to the final analysis would provide a more complete dataset to build the analysis procedure. This section will outline the process for determining to omit University Avenue from the analysis. The addition of the Fort Union Blvd. corridor will then be explained. The availability of data from the State Street, 800 North, and Fort Union Blvd. corridors will be summarized. The final selection of signals to be used for analysis will then be presented.

5.2.1 Removing University Avenue

Split failure was the first performance measure metric evaluated by the research team. Although the ATSPM information provided by UDOT suggested that University Avenue would have data for six signals for the split-failure performance measure, the aggregated data showed that split failure data were available for only two signals. The following tables summarize which signals should have the split-failure performance measure available and which actually do. The split failure data for University Avenue and State Street are displayed to make a comparison between the two corridors. Table 5-1 displays the data for the University Avenue corridor, while Table 5-2 displays this for the State Street corridor.

Table 5-1. Disparities in Split Failures for University Avenue

Signals with Split Failures on University Avenue	
Theoretically Available Cross Street	**Actually Available Cross Street**
100 North	700 North
200 North	800 North
500 North	
700 North	
800 North	
Canyon Road	

Table 5-2. Disparities in Split Failures for State Street

Signals with Split Failures on State Street	
Theoretically Available Cross Street	**Actually Available Cross Street**
800 North	800 North
400 North	400 North
Center Street	Center Street
400 South	800 South
800 South	1600 North
University Pkwy	
1600 North	

Although State Street is also missing data that could be available for split failures, the disparity is much less than that of University Avenue. As such, it was determined that State Street could still be used in the final analysis. The 800 North corridor displayed split failure data for all locations where data were expected. Due to the missing data for University Avenue, a decision was made not to use this corridor in the final analysis. Another reason to remove University Avenue from the final analysis was the recent addition of the Utah Valley Express bus rapid-transit line in Provo and Orem. The construction of these bus lanes likely impacted the flow of traffic for the 2018 data collected for this research.

5.2.2 Addition of Fort Union Blvd. Corridor

Due to the removal of an analysis corridor, there was a need for more data to be collected for this research. The TAC recommended using the signals on the Fort Union Blvd. corridor in

Cottonwood Heights as an alternative to the University Avenue corridor. This corridor had been calibrated a few years prior and all available detection types were operating. Table 5-3 displays the signal IDs and the associated street names for each selected intersection on the Fort Union Blvd. corridor.

Table 5-3. Selected Intersections on Fort Union Blvd. Corridor

Signal ID	Primary Name	Secondary Name
4024	Fort Union Blvd.	1300 East
4029	7200 South	700 East
4090	Fort Union Blvd.	2000 East (Highland)
4165	Fort Union Blvd.	2200 East (Whitmore)
4301	Fort Union Blvd.	1090 East (Union Park)
4388	1435 East	Fort Union Blvd
4704	Fort Union Blvd.	2300 East
4705	Fort Union Blvd.	2700 East
4706	Fort Union Blvd.	3000 East
7207	900 East	7105 South

5.2.3 Data Availability

Although Section 5.2.1 showed a useful representation of availability of the split-failure performance measure for some of the analysis corridors, a more holistic summary of performance measure availability for the 800 North, State Street, and Fort Union Blvd. corridors will be displayed in this section. Table 5-4 shows the availability of data for all metrics for the 800 North, State Street, and Fort Union Blvd. corridors. A “Y” denotes that the ATSPM database shows that this performance measure has data and the collected data reflects this. A “Y*” denotes that the ATSPM database shows that this performance measure has data, but one or more approaches are missing data. A “-” denotes that the ATSPM database shows that this performance measure doesn’t have data, and the collected data reflects this. A “N” denotes that the ATSPM database shows this performance measure should have data, but the collected data does not show any data for the performance measure.

Table 5-4. ATSPM Database Data and Collected Data

Primary Name	Secondary Name	Force-off	Max Out	AOG	AOR	PR	SF	RLV
7000 South (Fort Union Blvd.)	1300 East	Y	Y	Y	Y	Y	Y	Y
7200 South	700 East	Y	Y	Y	Y	Y	Y	Y
7000 South (Fort Union Blvd.)	2000 East (Highland)	Y	Y	Y	Y	Y	Y	Y
7000 South (Fort Union Blvd.)	2200 East (Whitmore)	Y	Y	Y	Y	Y	Y	Y
7000 South (Fort Union Blvd.)	1090 East (Union Park)	Y	Y	Y	Y	Y	Y	Y*
1435 East	Fort Union Blvd.	Y	Y	Y	Y	Y	Y*	Y*
7000 South (Fort Union Blvd.)	2300 East	Y	Y	Y	Y	Y	Y	Y
7000 South (Fort Union Blvd.)	2700 East	Y	Y	Y	Y	Y	Y	Y
7000 South (Fort Union Blvd.)	3000 East	Y	Y	Y	Y	Y	Y*	Y*
900 East	7105 South (Fort Union Blvd.)	Y	Y	Y	Y	Y	Y	Y
State Street	800 North	Y	Y	-	-	-	Y	*
Main Street	800 North	Y	Y	-	-	-	Y	Y
400 East	800 North	Y	Y	Y	Y	Y	Y	Y
800 East	800 North	Y	Y	Y	Y	Y	Y	Y
Geneva Road	800 North	Y	Y	Y	Y	Y	Y	Y
800 North (Orem)	I-15 SPUI	Y	Y	Y	Y	Y	-	-
1200 West	800 North	Y	Y	Y	Y	Y	Y	-
980 West	800 North	Y	Y	Y	Y	Y	-	-
State Street	800 North	Y	Y	-	-	-	Y	N
State Street	400 North	Y	Y	-	-	-	Y	N
State Street	Center Street	Y	Y	Y	Y	Y	Y	Y
State Street	400 South	Y	Y	N	N	N	N	N
State Street	800 South	Y	Y	-	-	-	Y	Y
State Street	1200 South	Y	Y	Y	Y	Y	-	-
State Street	University Parkway	Y	Y	Y	Y	Y	N	Y
State Street	1600 North	Y	Y	Y	Y	Y	Y	-

Note 1: Y is data that was expected and is available, Y* is data that was expected but is not available at all approaches for the intersection, N is data that was expected but is not available, - is data that was not expected and is not available

Note 2: AOG is arrivals on green, AOR is arrivals on red, PR is platoon ratio, SF is split failures, RLV is red-light violations

5.2.4 Final Signal Selection

For Fort Union Blvd., none of the signals were removed because there was sufficient data at each signal. Some data were missing for minor and turning approaches, but overall the availability of data was good. For State Street, the intersection of University Parkway was removed due to the presence of the new bus rapid-transit line. For 800 North, the intersection containing the I-15 interchange was removed because it is the on-ramp to I-15. This SPUI has unusual signal phasing and would not contribute to the overall performance of the corridor. The intersection at Geneva Road was removed because it is west of the SPUI and therefore not part of the corridor's progression. The intersection containing 1200 West was removed because only one approach was listed in the SQL table for approaches. It was determined that the data collected for this signal may be unreliable. The intersection of State Street and 400 South was removed because it didn't have enough data available to be useful for research. Table 5-5 shows the final selected corridors for the analysis.

Table 5-5. Intersections Selected for Analysis

Corridor	Signal ID	Cross Street	Signal ID	Cross Street
800 North, Orem	6303	State Street	6304	Main Street
	6305	400 East	6306	800 East
	6399	980 West		
State Street, Orem	6303	800 North	6308	400 North
	6311	Center Street	6313	400 South
	6314	800 South	6323	1200 South
	6393	1600 North		
Fort Union Blvd., Cottonwood Heights	4024	1300 East	4029	700 East
	4090	2000 East	4165	2200 East (Whitmore)
	4301	1090 East (Union Park)	4388	1435 East
	4704	2300 East	4705	2700 East
	4706	3000 East	7207	900 East

5.3 Adjusting Performance Measures

It was necessary to adjust the selection of performance measures following the collection of data and the addition of a corridor. Each performance measure that was dropped from the analysis will be discussed and the reasoning for no longer using the performance measure will be explained. Although red-light violations were not dropped from the final analysis, the data collected from this performance measure had some irregularities that will be discussed. This section will first cover the omission of the arrivals-on-red performance measure, then the omission of max-outs and force-offs will be discussed. The issues encountered when calculating the volume-to-capacity ratio will be described and the issues with the red-light violation performance will then be explained. A final summary of the performance measures to be used for analysis will then be presented.

5.3.1 Arrivals on Red

It was determined that including the performance measures for both arrivals on red and green was superfluous. For example, if an intersection had a high percentage of vehicles arriving on green, this is already an indicator that there is a low percentage of vehicles arriving on red. It is unnecessary to include the values for both performance measures in the final analysis. The arrivals-on-red performance measure was determined redundant and removed from the final analysis.

5.3.2 Max-Outs and Force-Offs

It was determined after discussion with the TAC that max-outs and force-offs are very similar. As such, only one of the two performance measures was necessary for analysis. The research team initially decided to only use force-offs, but later discovered from the TAC that force-offs are difficult to compare between coordinated and non-coordinated signals. This became problematic because the Fort Union Blvd. corridor is coordinated while the 800 North and State Street corridors are non-coordinated. It was decided that force-offs should not be used in analysis.

Although the research team determined not to use force-offs, there is one issue with the calculation of this performance measure that should be noted. The research team attempted to use force-offs per cycle the same way as the split failures per 15-minute bin was calculated. However, many of these values were close to 2.0. The maximum amount of force-offs that could occur during a 15-minute bin should be equal to the number of cycles in that bin. In this case, the force-offs per cycle would be equal to 1.0. Upon further investigation, this issue was only present at the intersection of Fort Union Blvd. and 1090 East. The TAC stated that this signal had issues in the past and should be left out of the force-off analysis. Figure 5.1 shows the distribution of force-offs per cycle with all selected signals in the UDOT ATSPM dataset. The concentration of values surrounding 2.0 show the effect of including intersections that have unpredictable data.

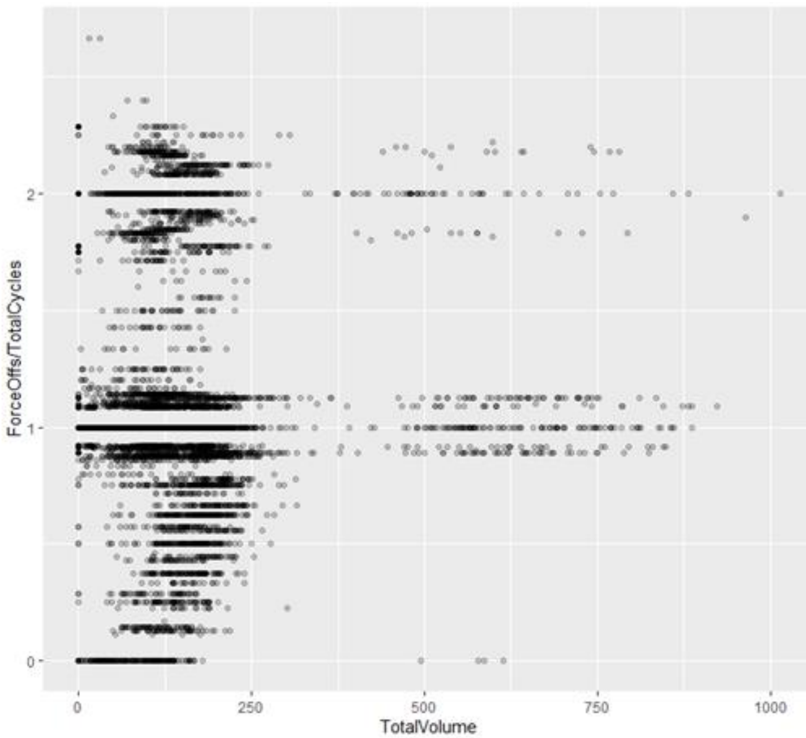

Figure 5.1. Force-offs per cycle vs. total volume.

<u>5.3.3 Volume-to-Capacity Ratio</u>

The research team also decided to investigate the usefulness of the volume-to-capacity ratio. This ratio was used by Day et al. (2018) in their research. The research team attempted to use this metric but ran into issues calculating it. One issue was the lack of clarity on whether the volume of cars detected at the intersection included right-turning vehicles. This would affect the number of lanes associated with each through movement, and therefore the total capacity of the intersection. The number of lanes were available for some approach IDs, but not for others. There was also an issue with determining the saturation flow rate for each lane. The number of lanes each approach had and whether this included a right-hand turn lane would change the saturation flow rate for the approach. If calculated correctly, the volume-to-capacity ratio should never be greater than 1.0, but the calculations by the research team violated this theory.

Equations 5.1, 5.2, 5.3, and 5.4 were used to calculate the volume-to-capacity ratio. Equation 5.1 displays the method used for calculating the saturation flow rate for an approach. The number 1969, used in the equation, is the maximum saturation flow rate determined from a comprehensive study of saturation flow rates conducted in 1987 and 1988 (Roess et al., 2019). This value is in vehicles per hour; n is the number of lanes. Equation 5.2 has units of vehicles per period. The saturation flow rate is originally in vehicles per hour. This rate is converted to the saturation flow rate *per cycle* through multiplying by the total green phase seconds in a 15-minute bin and converting hours to minutes. Equation 5.3 shows that the percentage of green time per period is the total green time in that period divided by the total time. Equation 5.4 has no units; hence the term "ratio" is used to describe the volume-to-capacity ratio. The numerator is in vehicles per period while the denominator contains the maximum vehicles per period in terms of the saturation flow rate multiplied by the percentage of green time.

$$Saturation = 1969 * n \tag{5.1}$$

$$SatInPeriod = \frac{Saturation * TotalTime}{60*60} \tag{5.2}$$

$$Percent_{greentime} = \frac{TotalGreentime}{TotalTime} \tag{5.3}$$

$$VC_{Ratio} = \frac{TotalVolume}{SatInPeriod * Percent_{greentime}} \tag{5.4}$$

Figure 5.2 depicts a plot of platoon ratio against the measured volume-to-capacity ratio with all selected signals in the UDOT ATSPM dataset. Day et al. (2018) utilized this type of plot to create threshold values for various signals used in their study as shown in Figure 5.3. Comparing Figure 5.2 to Figure 5.3 it is clear that the volume-to-capacity ratios calculated using the ATSPM data are well above the high values of the volume-to-capacity ratio calculated in the Day study. Theoretically, it should be impossible for the volume of an intersection to surpass its capacity – meaning a ratio of 1.0 is the theoretical maximum. In practice, however, capacity is itself a theoretical idea that cannot be precisely measured. That said, values substantially above 1.0 and approaching 2.0 do not lend confidence to using this ratio as any kind of comparable performance measure. It was determined that the volume-to-capacity ratio was not reliable enough to be used in the final analysis of the corridors.

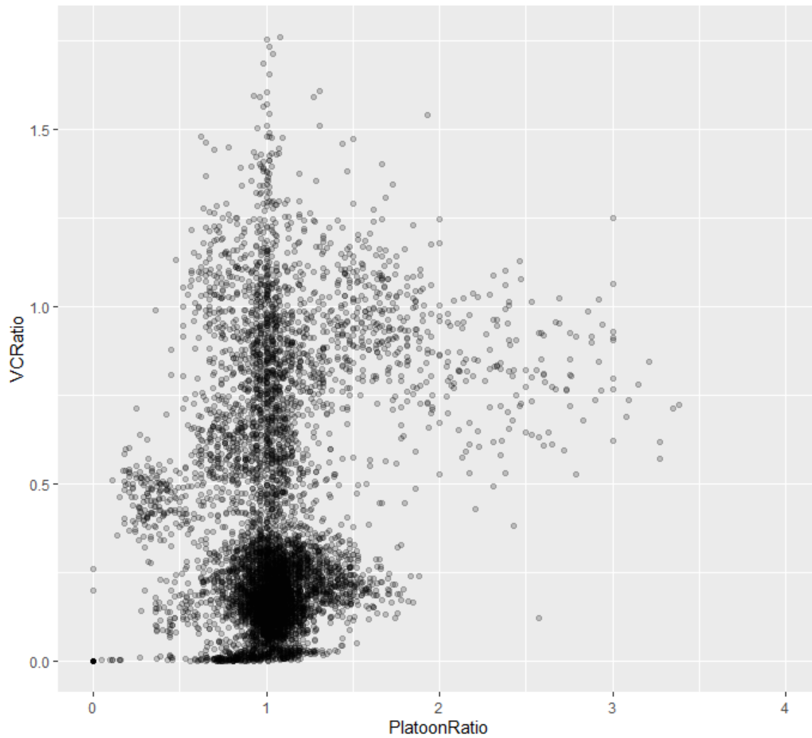

Figure 5.2. Plot of platoon ratio vs. volume-to-capacity (VC) ratio.

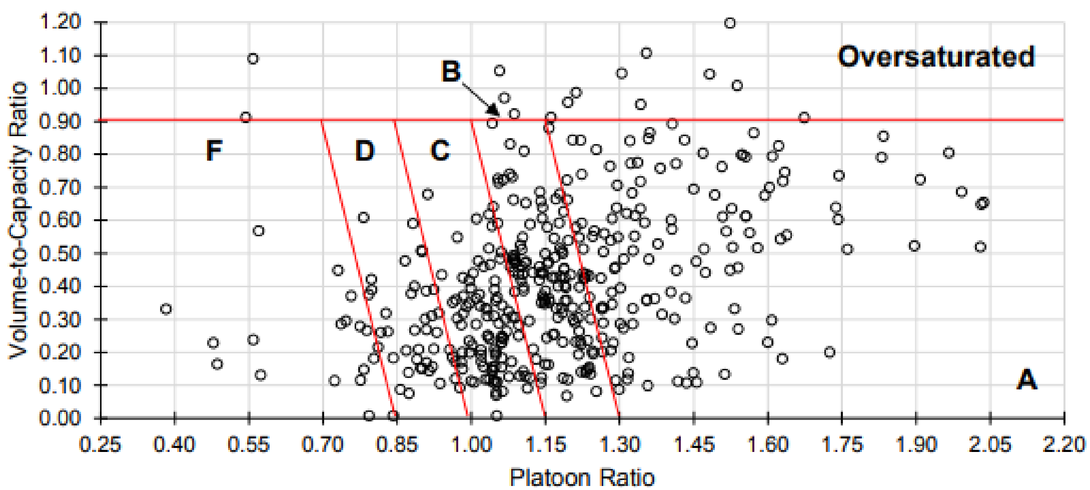

Figure 5.3. Platoon ratio vs. volume-to-capacity ratio (Day et al., 2018).

5.3.4 Red-Light Violations

After collecting data for red-light violations, it was noted that there were several instances of very high red-light violation counts. For a 15-minute bin, the highest value recorded was 35 red-light violations. These instances of extraordinarily high red-light violations were only found at two intersections: the intersection of Fort Union Blvd. and 1090 East and the intersection of State Street and Center Street in Orem. The TAC noted that one reason for these artificially high counts could be the inclusion of a lane that allows for through and right-turn movements. This could cause the detection to count a car turning right during a red phase as a red-light violation. Although the red-light violation performance measure has some inconsistencies when comparing across intersections due to the latency of each detector (see Section 3.2.5), it might still be possible to determine if individual signals are worsening, staying the same, or improving over time using this performance measure by comparing the same intersections longitudinally. This performance measure will also be useful in identifying which intersections are exhibiting abnormally high red-light violation values, a potentially serious safety issue that UDOT might investigate and address.

5.3.5 Performance Measure Summary

After determining which performance measures should be omitted from the final analysis, the research team decided on using the performance measures displayed in Table 5-6. These were selected based on a combination of the Delphi and the data-driver performance-based approaches. This table also includes the detection type used to obtain the performance measure and the tool used to display it.

Table 5-6. Performance Measures by Tool and Detection Type

Tool	Detection Type	Performance Measure(s)
Purdue Coordination Diagram (PCD)	Advanced Presence Detection	Percent Arrivals on Green, Platoon Ratio
Purdue Split Failure	Stop-Bar Detection (lane by lane)	Split Failures per 15-Minute Bin
Yellow and Red Actuations	Lane by lane with speed restriction	Red-Light Violations

5.4 Chapter Summary

Originally, the selection of performance measures was based on the Delphi approach where the TAC served as the expert panel. This section showed that a data-driven approach was also used in this research. The selection of performance measures and signals was modified based on the data that were collected. Although the approaches used in the collection and refinement of data were not as complex as those presented in Chapter 2, the methods used were still based on the literature review. In this section, a final selection of signals and performance measures to be used for analysis was determined. The next section will show how the data were evaluated and how scores were calculated for signals and corridors.

6.0 DATA EVALUATION

6.1 Overview

The research team used the R statistical analysis tool as the means of analysis for this project. The research team also created a data visualizer in the form of an application that allows the user to see results quickly and easily. The data visualizer assigns the performance measures to different groups by using a k-means cluster analysis that allows an analysis of threshold by clusters. These scores can be seen for each 15-minute bin or for wider ranges of time. Scoring the intersections allows for comparison between intersections and corridors. The scoring method was based on threshold values developed by the TAC and the research team. This chapter presents the k-means cluster analysis results through the data visualizer, the threshold values for each variable, the comparison between the real-time field data and calculated scoring, and the final overall scoring results at both the intersection and corridor level.

6.2 Data Visualizer

The research team created a data visualization tool that allows quick generation of the k-means cluster analysis for any combination of performance measures. The data visualizer quickly generates plots displaying the distribution of values for a specific performance measure or for a combination of performance measures. Using the data visualization results, the values where a separation of clusters, or group of data, occur can be used as threshold values. Recommendations from the TAC and published literature were also consulted to develop the threshold values. Figure 6.1 shows the interface of the ATSPM data visualizer hosted at: https://atspmevaluation.shinyapps.io/ATSPM-Shiny/.

In the data visualizer sidebar panel, the research team created a selector tool that allows the user to select the performance measures, corridors, time of day, intersections, and date range. Figure 6.2 shows the ATSPM data visualizer selector on the sidebar panel. By faceting the time of day or the corridor, the results are displayed separated by the facet scheme chosen.

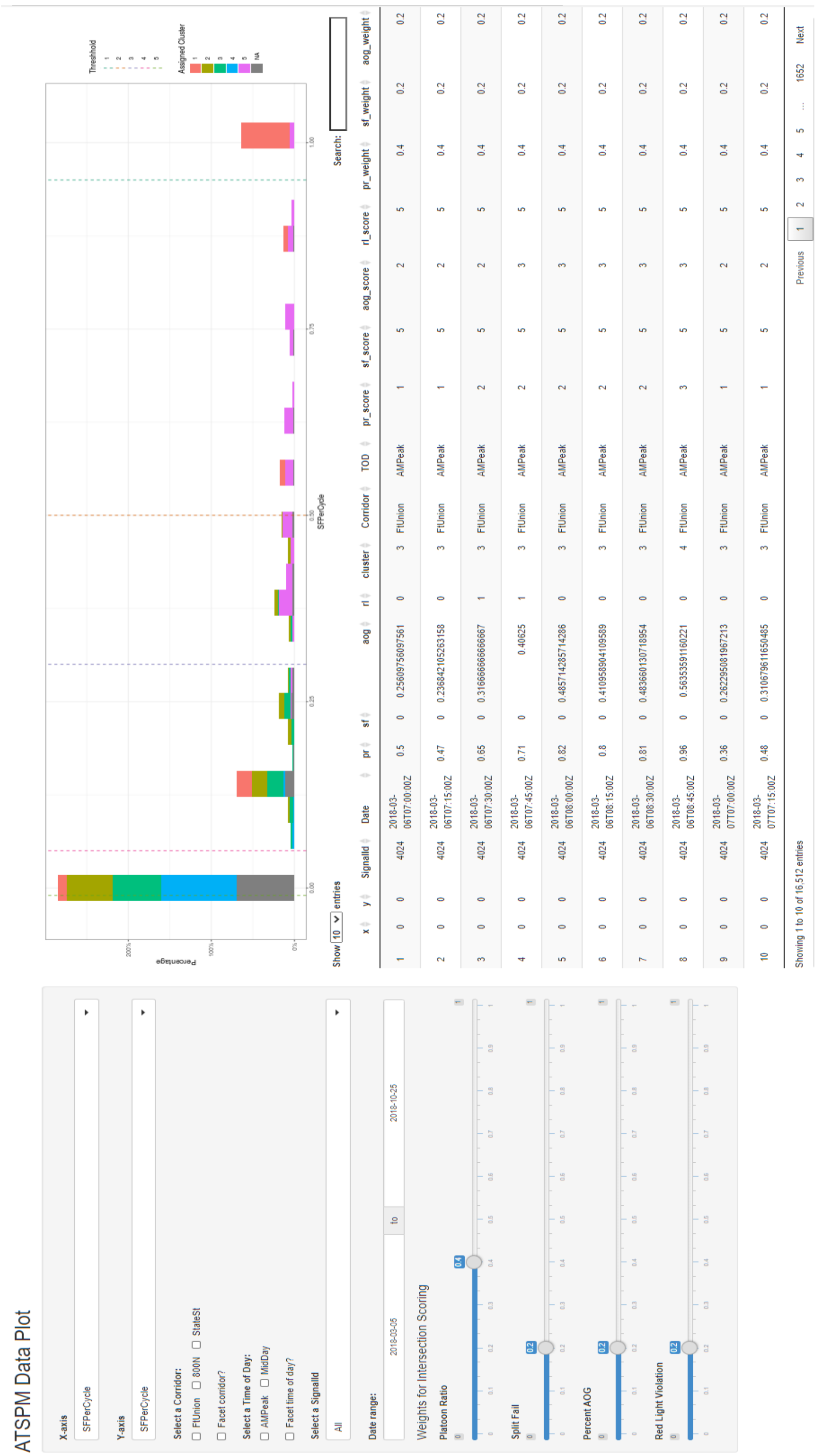

Figure 6.1. ATSPM data visualizer interface

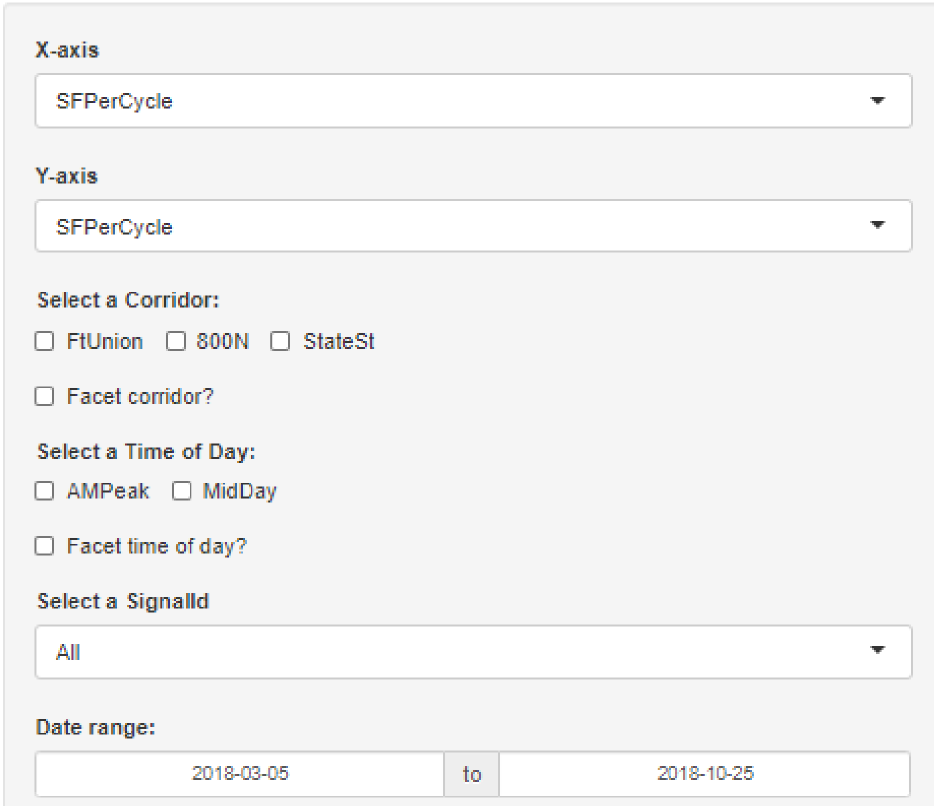

Figure 6.2. ATSPM data visualizer sidebar panel selector

If the X-axis and the Y-axis are chosen to have the same performance measure, the application produces a histogram displaying the distribution of that performance measure for a specific signal or corridor. These histograms are displayed in Section 6.3. If the X-axis and the Y-axis are chosen as different performance measures, the application produces a scatter plot comparing the two performance measures. In both cases, the individual data points represent an aggregated 15-minute bin at the signal. Although total volume is not a performance measure and is not included in the cluster analysis, it can provide context for the other performance measures and can be selected as a variable to display on the X-axis or the Y-axis for comparison of the data as illustrated in Figure 6.3 for percent arrivals on green.

The research team also created a selector panel that allows the user to assign different weights for each performance measure. Figure 6.4 shows the selector from the ATSPM data visualizer. More details on the weights for scoring will be discussed in Section 6.5.

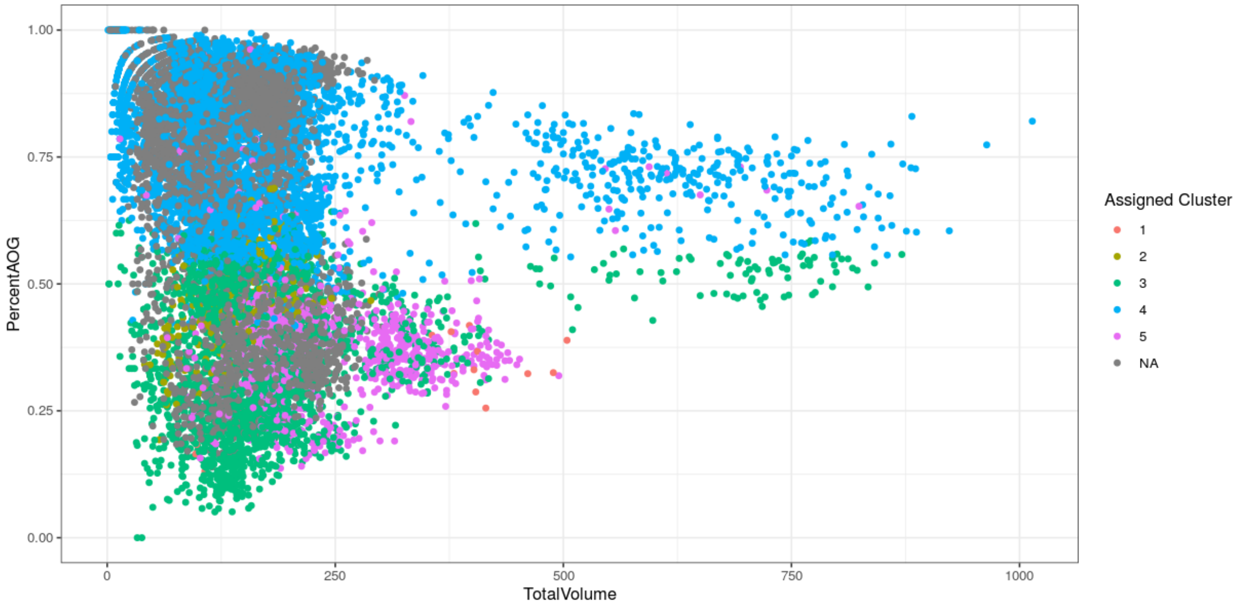

Figure 6.3. Plot of percent arrivals on green vs. total volume.

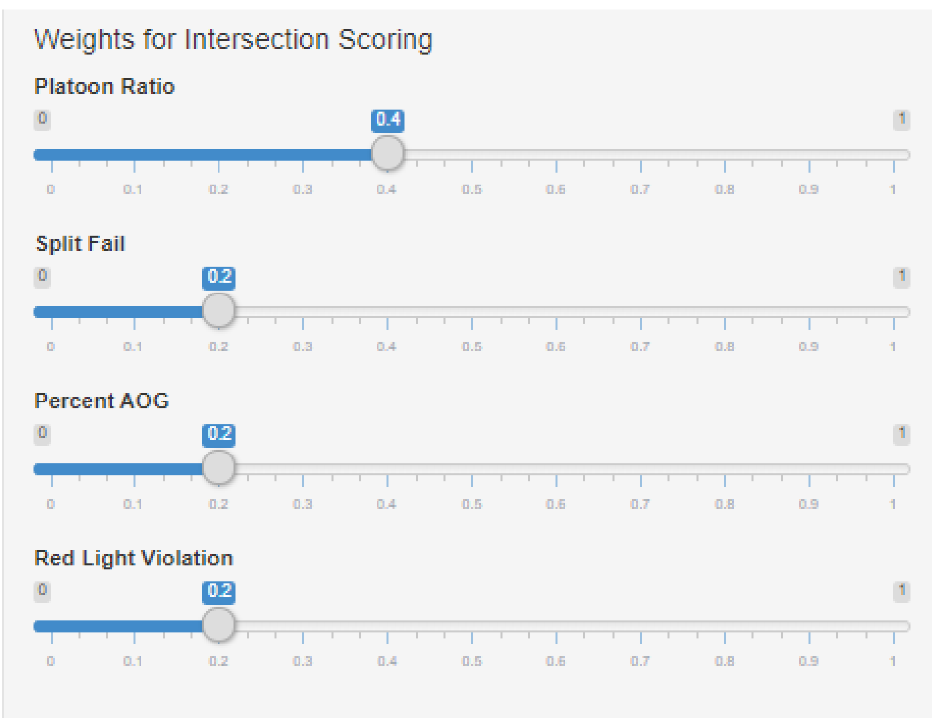

Figure 6.4. ATSPM data visualizer scoring weights.

6.3 Threshold Values

Threshold values to evaluate and compare different intersections were developed for each performance measure. These threshold values were derived from various sources including standardized manuals, the TAC, and the k-means cluster analysis. The threshold values for each performance measure correspond with a score for the applicable intersection. The scores range from 1 to 5. A score of 1 is a low score while a 5 is the highest score. The values 1 to 5 were used based on previous research that used five categories of scores ranging from A through E (Day et al., 2018). Rather than using a letter-based scoring, it was determined that numerical scores would be easier to use in subsequent calculations. Because there are five scoring categories in this research, it was decided to use a k-means cluster analysis that divides the data into five groups. If the performance measure data are unavailable for any reason in a 15-minute bin, the algorithm is unable to determine a cluster. This section summarizes the final threshold values used for each performance measure, including percent split failures, percent arrivals on green, platoon ratio, red-light violation, and force-offs.

6.3.1 Percent Split Failures

Figure 6.5 and Figure 6.6 depict the distribution for percentage split failures per 15-minute bin and the threshold values developed by the research team. The threshold values were initially set at 0.05, 0.20, 0.40, and 0.70 to split the data into percentiles and by cluster rather than fixed percentages. Figure 6.5 shows this distribution for 800 North, Fort Union Blvd., and State Street, while Figure 6.6 shows the distribution for all corridors combined. Upon further review of the k-means cluster analysis and in consultation with the TAC, it was determined that the threshold values for the percentage of split failures would be set at 0.05, 0.30, 0.50, and 0.95. The main reason for this change was to put signals with no split failures or all split failures in their own categories. Table 6-1 shows the final threshold values for split failures in tabular format.

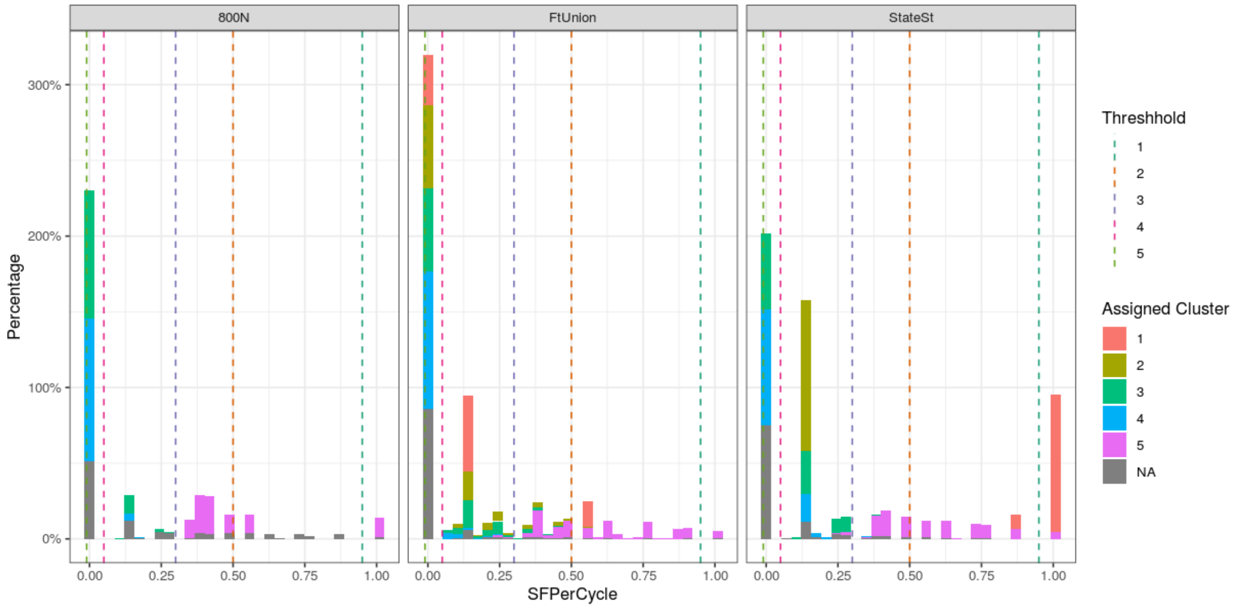

Figure 6.5. Percent split failures separated by corridor.

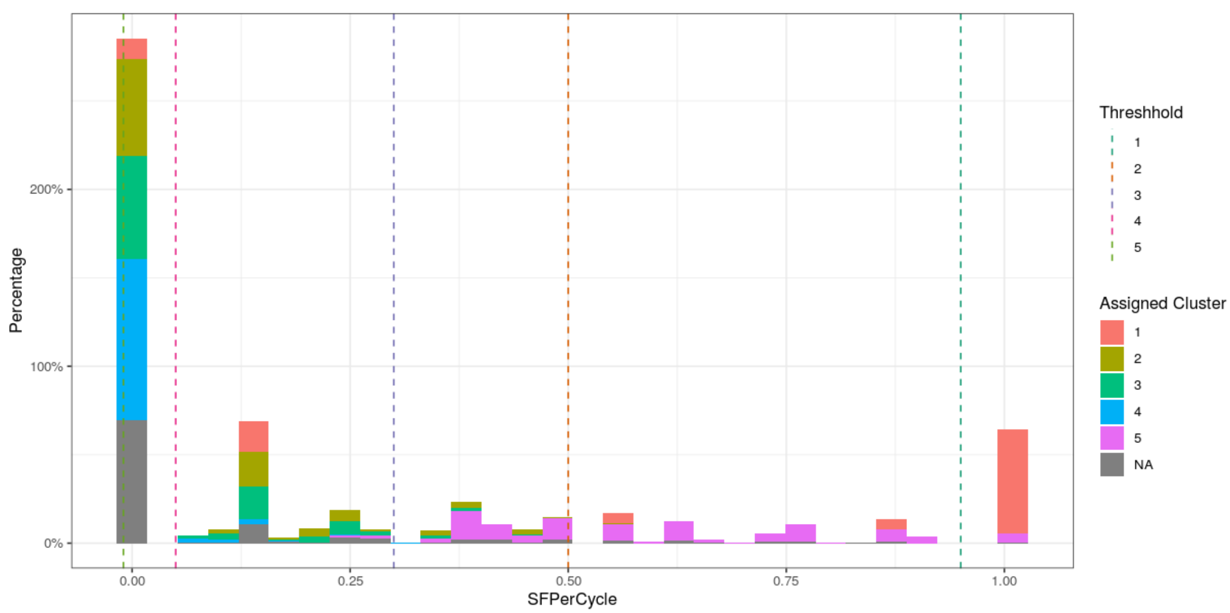

Figure 6.6. Percent split failures for all corridors.

Table 6-1. Final Percent Split Failure Threshold Values

Intersection Score	Percent Split Failures
5 (Exceptional)	≤ 0.05
4	0.05 ≤ 0.30
3	0.30 ≤ 0.50
2	0.50 ≤ 0.95
1 (Poor)	> 0.95

6.3.2 Percent Arrivals on Green

Figure 6.7 and Figure 6.8 depict the distribution of the percentage of arrivals on green and the threshold values developed by the research team. These threshold values were initially set at 0.2, 0.4, 0.6, and 0.8. The research team discussed the possibility of not considering percent arrivals on green when the volume of arriving cars is over 400 for any 15-minute bin as a large volume of cars can produce a falsely low percent arrivals score. However, it was determined that only the percent arrivals score would be looked at without taking the volume into account to simplify the analysis. Upon further review of the k-means cluster analysis and in consultation with the TAC, the final threshold values were determined to remain the same as the initial values. Figure 6.7 shows the distribution for 800 North, Fort Union Blvd., and State Street, while Figure 6.8 shows the distribution for all corridors combined. Table 6-2 shows the final distribution for percent arrivals-on-green threshold values.

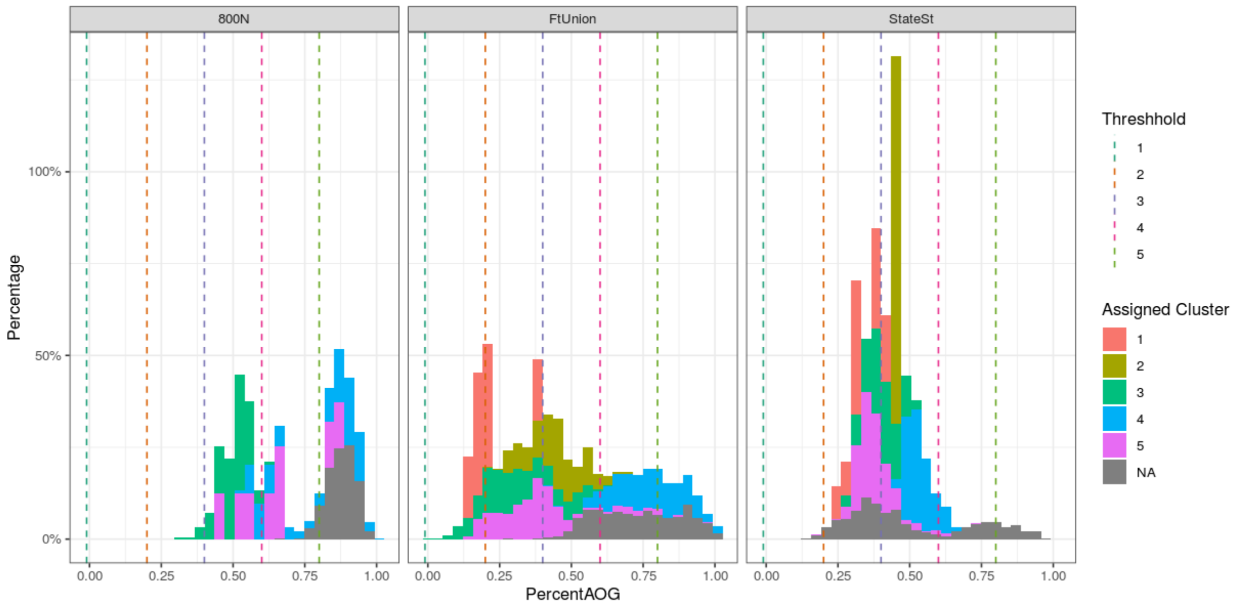

Figure 6.7. Percent arrivals on green separated by corridor.

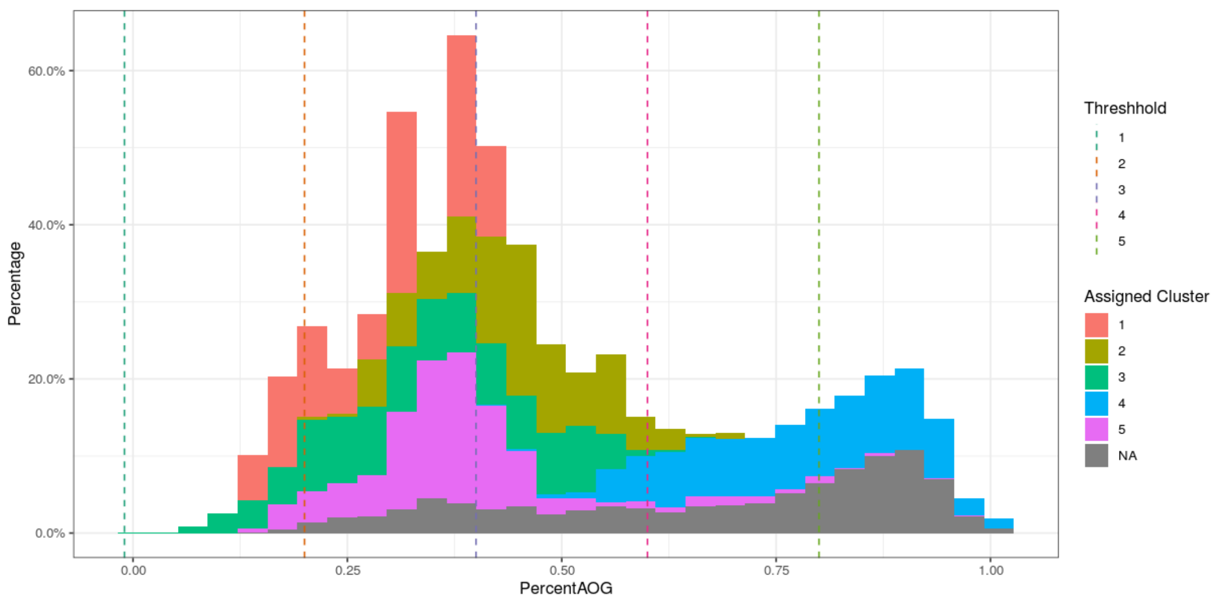

Figure 6.8. Percent arrivals on green for all corridors.

Table 6-2. Final Percent Arrivals-on-Green Threshold Values

Intersection Score	Percent Arrivals on Green
5 (Exceptional)	≤ 0.20
4	0.20 ≤ 0.40
3	0.40 ≤ 0.60
2	0.60 ≤ 0.80
1 (Poor)	> 0.80

6.3.3 Platoon Ratio

Figure 6.9 and Figure 6.10 depict the distribution of platoon ratios and the threshold values developed by the research team. These threshold values are 1.50, 1.15, 0.85, and 0.5. These values were chosen to separate the platoon ratio into five categories and are modeled after the thresholds found in the HCM (TRB, 2010). Figure 6.9 shows the distribution for 800 North, Fort Union Blvd, and State Street, while Figure 6.10 shows the distribution for all corridors combined. Table 6-3 shows the threshold values for platoon ratio in tabular format.

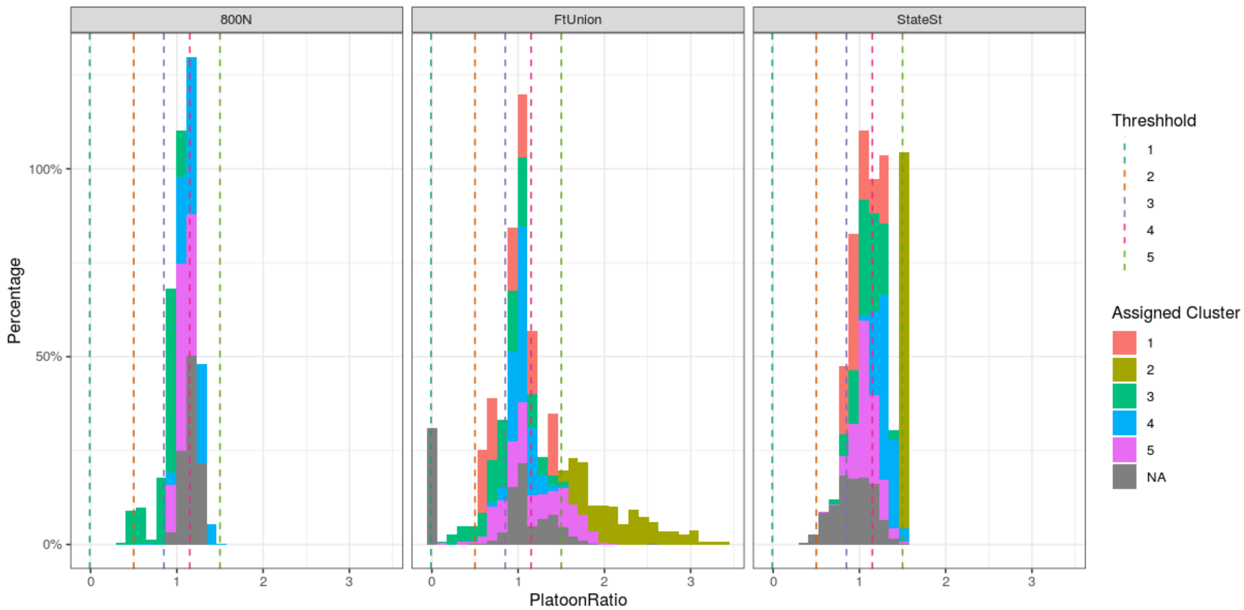

Figure 6.9. Platoon ratio separated by corridor.

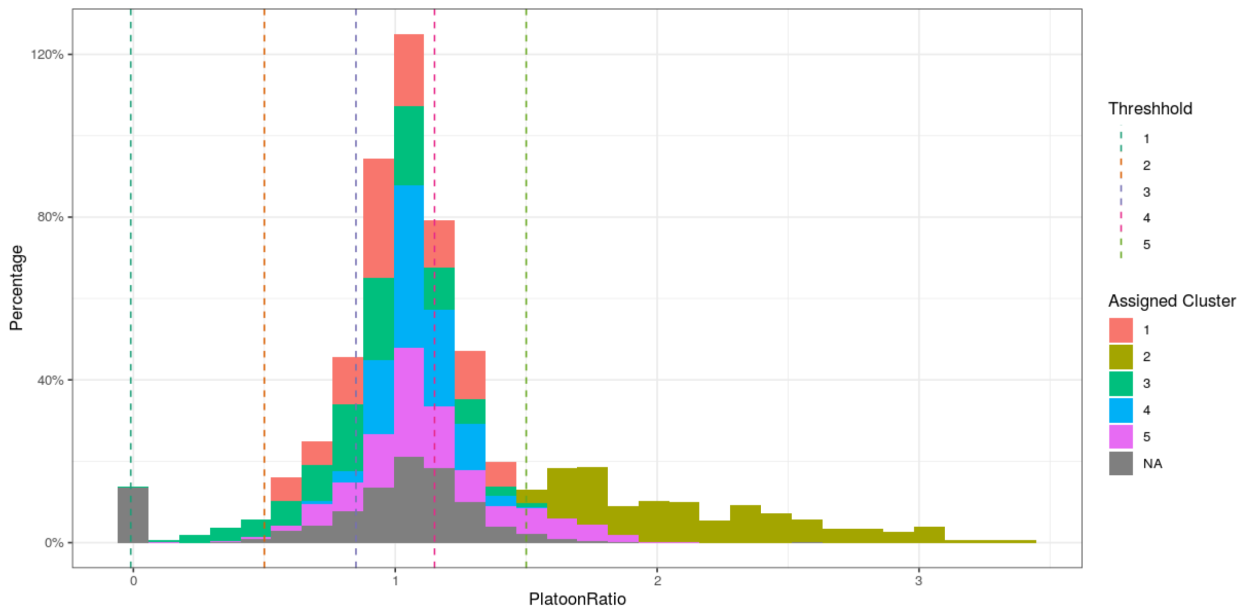

Figure 6.10. Platoon ratio for all corridors.

Table 6-3. Final Platoon-Ratio Threshold Values

Intersection Score	Platoon Ratio
5 (Exceptional)	> 1.50
4	1.15 ≤ 1.50
3	0.85 ≤ 1.15
2	0.50 ≤ 0.85
1 (poor)	≤ 0.50

6.3.4 Red-Light Violations

Figure 6.11 and Figure 6.12 depict the distribution of red-light violations and the threshold values developed by the research team. All intersections with no red-light violations are noted by the highest score, all intersections with 1-2 red-light violations are second best, 3-4 violations correspond with the third level, 5-9 violations correspond with the fourth level, and any value 10 or greater is in the lowest scoring category. Upon further review of the k-means cluster analysis and in consultation with the TAC, the final threshold values were changed to better reflect the distribution of violations. Figure 6.11 shows this distribution for 800 North, Fort Union Blvd., and State Street, while Figure 6.12 shows this distribution for all corridors combined. The final threshold values for red-light violations are found in Table 6-4.

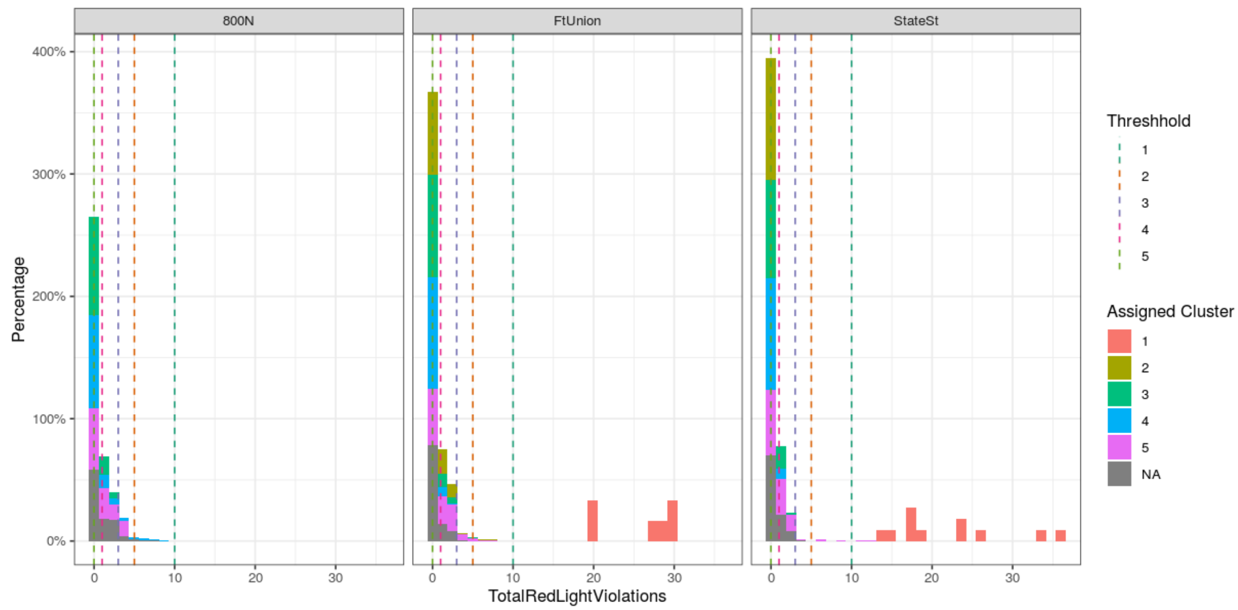

Figure 6.11. Red-light violations separated by corridor.

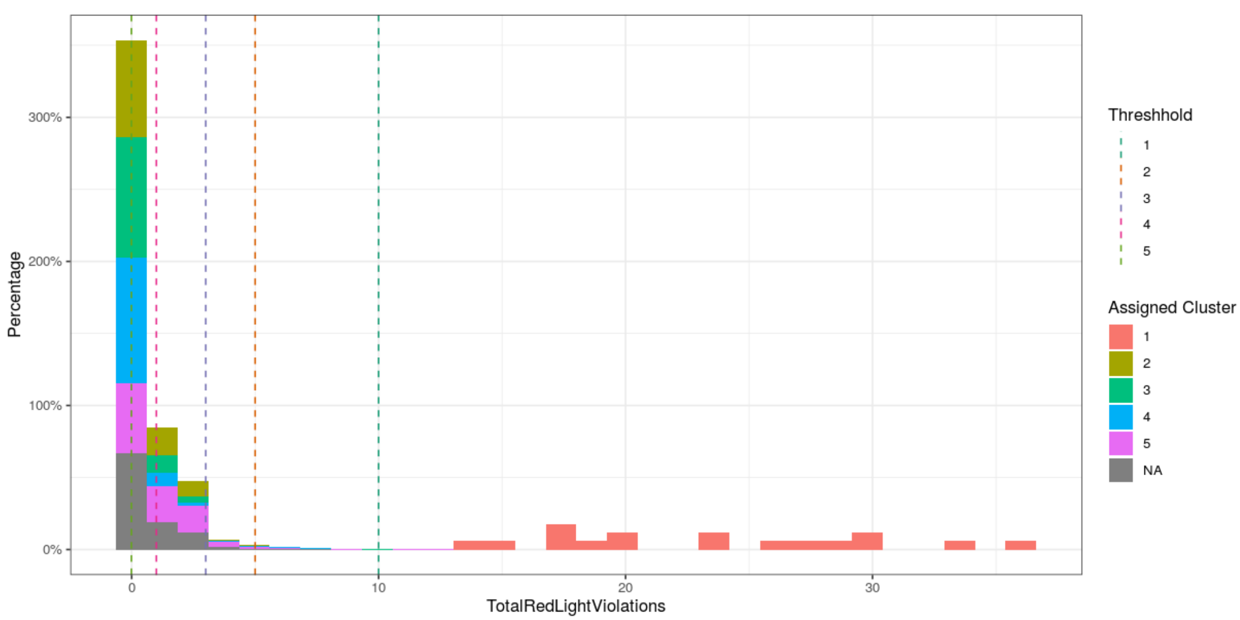

Figure 6.12. Red-light violations for all corridors.

Table 6-4. Final Red-Light Violation Threshold Values

Intersection Score	Red-Light Violations
5 (Exceptional)	0
4	1-2
3	3-4
2	5-9
1 (poor)	10+

6.3.5 Force-Offs

Figure 6.13 and Figure 6.14 depict the distribution of the percentage of force-offs and the threshold values developed by the research team. These threshold values are 0.2, 0.5, 0.8, and 0.95. The higher the percentage of force-offs, the worse the rating is for the intersection or corridor. Any value above 1.0 is interpreted as a 15-minute bin where every cycle ended in a force-off. Although force-offs were not used in the final analysis of the signals, these figures were included to show the difference between coordinated and non-coordinated signals. The non-coordinated signals are found in the 800 North and State Street corridors. The coordinated signals are found in the Fort Union Blvd. corridor. The coordination allows percentage of force-offs per cycle to vary depending on the traffic flow. For non-coordinated signals, the percentage of force-offs will remain constant despite variations in traffic flow. This can be seen by the lack of varying percentages in the State Street and 800 North corridors. Fort Union Blvd. displays varying percentages of force-offs.

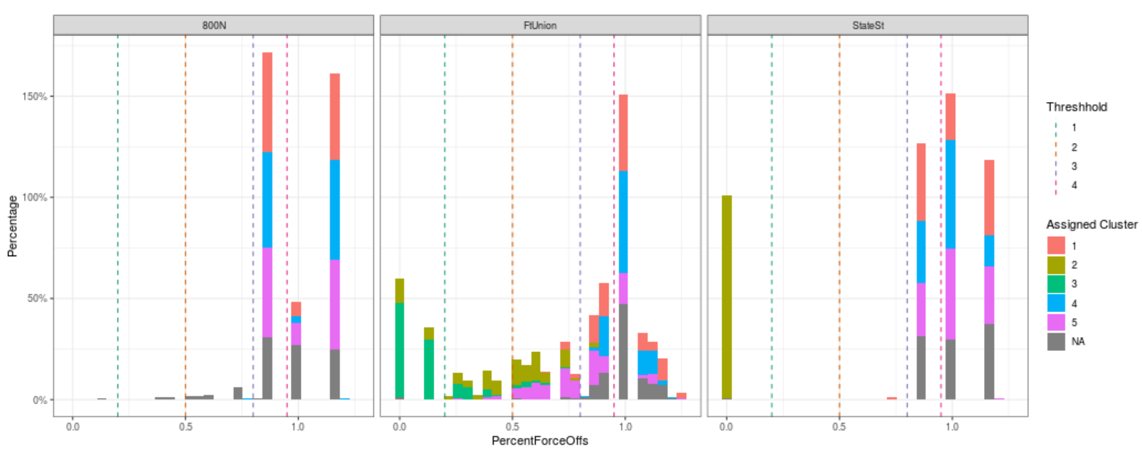

Figure 6.13. Percent force-offs separated by corridor.

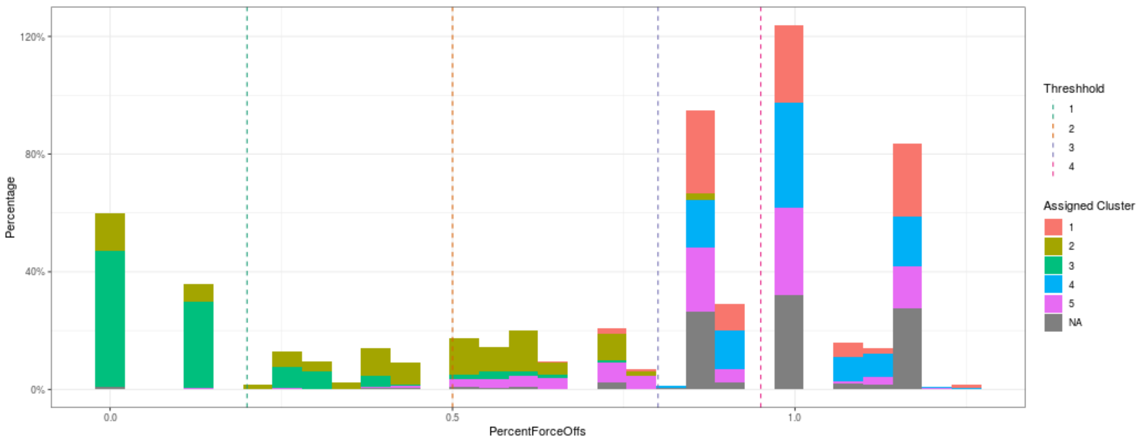

Figure 6.14. Percent force-offs on all corridors.

<u>6.3.6 Threshold Summary</u>

As a summary, a scoring method was developed that converts the threshold values into numerical levels. This scoring is as follows: 1 for poor performance, 2 for unfavorable performance, 3 for average performance, 4 for favorable performance, and 5 for exceptional performance. Table 6-5 summarizes the threshold values for each performance measure.

Table 6-5. Summary of Performance Measures Thresholds

Threshold for Level Score	Percent Split Failure	Percent Arrivals on Green	Platoon Ratio	Red-Light Violations
5 (Exceptional)	≤ 0.05	≤ 0.20	> 1.50	0
4	0.05 ≤ 0.30	0.20 ≤ 0.40	1.15 ≤ 1.50	1.0-2.0
3	0.30 ≤ 0.50	0.40 ≤ 0.60	0.85 ≤ 1.15	3.0-4.0
2	0.50 ≤ 0.95	0.60 ≤ 0.80	0.50 ≤ 0.85	5.0-9.0
1 (Poor)	> 0.95	> 0.80	≤ 0.50	10+

6.4 Field Data Validation

To adjust and verify the threshold values, the research team collected data for a sample of signals on the selected corridors. Data were collected on January 29 and January 30, 2020 for State Street and 800 North and on February 19 and February 20, 2020 for Fort Union Blvd.

Overall, the validation process was helpful in determining if the scores assigned to intersections were reflected in the events that occurred for the 15-minute bin being represented.

This validation process showed that the performance measures are being accurately detected and reflected in intersection scoring. The research team chose one or two intersections for each corridor to verify with field data. The field data were verified by video recording an intersection and comparing the video segments with the aggregated data obtained from UDOT for that intersection during the recorded time period. In general, once the data were obtained, periods of interest were identified, and the video data were compared with the aggregated data.

One issue in comparing the recorded data with the tabular data was the inconsistency in cycle length for each 15-minute bin. Due to the inconsistencies it was difficult to know at exactly what time to begin observing the data and at what time to stop. For example, a 15-minute bin from 9:00 AM to 9:15 AM may contain a total cycle time of 12 minutes. The data recorded for this bin could be the data collected from 9:00 AM to 9:12 AM or from 9:02 AM to 9:14 AM. However, this variation is slight and viewing the entire period from 9:00 AM to 9:15 AM was determined to provide a reasonably accurate representation of the data collected for the specific 15-minute bin.

The results from each corridor will be presented in the following subsections. The scoring for each 15-minute bin in this field comparison study was based on a method that weights the platoon ratio more heavily than the other measures. The purpose for this was to give the platoon ratio more influence due to the importance that UDOT generally places on this performance measure.

6.4.1 State Street Corridor

For State Street, the intersection of Center Street in Orem was selected for comparison. Approach 2075 and approach 5253 are northbound-through and southbound-through movements, respectively.

The first period of interest selected was for the southbound-through approach. This bin began at 12:00 PM on January 28, 2020 and received a score of 3.2. This period was chosen as an example of a lower score. The poor characteristics of this corridor were observed as unused green time and many arrivals during the red portion of the signal. However, the progression of the corridor seemed smooth. A visual of the unused green time during the 15-minutes bin from 12:02 PM can be seen in Figure 6.15.

Figure 6.15. Visual representation of the State Street intersection.

The second period of interest selected was also for the southbound-through approach. This bin began at 9:30 AM on January 28, 2020 and received a score of 4.2. The main observation from this period was the absence of split failures. This seemed to be the main factor contributing to the higher score.

<u>6.4.2 800 North Corridor</u>

For 800 North, the intersection at 800 East was chosen. Approach 2052 and approach 2051 are the eastbound-through and westbound-through movements respectively. Two 15-minute bins were initially selected for observation. The first selected bin was for the westbound-through movement on January 28, 2020 from 1:00 PM to 1:15 PM. The second selected bin was for the eastbound-through movement on January 28, 2020 from 1:45 PM to 2:00 PM.

The first selected bin received a score of 4.4. The platoon ratio for this bin was 1.2. This bin was compared to another bin that received a platoon ratio of 0.9. It was difficult to see a difference in the recorded footage between the platoon ratio of each 15-minute bin. Overall the traffic was observed to flow well.

The second selected bin received a score of 3.4 and the platoon ratio was 0.5. Although the overall score was good, the particularly low platoon ratio value warranted inspection. The most notable feature of this 15-minute bin was the lack of vehicles arriving during the green time resulting in a lot of unused green time. This is likely the reason for the lower platoon ratio value. Due to an average intersection performance, an overall score of 3.4 seems to reflect the performance of this intersection. A still photo from the footage representing unused green time and taken at 1:45 PM can be seen in Figure 6.16.

Figure 6.16. Visual representation of the 800 North intersection.

6.4.3 Fort Union Blvd. Corridor

For Fort Union Blvd., two signals were chosen for comparison: the intersections at Highland Drive and 900 East. There was ample data available for the intersection at Highland Drive. However, there was no traffic volume recorded for 2020. This resulted in a platoon ratio of zero for all time periods collected for this signal. As a result, it was decided to exclude the Highland Drive intersection from the field comparison study. All observed data for the signal at 900 East were recorded on February 19, 2020 for approach 11787 and February 20, 2020 for approach 11790.

Several periods of interest were identified for approach 11787. This approach represents the westbound-through movement for the 900 East signal. A lower scoring 15-minute bin was compared with a higher scoring 15-minute bin to determine the difference in the field observation of these bins. From 9:15 AM to 9:30 AM, an overall score of 3.0 was observed for a scoring schema that weights the platoon ratio slightly higher than the other performance measures. For this bin, a lower platoon ratio of 0.8 was recorded. It was observed that many of the vehicles arrived just prior to red or just after the light had turned red. As such, a large portion of the green time went unused during this time period. For these reasons, it seemed that a lower score of 3.0 reflected well what was happening in real time.

For the same approach (11787), the 15-minute bin from 8:30 AM to 8:45 AM received a score of 4.6. This intersection received a score of 5.0 for every performance measure except arrivals on green. The platoon ratio for this time period (1.8) was exceptionally high compared to the rest of the data collected for February 19, 2020. Figure 6.17 shows how the vehicles tended to travel in a platoon more effectively during this time period. The main difference between this time period and the time period beginning at 9:15 AM was the higher traffic volume. The vehicles also appeared to travel in a platoon more effectively than the previously observed time period.

Figure 6.17. Visual representation of the Fort Union Blvd. intersection.

6.5 Scores for Intersections and Corridors

This section summarizes the findings of the data evaluation using the threshold values developed by the research team. It includes the overall score at the intersection level and corridor level.

6.5.1 Overall Score at the Intersection Level

The weighted values for each performance measure were normalized so that the total of all performance measure weights sum to 1.0, regardless of the specific weight values input by the user in the data visualizer. An example of this process for split failures is provided in Equation 6.1. The overall score for intersection level is calculated based on the weighted average score for each performance measure as outlined in Equation 6.2.

$$Wts_{sf} = \frac{Sf_{wts}}{Pr_{wts}+Sf_{wts}+Aog_{wts}+Rl_{wts}} \tag{6.1}$$

where, Wts_{sf} = weight for the split failures

$$Overall = Sc_{pr} * Wts_{pr} + Sc_{sf} * Wts_{sf} + Sc_{aog} * Wts_{aog} + Sc_{rl} * Wts_{rl} \tag{6.2}$$

where, Sc = threshold value score for each performance measure
Wts = selected weight for each performance measure
pr = platoon ratio
aog = arrivals on green
sf = split failures
rl = red-light violation

To determine the effect of different weighting schemes on the intersection total score, the research team performed a sensitivity analysis. Figure 6.18 shows the empirical cumulative distribution of total score assigned to all 15-minute bins for different weighting schemes for two intersections at two times of day: Fort Union Blvd. and 1090 East and Fort Union Blvd. and 1300 East. The orange line displays a scheme where the weight for the platoon ratio is twice the value of the weights for the remaining measures. The green line shows a scenario where the weight for the red-light violations is twice the value of the weights for the remaining measures. The blue line represents weights for both the platoon ratio and red-light violations being twice the value of the weights for the arrivals on green and split failures. The purple line shows weight for the split failures is twice the value of the weights for the remaining measures.

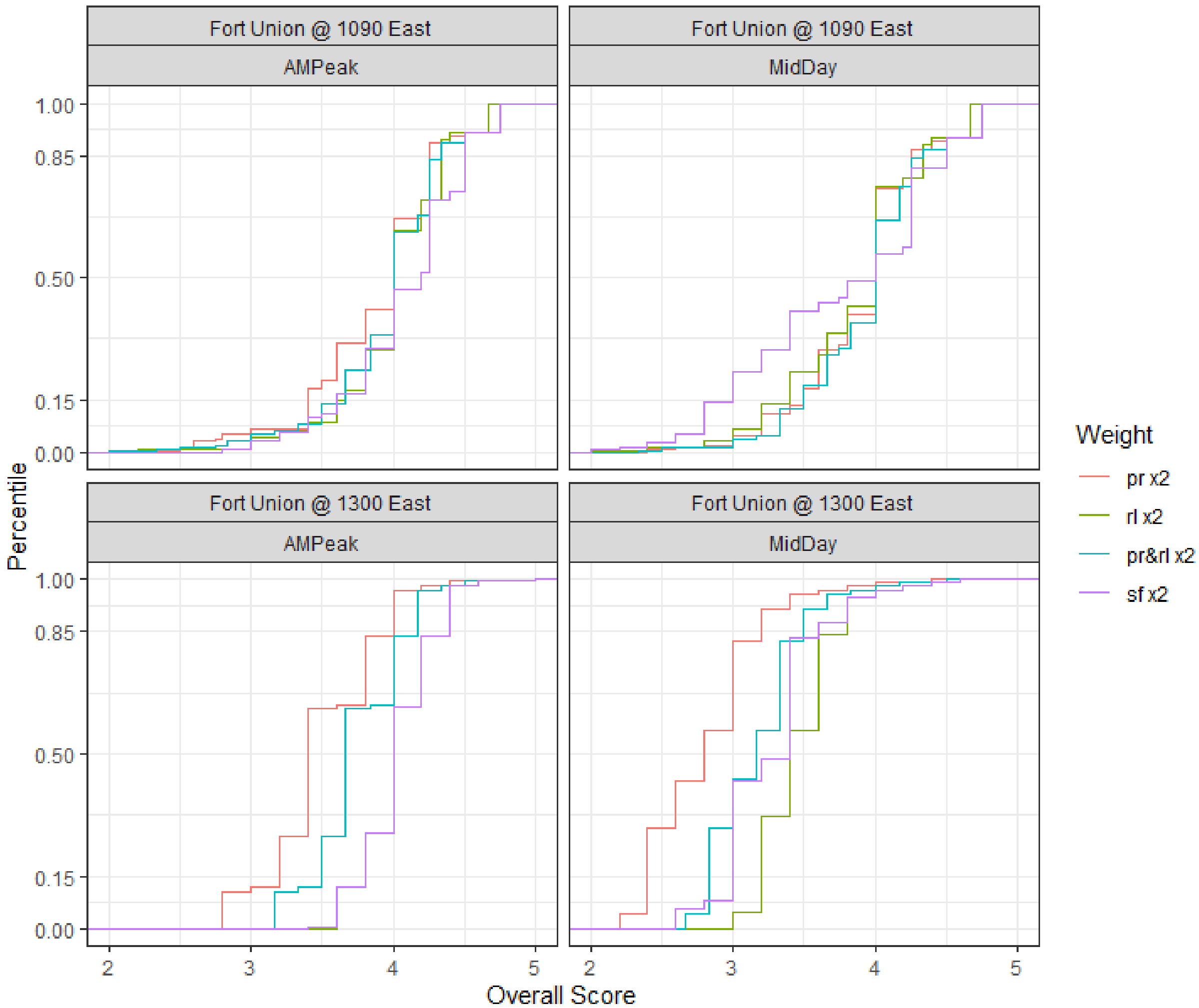

Figure 6.18. Empirical cumulative distribution for different weighting schemes.

The research team chose the two different intersections displayed in Figure 6.18 as representative examples of these plots for all intersections. The plot for the 1090 East intersection shows a wider distribution of scores. The plot for the 1300 East intersection shows a narrower distribution of scores. The plot for the intersection of Fort Union Blvd. and 1090 East shows that the different weighting schemes only change the results slightly. The plot for the intersection of Fort Union Blvd. and 1300 East shows that when the platoon ratio weight is higher than the weights for the other measures, the overall score is lower. The research team decided to adopt this scheme – the orange line in Figure 6.18 – because it provides the most conservative scoring for the intersections, while still representing the variation in scores. Because the signals behave differently for the two time periods collected, 7:00 AM to 9:00 AM and 12:00

PM to 2:00 PM, the results are separated by these time periods. The time period from 7:00 AM to 9:00 AM is the AM peak. The time period from 12:00 PM to 2:00 PM is labeled as Mid-day.

Table 6-6 shows the overall score for the signalized intersections on Fort Union Blvd., 800 North, and State Street in the AM peak and Table 6-7 shows the overall scores during the Mid-day peak. Both tables were developed using the weighting scheme where the platoon ratio weight is two times higher than the other measures. The overall score was calculated for every 15-minute bin from the selected time period. The overall scoring schemes include the minimum, 15^{th} percentile, median, 85^{th} percentile, maximum, mean, and the difference between the 85^{th} percentile and the 15^{th} percentile. The overall scores are sorted from smallest to largest based on the mean value of the distribution of scores for that intersection. The colors from red to green represent the overall score from poor to exceptional for each corridor independent of the other corridor scores. It is important to note that the 85^{th} – 15^{th} percentile column has the opposite value rank than other columns because a smaller difference between the 85^{th} percentile and the 15^{th} percentile means a greater consistency in intersection performance. As such, the 85^{th} – 15^{th} percentile scoring method could be used as a secondary scoring to differentiate between identical values in a primary scoring method. Although in Table 6-6 and Table 6-7 the scores are sorted separately for each corridor, the scores could also be ranked for all intersections included in the analysis regardless of corridor.

There are many scoring schemes that could be chosen for ranking the intersections and there are several examples of how choosing a different scoring scheme would change the ranking. On the Fort Union Blvd. corridor, for example, the worst-performing intersection in four of the seven scoring schemes in the AM period is the 1300 East intersection. However, it also has the second narrowest spread between its 15^{th} and 85^{th} percentile scores, meaning that the intersection performs consistently, although poorly. It may be that UDOT would prefer to identify signals where there is inconsistent performance. Another example on the Fort Union Blvd. corridor can be seen from the 2200 East intersection. The best-performing intersection in the AM peak period is 2200 East. It does not have the highest overall score on the 85^{th} percentile and maximum column, but it has the narrowest spread between its 15^{th} and 85^{th} percentile scores, which means the intersection performs most consistently and at an exceptional level. It can also be seen from both the AM and Mid-day peak tables that using the maximum score does not appear to be very useful. Even if an intersection has a perfect maximum score, there is no information on the distribution of scores for this intersection. An intersection could generally perform poorly and have a perfect maximum score.

Table 6-6. Overall Score for All Intersections (AM Peak)

Primary Road	Cross Road	Min	15th	Median	85th	Max	Mean	85th - 15th
Fort Union Blvd.	1300 East	2.40	3.20	3.40	3.58	5.00	3.47	0.38
	2000 East	2.60	3.20	3.60	4.00	5.00	3.55	0.80
	3000 East	2.67	3.67	3.80	4.20	4.67	3.87	0.53
	1090 East	2.00	3.40	4.00	4.25	4.75	3.90	0.85
	700 East	3.20	3.80	4.00	4.20	4.60	4.01	0.40
	900 East	2.40	3.20	4.40	4.60	5.00	4.07	1.40
	2700 East	3.20	3.80	4.00	4.40	5.00	4.07	0.60
	1435 East	2.67	3.67	4.20	5.00	5.00	4.08	1.33
	2300 East	3.20	3.80	4.00	4.40	4.60	4.08	0.60
	2200 East	3.40	4.20	4.20	4.20	4.60	4.18	0.00
800 North	800 East	2.60	3.40	3.80	4.00	4.60	3.73	0.60
	State Street	1.00	2.00	4.00	5.00	5.00	3.94	3.00
	980 West	3.33	3.67	4.33	4.33	5.00	4.08	0.66
	400 East	3.40	4.20	4.60	4.60	4.60	4.39	0.40
	Main Street	3.00	4.50	5.00	5.00	5.00	4.74	0.50
State Street	1600 North	1.75	2.50	3.00	4.00	4.25	3.14	1.50
	1200 South	2.33	3.00	3.67	4.33	4.33	3.57	1.33
	Center Street	2.60	3.60	3.80	4.20	4.40	3.85	0.60
	800 South	4.00	5.00	5.00	5.00	5.00	4.98	0.00
	400 North	4.00	5.00	5.00	5.00	5.00	5.00	0.00

Table 6-7. Overall Score for All Intersections (Mid-Day Peak)

Primary Road	Cross Road	Min	15th	Median	85th	Max	Mean	85th - 15th
Fort Union Blvd.	1300 East	2.20	2.40	2.80	3.20	4.40	2.81	0.80
	2000 East	2.00	3.20	3.40	3.60	4.40	3.40	0.40
	900 East	1.80	2.60	3.60	4.40	5.00	3.51	1.80
	1435 East	2.33	3.33	3.80	5.00	5.00	3.91	1.67
	1090 East	2.40	3.50	4.00	4.25	4.75	3.92	0.75
	2300 East	2.00	3.60	4.00	4.40	4.80	3.94	0.80
	3000 East	2.33	3.33	4.00	4.60	5.00	3.94	1.27
	700 East	2.80	3.80	4.00	4.00	4.60	3.97	0.20
	2700 East	2.80	3.80	4.00	4.20	4.60	4.02	0.40
	2200 East	3.00	4.00	4.00	4.20	4.60	4.07	0.20
800 North	State Street	1.00	2.00	3.00	4.00	5.00	3.30	2.00
	Main Street	3.00	4.50	5.00	5.00	5.00	4.86	0.50
	400 East	3.60	4.20	4.60	4.60	4.60	4.48	0.40
	800 East	2.80	3.60	3.80	4.20	4.40	3.88	0.60
	980 West	3.33	3.67	4.33	4.33	5.00	4.09	0.66
State Street	1600 North	2.00	2.50	3.00	3.50	4.25	2.98	1.00
	Center Street	1.60	3.00	3.20	3.60	4.60	3.22	0.60
	1200 South	1.67	2.67	3.50	4.00	4.33	3.54	1.33
	800 South	3.50	4.50	5.00	5.00	5.00	4.88	0.50
	400 North	4.00	5.00	5.00	5.00	5.00	4.94	0.00

6.5.2 Overall Score at the Corridor Level

To calculate the overall score at the corridor level, several alternatives were considered. Table 6-8 and Table 6-9 show the scores for each corridor based on different corridor scoring schemes and intersection scoring schemes. For the corridor scoring, three schemes were considered: minimum intersection score, mean intersection score, and maximum intersection score. The research conducted by Day et al. (2018) utilized the minimum overall score of any one intersection along the corridor to represent the overall score at the corridor level. Each of these corridor scoring methods was performed for each intersection scoring method. The intersection scoring schemes are represented in the columns. They include the minimum, 15^{th} percentile, median, 85^{th} percentile, maximum, and mean scoring methods. The research team prefers the mean or median overall score because they result in similar rankings and would be the best to represent the overall performance for each intersection. It should be noted, however, that were UDOT to select a different scheme for scoring corridors, it could in some cases result in a different, yet meaningful ranking.

Table 6-8. Overall Score for Corridors (AM Peak)

Corridor	Overall Score	Min	15th	Median	85th	Max	Mean
Fort Union Blvd.	Min	2.00	3.20	3.40	3.58	4.60	3.47
	Mean	2.77	3.59	3.96	4.28	4.82	3.93
	Max	3.40	4.20	4.40	5.00	5.00	4.18
800 North	Min	1.00	2.00	3.80	4.00	4.60	3.73
	Mean	2.67	3.55	4.35	4.59	4.84	4.18
	Max	3.40	4.50	5.00	5.00	5.00	4.74
State Street	Min	1.75	2.50	3.00	4.00	4.25	3.14
	Mean	2.94	3.82	4.09	4.51	4.60	4.11
	Max	4.00	5.00	5.00	5.00	5.00	5.00

Table 6-9. Overall Score for Corridors (Mid-Day Peak)

Corridor	Overall Score	Min	15th	Median	85th	Max	Mean
Fort Union Blvd.	Min	1.80	2.40	2.80	3.20	4.40	2.81
	Mean	2.37	3.36	3.76	4.19	4.72	3.75
	Max	3.00	4.00	4.00	5.00	5.00	4.07
800 North	Min	1.00	2.00	3.00	4.00	4.40	3.30
	Mean	2.75	3.59	4.15	4.43	4.80	4.12
	Max	3.60	4.50	5.00	5.00	5.00	4.86
State Street	Min	1.60	2.50	3.00	3.50	4.25	2.98
	Mean	2.55	3.53	3.94	4.22	4.64	3.91
	Max	4.00	5.00	5.00	5.00	5.00	4.94

6.6 Chapter Summary

In this research, all the performance measures for each selected intersection and bin were combined into one accessible table. The research team then used a k-means cluster analysis to group all the intersections with similar characteristics. The research team used a combined

Delphi method (with the TAC serving as the expert panel) and data-driven performance-based approach, standardized manuals, and the results of the k-means cluster analysis to determine the threshold values for each performance measure. The research team also collected field data for 2020 and compared aggregated data from the same time period to verify if the intersection scoring was reasonable. Scores for individual intersections and for each corridor used in analysis were then calculated and presented.

7.0 CONCLUSIONS

7.1 Overview

The first objective of the research was to evaluate performance measurement data collected through the ATSPM database and determine which performance measures could be used for evaluation of maintenance and operations. The second objective was to develop threshold values for each selected performance measure. The final objective was to provide a process that could be used for an overall evaluation of the historic quality of signal system operations across the state.

This report uses a sample of high-resolution data in the UDOT ATSPM database to provide a method of evaluating the quality of signal operations at both the intersection and corridor level. It will help to introduce and provide context for performance measure data and to provide a history of this context over time. This chapter will provide a summary of the methodology for this research, the limitations and challenges of this research, and ideas for future research.

7.2 Methodology Summary

The data workflow for this research is presented in Figure 7.1. The raw data from the SQL server at BYU were aggregated and placed into separate aggregation tables. These tables were combined using the R analysis tool. Charts and plots were then produced from the combined data utilizing the data visualizer created by the research team. This application provides a method for producing scores for each intersection included in the analysis. These scores are then utilized to provide an overall corridor score for each corridor analyzed.

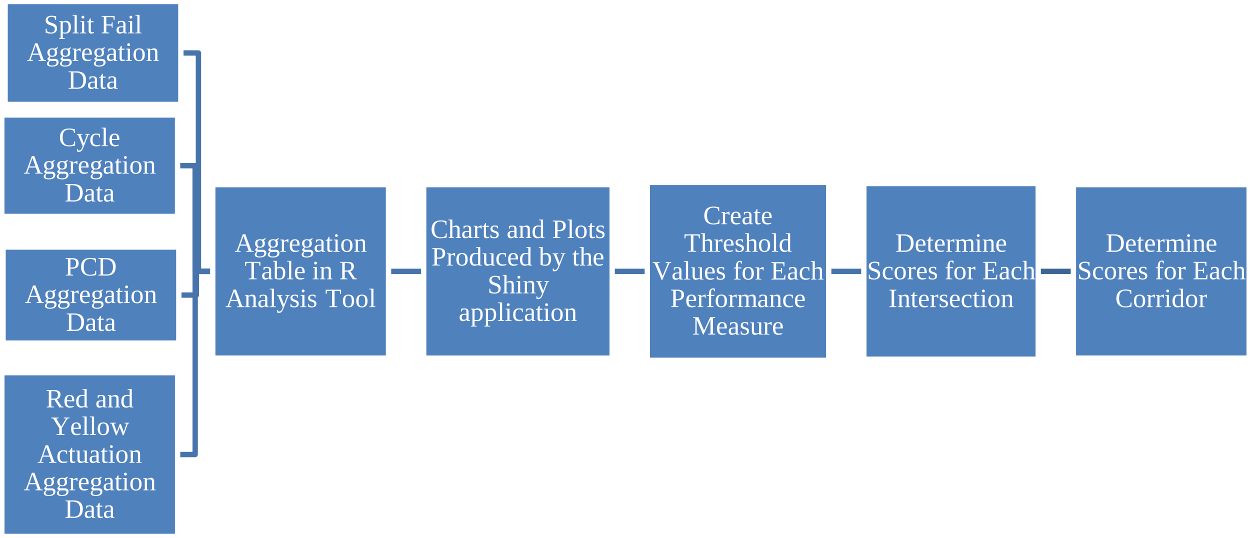

Figure 7.1. Data workflow.

7.3 Limitations and Challenges

One of the greatest challenges experienced as part of the research was that the ATSPM database was not as complete as the research team expected. In some locations, data were missing and for certain performance measures, there were several extreme values. This made data evaluation and analyzing more challenging than expected.

As mentioned in Sections 5.2.1 and 5.2.3, there were some locations where data were expected but not available. This was primarily an issue with the University Avenue corridor where it was expected that split failure data would be available for six signals, but only two signals had this data.

A record of data availability for all the signals used in the final analysis can be found in Section 5.2.3. Although the difference between expected and actual data is not as severe as that found on University Avenue, there were still several areas where one or more approaches were missing data despite the understanding that the data would be available. This created problems when attempting to select intersections. It is anticipated that this would be the case with several corridors if performing a statewide analysis.

Some performance measures were found to have extreme values. This includes the red-light violation and force-off performance measures. Both issues were contained to specific signals and not found at every signal being aggregated.

Section 5.3.2 discusses the extreme values encountered with the force-off performance measure for the intersection of Fort Union Blvd. and 1090 East. Although force-offs were not used in the final analysis, it is important to note that other signals could also experience this phenomenon and produce atypical data.

The issue with the red-light violation performance measure was mentioned in Section 5.3.4. The red-light violation metric typically yields values between 1 and 7 for a 15-minute bin. However, the values collected were as high as 35 in a 15-minute bin for some signals. These extreme values occurred for the intersection of Fort Union Blvd. and 1090 East and the intersection of State Street and Center Street.

7.4 Future Research

There are several opportunities for future research identified by the research team. This section will describe the future research opportunities, which include evaluating signal performance over time, expanding the dataset, and including more performance measures.

One suggestion for future research is evaluating signal performance longitudinally over time. The methodology for scoring intersections has been established. Comparing these scores over time enables determining whether the intersection performance is worsening, staying the same, or improving.

Another suggestion for future research is focusing on other phases of an intersection. The current research focuses primarily on phases 2 and 6 (or sometimes phases 4 and 8) of each intersection. The determination of phases to be used was primarily based on which phases had a flow of traffic in the direction of the corridor being analyzed. By focusing on through movements, the data became comparable across all signals. Using other movements would be useful in determining the performance and maintenance of intersections. Using left turns would require considering the difference between protected and permissive phases.

Another suggestion for future research would be to investigate more corridors. This research project focused on ensuring that the data were aggregating correctly. As such, the signal selection was somewhat limited. It would be interesting to observe the differences in corridors in a wider selection of data.

The inclusion of more performance measures is recommended for future research. As explained in Section 5.4.5, the force-off performance measure was omitted from the final analysis due to the difference between coordinated and non-coordinated intersections. In future research, two groups of signals could be chosen: coordinated and non-coordinated signals. This would allow for the force-offs to be used as long as the two types of signals are not compared with one another. It is also important to note the potential issues with calculating force-offs. Some of the values calculated for force-offs per cycle were close to 2.0. This shows that the force-off values for these intersections are artificially high. It will be important to identify signals yielding these extraordinarily high values and determine how best to analyze them.

REFERENCES

Abalo, J., Varela, J., and Manzano, V. (2007). “Importance values for Importance–Performance Analysis: A formula for spreading out values derived from preference rankings.” *J. Bus. Res.*, 60(2), 115-121.

Bonow, R., Ganiats, T., Beam, C., Blake, K., Casey, D., Goodlin, S., Grady, K., Hundley, R., Jessup, M., Lynn, T., Masoudi, F., Nilasena, D., Piña, I., Rockswold, P., Sadwin, L., Sikkema, J., Sincak, C., Spertus, J., Torcson, P., Torres, E., Williams, M., and Wong, J. (2012). “ACCF/AHA/AMA-PCPI 2011 Performance Measures for Adults with Heart Failure.” *J. Am. Coll. Cardiol.* 59(20), 1812-1832.

Bullock, D. M., Clayton, R., Mackey, J., Misgen, S., Stevens, A. L., Sturdevant, J., and Taylor, M. (2014) “Helping Traffic Engineers Manage Data to Make Better Decisions: Automated Traffic Signal Performance Measures.” *ITE Journal*, 84(3).

BYU Transportation Lab (2020). “Aggregate Data with Start and End Dates for Specific Signals” <github.com/byu-transpolab/ATSPM/commit/a061997cd22044e81d0a255391497 1316ab541cb> (June 3, 2020).

Cavalli-Sforza, V., and Ortolano, L. (1984). “Delphi Forecasts of Land Use: Transportation Interactions.” *J. Transp. Eng*., 110(3), 324-339.

Chang, W., Cheng, J., Allaire, J., Xie, Y., and McPherson, J. (2020). “Shiny: Web Application Framework for R; R package version 1.4. 0.2; 2020.” <https://CRAN.R-project.org/ package=shiny> (June 23, 2020).

Connecticut Transportation Institute (CTI). (2018). “Automated Traffic Signal Performance Measures.” *Tech Brief Series.* <https://www.t2center.uconn.edu/pdfs/Traffic%20Signal %20Brief_2018_1_.pdf> (Apr. 17, 2019).

Davis, A. (2017). “Focused Operations: Measuring Arterial Performances Using Automated Traffic Signal Performance Measures.” *Using Performance Measures to Justify Signal Systems on Arterials.* I-95 Corridor Coalition, <https://i95coalition.org/wp-content/ uploads/2017/05/I-95CC-Signal_PM-Coalition_Slides-ver11-Compiled.pdf?x70560> (Apr. 8, 2019).

Day, C. M., Bullock, D. M., Li, H., Remias, S. M., Hainen, A. M., Freije, R. S., Stevens, A. L., Sturdevant, J. R., and Brennan, T. M. (2014). “Performance Measures for Traffic Signal Systems: An Outcome-Oriented Approach.” Purdue University, West Lafayette, Indiana, 2014. <http://dx.doi.org/10.5703/1288284315333> (Feb. 27, 2019).

Day, C. M., Haseman, R., Premachandra, H., Brennan, T. M., Wasson, J. S., Sturdevant, J. R., and Bullock, D. M. (2010). “Evaluation of Arterial Signal Coordination: Methodologies for Visualizing High-Resolution Event Data and Measuring Travel Time.” *Transp. Res. Rec*., 2192(1), 37-49.

Day, C. M., Li, H., Sturdevant, J. R., and Bullock, D. M. (2018). "Data-Driven Ranking of Coordinated Traffic Signal Systems for Maintenance and Retiming." *Transp. Res. Rec.*, 2672(18), 167-178.

Day, C., O'Brien, P., Stevanovic, A., Hale, D., and Matout, N. (2020). "A Methodology and Case Study: Evaluating the Benefits and Costs of Implementing Automated Traffic Signal Performance." *FHWA-HOP-20-003*, FHWA, U.S. Department of Transportation.

Day, C. M., Smaglik, E. J., Bullock, D. M., and Sturdevant, J. R. (2008). "Quantitative Evaluation of Fully Actuated versus Nonactuated Coordinated Phases." *Transp. Res. Rec.*, 2080(1), 8-21.

Federal Highway Administration (FHWA). (2018). "Traffic Data Computation Method Pocket Guide." <https://www.fhwa.dot.gov/policyinformation/pubs/pl18027_traffic_data_pocket_guide.pdf> (Sept. 4, 2018).

Federal Highway Administration (FHWA). (2019). "Automated Traffic Signal Performance Measures (ATSPM)." <https://www.fhwa.dot.gov/innovation/everydaycounts/edc_4/atspm.cfm> (Jan. 31, 2019).

Georgia Department of Transportation (GDOT). (2019). "Georgia DOT's Smart Signal System key to moving Super Bowl traffic." *Roads & Bridges.* <https://www.roadsbridges.com/georgia-dot's-smart-signal-system-key-moving-super-bowl-traffic> (Apr. 17, 2019).

Gunasekaran, A., Tirtiroglu, E., and Patel, C. (2001). "Performance Measures and Metrics in a Supply Chain Environment." *Int. J. Oper. Prod. Manage.*, 21(1), 71-87.

Gupta, U. G., and Clarke, R. E. (1996). "Theory and Applications of the Delphi Technique: A Bibliography (1975–1994)." *Technol. Forecasting and Social Change*, 53(2), 185-211.

Hendren, P., and Niemeier, D. (2006). "Evaluating the Effectiveness of State Department of Transportation Investment Decisions: Linking Performance Measures to Resource Allocation." *J. Infrastruct. Syst.*, 12(4): 216-229.

Hirschhorn, F., Veeneman, W., and van de Velde, D. (2017). "Experts' Inventory and Rating of Core Performance Indicators and Organisational Features in Public Transport: A Global Delphi Survey." *Int. Conf. Ser. Competition and Ownership in Land Passenger Transport*, Thredbo 15, Stockholm, Sweden.

Institute of Transportation Engineers (ITE). (2014). "Automated Traffic Signal Performance Measures: Case Studies." *Institute of Transportation Engineers Webinar Part 2.* <http://aii.transportation.org/Documents/ATSPMs/atspms-itewebinar-part2-05072014.pdf> (Feb. 20, 2019).

Jansen, S., Coolen, H., and Goetgeluk, R. (2011). "The Multi-Attribute Utility Method." Chapter 5 in *The Measurement and Analysis of Housing Preference and Choice*. Springer, New York, NY, 101-125.

Kittelson & Associates, and Purdue University. (2017). “Phase 1 Report to the National Cooperative Highway Research Program (NCHRP) on Project 03-122: Performance-Based Management of Traffic Signals.” Transportation Research Board. <http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP03-122_PHASE1REPORT.pdf> (May. 20, 2020).

Lavrenz, S., Sturdevant, J., and Bullock, D.M. (2017). “Strategic Methods for Modernizing Traffic Signal Maintenance Management and Quantifying the Impact of Maintenance Activities.” *J. Infrastruct. Syst.*, 23(4), 05017004.

Linstone, H. A., and Turoff, M. (1975). *The Delphi Method*. Addison-Wesley Pub. Co., Advanced Book Program, Reading, MS.

Liu, X. C., and Chen, Z. (2017). “Data-Driven Freeway Performance Evaluation Framework for Project Prioritization and Decision Making.” *Mountain-Plains Consortium*., 17-316.

Liu, H. X., Ma, W., Hu, H., Wu, X., and Yu, G. (2008). “SMART-SIGNAL: Systematic Monitoring of Arterial Road Traffic Signals.” *2008 11th Int. IEEE Conf. Intell. Transport. Syst.*, 1061-1066.

Mackey, J. (2017). “Configuration Utility-UDOT Automated Traffic Signal Performance Measures.” *UDOT ATSPM Train-the-trainer Workshop.* Salt Lake City, UT. (Jan. 18-19, 2017). <https://udottraffic.utah.gov/ATSPM/Images/TTTJamieMackey.pdf> (Feb. 16, 2019).

National Transportation Safety Board (NTSB). (2017). “Fire Damage to Bridge and Subsequent Collapse, Atlanta, Georgia, March 30, 2017.” *Highway Accident Brief.* <https://www.ntsb.gov/investigations/AccidentReports/Reports/HAB1802.pdf> (Apr. 17, 2019).

R Core Team (2020). “R: A language and environment for statistical computing.” *R Foundation for Statistical Computing,* Vienna, Austria. <https://www.R-project.org> (May 29, 2020).

Roess, R. P., Prassas, E. S., and McShane, W. R. (2019). *Traffic Engineering.* New York City, NY: Pearson.

Schultz, G. G., and Jensen, A. P. (2009). “Evaluation and Installation Guidelines for Advance Warning Signal Systems.” *IET Intel. Transport Syst.*, 3(3), 247-256.

Transportation Research Board (TRB). (2010). “Highway Capacity Manual.” Washington, DC.

University of Cincinnati (UC). (2016). “UC Business Analytics R Programming Guide.” <https://uc-r.github.io/kmeans_clustering> (June 7, 2020).

Utah Department of Transportation (UDOT). (2019a). “ATSPM Frequently Asked Questions.” <https://udottraffic.utah.gov/ATSPM/FAQs/Display> (Jan. 31, 2019).

Utah Department of Transportation (UDOT). (2019b). “Automated Traffic Signal Performance Measures Case Studies.” <https://ops.fhwa.dot.gov/publications/fhwahop18048 /index.htm> (Feb. 26, 2019).

Utah Department of Transportation (UDOT). (2019c). “Automated Traffic Signal Performance Measures (ATSPM).” <https://udottraffic.utah.gov/ATSPM> (Jan. 7, 2019).

Utah Department of Transportation (UDOT). (2020). “udotdevelopment/ATSPM” <https://github.com/udotdevelopment/ATSPM> (May 29, 2020).

Wang, J., Chen, M., Yan, W., Zhi, Y., and Wang, Z. (2018). “A Data-driven Approach to Estimate the Probability of Pedestrian Flow Congestion at Transportation Bottlenecks.” *ASCE J. Civ. Eng.*, 23(1), 251-259.

Wetzel, C. (2016). “Signal Performance Measures.” <https://docs.lib.purdue.edu/cgi/viewcontent .cgi?article=1032&context=atspmw > (Feb. 16, 2019).