RESEARCH

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Report No. UT-21.12

EVALUATION OF METHODS FOR LEFT TURN GAP ANALYSIS USING HIGH-RESOLUTION SIGNAL DATA

Prepared For:

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Final Report
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16. Abstract

This project evaluates the most under-utilized but potentially the most useful ATSPM measure in decision making for left turn phasing at signalized intersections. Lack of data quality control or quality checks and a difficulty in using the currently presented measure on the website have been identified as shortcomings of the "left turn gap analysis" measure. The purpose of this project is to develop an automated method of flagging intersection approaches in need of left turn phasing changes based on availability of gaps in opposing through traffic. Through comparison with manually collected data, high-resolution data from selected approaches were validated. The validated sample data was then used to develop a gap analysis tool, which in conjunction with identified automated measures, can identify and flag left turn locations requiring phasing changes (permissive to protected-permissive or protected only). The tool, which was developed in Microsoft Access, is currently being migrated to the ATSPM website to be made available to consultants in the form of a password-protected online tool. Furthermore, the research team has also validated left turn gap aggregates which are produced as part of UDOT's effort to reduce calculation delays. Recommendations have also been made for possible improvements to the measure on the ATSPM website which is currently in the development phase.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
ATSPM	Automated Traffic Signal Performance Measures
BYU	Brigham Young University
CFI	Continuous Flow Intersection
DTS	Department of Technology Services
FHWA	Federal Highway Administration
FYA	Flashing Yellow Arrow
GDOT	Georgia Department of Transportation
GUI	Graphical User Interface
HCM	Highway Capacity Manual
ITE	Institute of Transportation Engineers
MD	Mid-day
MS	Microsoft
PDF	Portable Document Format
PO	Protected Only
POV	Principle Other Vehicle
PPLT	Protected-Permissive Left Turn
SQL	Structured Query Language
SSAM	Surrogate Safety Assessment Model
SV	Subject Vehicle
TMC	Turning Movement Count
TOC	Traffic Operations Center
UDOT	Utah Department of Transportation
VBA	Visual Basic for Applications
vph	Vehicles per Hour
vphg	Vehicles per Hour Green
vphpl	Vehicles per Hour per Lane

EXECUTIVE SUMMARY

The purpose of this project is to develop an automated method of flagging signalized intersection approaches in need of left turn phasing changes based on the availability of gaps in traffic, conflicting with a left turn movement. Sample data was collected from 44 approaches representing a total of 9 intersection configurations. The initial data collection process involved collection of 24-hour data with Jamar tube counters (manual data collection) which was then compared to high-resolution data collected by signal controllers and detectors to identify any possible complications with manual data or detector settings. After the validation of datasets and final data collection effort, manual counts were used to verify the accuracy of the high-resolution counts used on the Automated Traffic Signal Performance Measures (ATSPM) website. Furthermore, with the help of high-resolution data, potential automated measures were identified that could be used in conjunction with the gap analysis to determine needs for left turn phasing. Among them, several were found useful, especially the critical gap calculation and turning movement counts. A flowchart for flagging left turns for phasing changes was developed from the identified automated measures. Following the flowchart, a left turn gap analysis tool was developed in Microsoft (MS) Access. Following the successful demonstration of the MS Access tool with the Technical Advisory Committee (TAC), the Utah Department of Transportation (UDOT) began the process of migrating the tool to the ATSPM website; this process is still underway. As part of recent UDOT efforts to reduce calculation delays, it was determined that the left turn gap analysis measure would be aggregated in 15-minute bins along with other ATSPM measures. Before the aggregated results are made available, the results were validated by taking the raw high-resolution data and performing manual counts and sums in MS Excel. After several rounds of debugging, aggregation results adequately matched the manual calculations and the aggregation code was approved.

Over the course of the project, the research team has routinely organized update meetings with the TAC and has presented results in the form of reports, PowerPoint presentations, and the MS Access database (tool). The final deliverables provided to UDOT include:

Research Report: Includes the detailed workflow of the project.

Left Turn Flagging Flowchart: A flowchart of the decision-making and flagging process in form of a .pdf.

Left Turn Graphical User Interface (GUI) Concept: a GUI in MS Access to guide a user through the steps of the analysis and perform automated calculations.

1.0 INTRODUCTION

1.1 Problem Statement

Automated Traffic Signal Performance Measures (ATSPMs) have been developed to equip traffic signal controllers with high-resolution data-logging capabilities and to utilize these to generate performance measures. State-of-the-art ATSPM systems primarily present raw data in graphic representations with the goal of providing tools for visual queries to traffic signal experts. The tool has been very useful for data-driven management of traffic signal systems and has been adopted and modified by several agencies. Over time, ATSPM data has become a huge resource for research activities.

In Utah, as a part of continuous monitoring of statewide signals, the Utah Department of Transportation (UDOT) responds to every complaint call from the public. Prior to ATSPMs, UDOT responded to every complaint call with a field visit. With the implementation of ATSPMs, the calls are addressed much more efficiently because the problems can be investigated with data before they are checked in the field. At present, the ATSPM system is heavily used to identify detection channel issues such as missing data, excessive max outs (phase termination due to reaching the designated maximum green time for the phase), force offs (phase termination regardless of continued demand to ensure that the coordinated phases are provided a minimum amount of green time), and many more. As of November 22, 2020, 14 measures available through the UDOT ATSPM website [1] – a) Purdue Phase Termination, b) Split Monitor, c) Pedestrian Delay, d) Preemption Details, e) Turning Movement Counts, f) Purdue Coordination Diagram, f) Approach Volume, g) Approach Delay, h) Arrivals on Red, i) Approach Speed, j) Yellow and Red Actuations, k) Purdue Split Failure, l) Timing and Actuation, and m) Left Turn Gap Analysis.

Although the overall website has been very useful for data-driven management of traffic signal systems and signal performance monitoring, some of the measures are used less often than others. Figure 1.1 shows the usage of different measures as reported in the ATSPM website on November 11, 2020. The values represent a typical day chart usage for ATSPM.

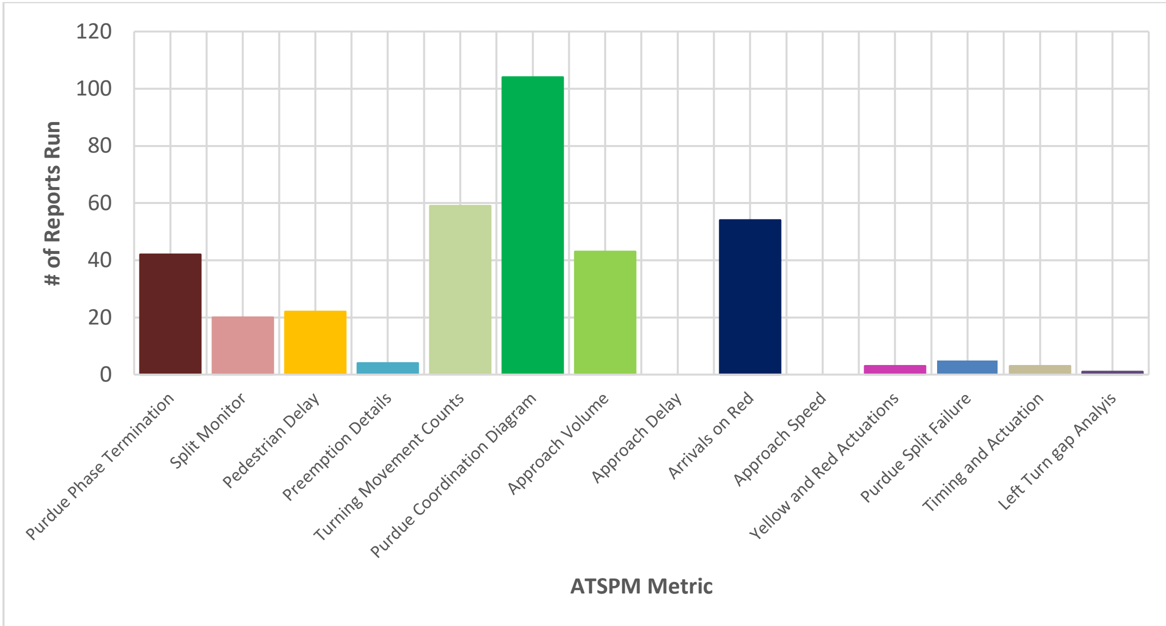


Figure 1.1 Usage frequency of ATSPM Measures on November 11, 2020 (Data Source: ASTPM Chart Usage Report)

As presented in Figure 1.1, the "Left Turn Gap Analysis" measure is one of the least used charts in the system. This measure has been added to the ATSPM website in the January 2020 update [2] and was developed by Georgia Department of Transportation (GDOT) and Kimley-Horn. Many of the public complaints in the state of Utah focus on issues with left turns at signalized intersections (e.g., not getting enough gaps or lower number of acceptable gaps to make safe left turn maneuvers). In addressing these comments, "Left Turn Gap Analysis" can be a very powerful tool as the data is valuable in evaluating gaps in opposing traffic that are required to allow vehicles to safely make left turns. From conversation with UDOT, the two main shortcomings in using the gap data are: (i) the tool currently uses raw data feeds but has very little data quality control or quality checks in place, and (ii) there is currently no process for efficient use at the system-wide management level based on the way the data is currently presented in the ATSPM website. In an effort to better respond to complaints and better utilize the left turn gap data, Avenue Consultants has performed the following study to develop a methodology using the ATSPM data to analyze gaps for left turn movements. The study identifies which data and measures are best suited to be used in the analysis. Additionally, Avenue has completed a test analysis on a sample of signalized intersections within a designated area of Utah. The end results of the study were a tool and methodology flowchart to be used by UDOT.

1.2 Objectives

The objective of this research project is to determine if ATSPM gap analysis data can be used in regulating the need for and potential impacts of left turns with permissive, protected-permissive, and protected-only phasing. In addition, the ATSPM high-resolution data will be used to provide additional measures of gap availability and acceptance for left turn movements. The operational recommendations are presented as a methodology flowchart that demonstrates how the high-resolution data can be used in this process. Results of this study will be incorporated into a left turn flagging tool to be used by UDOT.

1.3 Scope

The project objective will be approached through the following major tasks:

1. Synthesis of Literature and Practices. Review literature and practice regarding left turn phasing considerations, left turn gap acceptance, current practices in UDOT gap studies.

2. Location Selection and Data Validation. The primary purpose of this task is to prepare a cross-section of intersection approaches to provide both variation and statistical validity.

3. Development and Evaluation of Potential Gap Analysis Measures. After the validation of the ATSPM high-resolution data against manually collected data is performed, the high-resolution data will be used to examine several automated measures that could potentially be used in conjunction with the gap analysis to determine the needs for left turn phasing. The preliminary evaluations found that all nine measures under consideration could be developed from the high-resolution data except for one, which required some additional data. Some of the potential measures did not warrant further evaluation in this study based on their projected use in evaluating the need for left turn phasing. The study provides a detailed evaluation of each

measure which includes a brief description, example outputs, methodology to create the measure, and any potential applications.

4. Methodology Framework and Tool Development. Development of a detailed framework for addressing left turn complaints/issues by consultants. This will include initial processing, gap data analysis and measures that can be helpful in improving overall left turn performance.

5. Graphical User Interface (GUI) Concept and Deliverables. A detailed framework will be developed to allow users to query left turn gap analysis results.

1.4 Outline of Report

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

- Chapter 1 includes an introduction of the research, project objectives, and the organization of the report
- Chapter 2 includes a literature review assessing differences in safety between left turn treatments, left turn phasing practices in different states of the U.S., and a review of left turn gap research
- Chapter 3 includes Location Selection and issue corrections
- Chapter 4 includes final Data Collection Methodology and comparison of different data sources
- Chapter 5 includes Gap Data Evaluation and discussion of potential automated measures
- Chapter 6 includes Methodology and Tool Development
- Chapter 7 includes Conclusions and Recommendations
- A reference list follows the main chapters

2.0 SYNTHESIS OF LITERATURE AND PRACTICE

2.1 Overview

A traffic signal serves the primary purpose of regulating movements at an intersection. Additionally, every intersection is also part of a roadway system, which typically contains multiple signalized intersections. Coordination of individual signalized intersections is often expected to achieve an overall better roadway performance. Each of these signals are a combination of several different systems working together, which can be studied and analyzed to improve the overall signal performance. Safety and efficiency of an at-grade intersection is greatly dependent on the performance of the left turns. This chapter discusses prior research on left turn phasing along with the importance of including the gap acceptance as a determining factor for left turn phasing. Furthermore, this chapter presents a brief overview of ATSPM and the different components of the Left Turn Gap Analysis performance measure.

First, in order to investigate the safety effects of different left turn phasing options, this chapter presents an overview of past studies on left turn phasing. Second, the study summarizes the left turn policies of different states in the United States which was compiled in a prior UDOT-funded research project. And finally, the review includes an examination of previous left turn gap studies and presents an overview of ATSPM left turn gap measure.

2.2 Literature Review

2.2.1 Review of Research on Left Turn Phasing

A crucial issue in designing an at-grade signalized intersection is to accommodate all left turn movements safely (minimizing crashes) and efficiently (minimizing delay). There are several types of left turn phasing in use: permissive-only, protected only (PO), protected-permissive (PPLT), split phasing and, prohibited left turn [3]. Various phasing designs can improve signal efficiency, increase capacity, and improve vehicular and pedestrian safety. PPLT is used more often to accommodate left turn movements at signalized intersections because it increases left turn capacity by providing a protected turn phase as well as a permissive phase during which left turns can be made, as opposing traffic allows [4]. However, safety is a major concern in the implementation of the PPLT control. Medina [5] evaluated the approach-level safety performance of left turn phases including permissive, PPLT, and protected indications, and the more recent flashing yellow arrow (FYA). A time-of-day analysis of crashes revealed higher-than-expected concentration of crashes in the hours preceding afternoon peaks (2pm-4pm), pointing at opportunities to reduce crashes during these periods perhaps by extending operational strategies from peak hours into the off-peak hours whenever possible. Qi [6] developed a method for quantifying the benefit and cost of the PPLT control mode compared with the PO mode based on the intersection traffic flow information and signal timing components. In this study, analytical models were developed for estimating the delay reduction and safety risk associated with the use of the PPLT control mode. Furthermore, a case study was presented that quantified the delay reduction and safety cost of using the PPLT mode instead of PO mode in dollar amounts. Identifying the right volume or the correct decision boundaries for a transition from PPTL to PO have also been investigated by researchers at Brigham Young University (BYU) [7]. Along with looking at the historic crash data, their study gathered simulated data using VISSIM traffic modeling software, and safety data were extracted from these simulations using the Surrogate Safety Assessment Model (SSAM) created by the Federal Highway Administration to identify decision boundaries between each left turn treatment. Equations were derived using the simulated data; these equations were then charted, and final decision boundaries were developed for the 1-, 2-, and 3-lane configurations between permitted and protected-permissive phasing as well as between protected-permitted and protected phasing.

2.2.2 State of Practice: Left Turn Phasing

Signal operation, management, and control is different for each state. Medina [5] has conducted an outreach effort to contact all 50 states regarding their left turn policies and determine the current state of practice throughout the U.S. This effort was important to identify common criteria, significant differences, and factors that states prioritize to make decisions regarding left turn phasing. Policies for left turn phasing from all states were divided into five groups and summarized in Table 2.1.

Table 2.1 Left Turn Phasing Policies by State [5]

ITE Flowchart	FHWA Guidelines	State Adapted Criteria	Formulaic Demand	No Statewide Guidelines
Alaska Delaware Louisiana North Dakota Rhode Island South Dakota Texas Wyoming	Hawaii Kentucky Nevada Vermont	Arizona Georgia Michigan Minnesota Mississippi Nebraska New York North Carolina Oregon Pennsylvania South Carolina Tennessee Utah Wisconsin	Alabama Idaho Illinois Indiana Missouri Montana	Arkansas Connecticut Florida Iowa Kansas Maine Massachusetts New Hampshire Ohio Oklahoma Virginia Washington

The first two state groupings are following the flowchart and guidelines without modifications. A total of 14 states (including Utah) in the third category choose to modify, remove, or add warranting criteria to the crash history table, as well as to the left turn volumes and the cross-product values described in the Institute of Transportation Engineers (ITE) Flowchart or Federal Highway Administration (FHWA) Guidelines. Guidelines for UDOT are discussed in detail in the following paragraphs. The fourth group in the table do not use set warranting values and opted instead to use a formulaic approach. Consideration for left turn capacity is common to all 5 states in this category. Safety is also a consideration for each state using the formulaic approach, but only Alabama and Idaho have given an assigned crash history warrant [5]. The states listed in the fifth group of the table have not adopted guidelines or other techniques to determine left turn phasing and instead rely on engineering judgment and analysis on a case-by-case basis.

In the process for evaluating the state of practice for Utah, UDOT's most recent guidelines for left turn phasing at signalized intersections were reviewed. The guidelines are presented in Figure 2.1 [8]. According to these guidelines, the user must first choose between three options based on the left turn volume on each approach of the intersection: below 100 vehicles per hour (vph), between 100 and 250 vph, or over 250 vph. Each of these options leads to the next criterion in the flowchart. The flowchart is followed as "yes or no" questions are answered. Once all the criteria on the flowchart have been identified, the flowchart yields the recommended left turn phasing for each approach of the intersection [8].

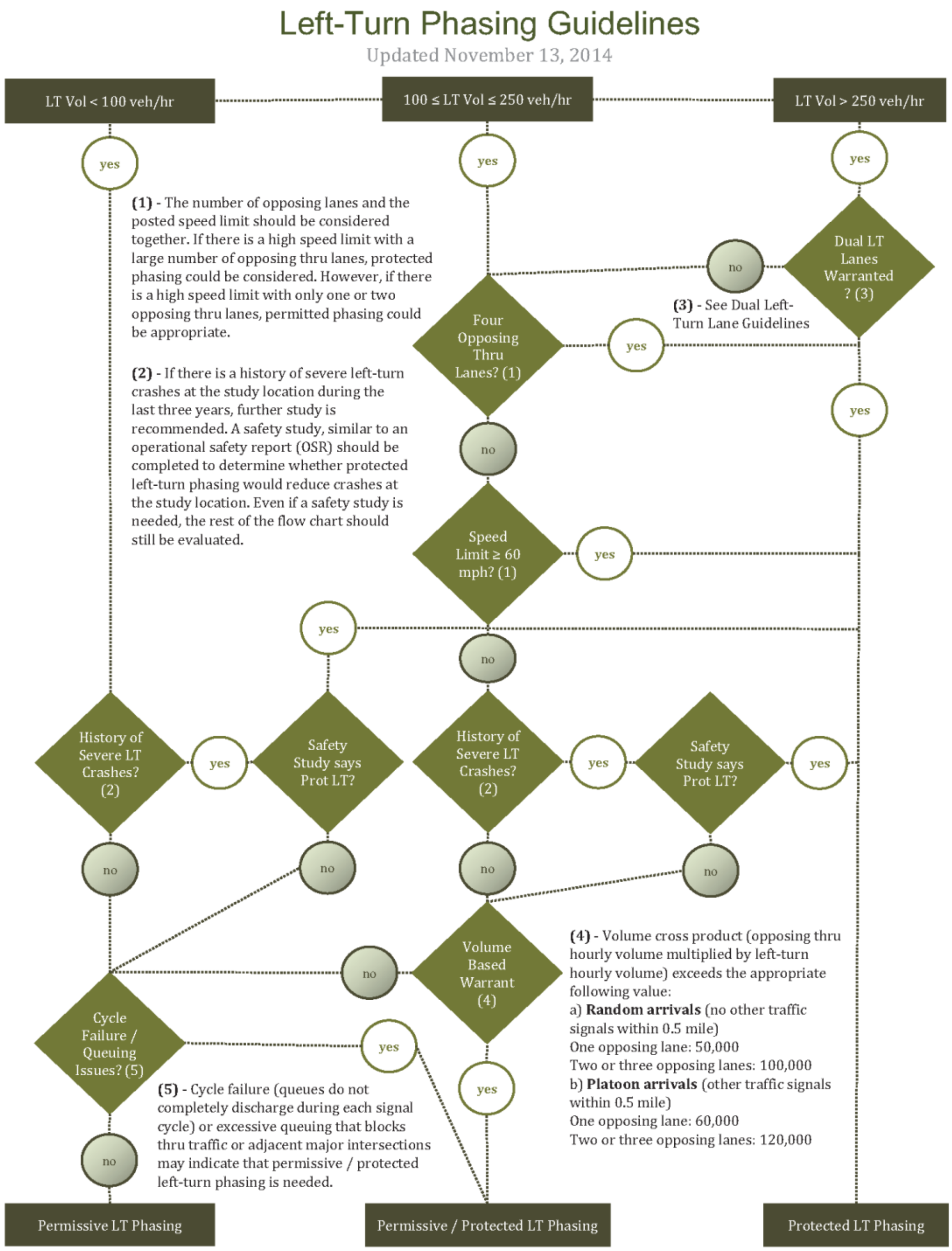


Figure 2.1 UDOT left turn phasing flowchart

The previous two sections indicated that throughout the United States, safety and operations (delay) have been explored as determining factors for left turn phasing. However, the application of left turn gap data, which has been a popular research topic for unsignalized intersections, has been limited when it comes to determining the need for and potential impacts of left turns with permissive, protected-permissive, and protected-only phasing at signalized intersections.

2.2.3 State of Practice: LT Gap Acceptance

Rangland [9] defined a "gap" as the opportunity to turn left before the left-turning vehicle (subject vehicle (SV)) must clear the intersection for an oncoming vehicle (Principle Other Vehicle (POV)). The length of the gap is measured as the time between the moment when the SV is presented with the POV opportunity (such as a green light or clear intersection) and can reasonably be assumed to be ready to initiate the left turn, and the moment that a POV arrives at the path to be taken by the SV. According to this study, an acceptable gap ranges from 3 to 12 seconds.

A critical gap is defined as the minimum time interval within which the left-turning vehicle can safely complete the turning maneuver. Some methods of developing critical gaps based on intersection configuration are detailed in the Critical Headway section of Chapter 5.

Many agencies are developing left turn gap measures and making the data available to both consultants and the general public. The ATSPM website also presents a "Left Turn Gap Analysis" measure based on detector events which can be used to evaluate available gaps in opposing traffic for a left turn to make a permissive movement. The measure, developed by engineers from GDOT and Kimley-Horn, looks at opposing through detector actuations, relative to the left turn under evaluation, to provide insight into the availability of permissive left turn movements. The report for this metric only appears in the available measures list if an intersection has lane-by-lane count or stop bar presence detection on an approach [10]. Figure 2.2 shows an example of the Left Turn Gap Analysis measure from the ATSPM website.

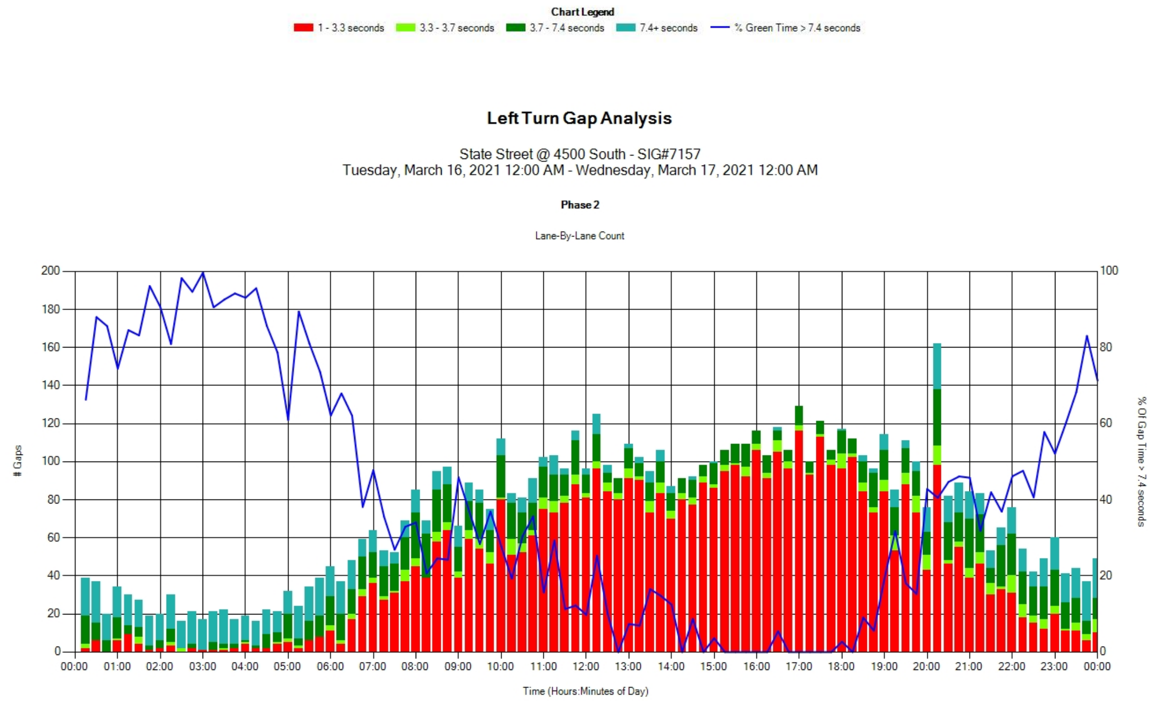


Figure 2.2 Left turn gap analysis measure [1]

There are two components of the chart: i) the bins that count the number of opposing through gaps by their duration (1 - 3.3 seconds, 3.3 - 3.7 seconds, 3.7- 7.4 seconds, and 7.4+ seconds in order along the X-axis) and ii) the line that represents the percent of green time where available gaps are over a user-defined threshold (+7.4 seconds is the default). The chart gives a general idea of gap availability based on time of day. For example, phase 2 for State Street and 4500 South has few or no available gaps between 11 AM and 6 PM on March 17, 2021.

2.3 Summary and Conclusion

Left turn gap analysis is an important measure in left turn phasing decisions. A wealth of research has been conducted evaluating left turns at at-grade intersections. This chapter has summarized policies employed by different state departments of transportation for their left turn phasing as well as describing UDOT's current left turn phasing guidelines. Developing a performance measure presents many opportunities—first, it can provide real feedback on a recently retimed signal or an intersection where a considerable investment has been made to determine if performance has actually improved; second, it provides an opportunity to continuously monitor a system to evaluate the quality of service; and third, it makes it easier to address complaint calls from the public.

3.0 LOCATION SELECTION

3.1 Overview

A cross-section of intersection approaches was needed to provide both variation and statistical validity for the analysis. A sample of approaches was selected representing each of the nine configurations represented in this study (shown in Table 3.1). For each approach, data was collected from both the ATSPM system and on-site pneumatic tubes. This chapter documents the process of approach selection including the methodology and assumptions for both the initial and final selection of the study approaches.

Table 3.1 Data Configurations and Sites

Data Collection Matrix			
Number of Opposing Through Lanes	Left Turn Phasing		
	Permissive Only	Protected-Permissive	Single Lane Protected Only
1	5	5	5
2	5	5	5
3	4	5	5

3.2 Methodology

The study included collection of raw ATSPM data and more conventional tube data collection for 44 signalized intersection approaches to develop an accurate evaluation of the newly developed left turn gap measure. The intersection approaches were selected based on detector and left turn configurations along with the number of opposing through lanes. Each location represented a combination of three left turn phase configurations and three different lane configurations, totaling nine unique intersection approach configurations. It was determined that five locations for each configuration were needed to provide statistically valid results. It was also determined that multiple approaches from the same intersection could be included which may minimize the cost and ease of data collection.

Working with UDOT personnel, several requirements were identified to provide consistency and eliminate potential confounding factors in the data analysis. All intersection approaches included in the sample met the following criteria:

- Connected to the central system at the Traffic Operations Center (TOC)
- Equipped with Radar-type detection with the following detection:
    - Lane-by-Lane Stop Bar Detection
    - Lane-by-Lane Presence Detection
    - Lane Group Presence Detection
        - For permissive and protected locations, only FYA signal head configurations will be considered.
        - All approaches must have data available in the UDOT ATSPM database
- The system had to be active for at least one month prior to data collection

The selection process included three primary steps: first, using available datasets to identify a potential list of approaches; second, a review with UDOT staff to eliminate locations with known issues or complications; and lastly, a review of locations by the data collection team to confirm eligibility. These steps required several iterations to ensure the final list met all requirements. These steps are explained further in the following sections.

3.2.1 Automated Evaluation Using Datasets

With over 2,000 traffic signals in the state of Utah it was important to create a quick method for determining which of these signals met the criteria for selection in this study. As one of the main criteria was the availability of necessary count and stop-bar detection, it was decided that using the detection information from the ATSPM database would allow for a quick evaluation of all signals. For a signal to be in the ATSPM system, the detectors associated with the measures for each movement must be assigned. Based on this, a simple database query provided a list of the detection at each signal along with the purpose of each detector zone.

This list of detection from ATSPM data was then used to create a list of signals with permissive, protected-permissive, and protected left turn phasing. Since each of these left turn phasing configurations required a different detector configuration, queries were used to look for each configuration. For example, a left turn lane with a detector calling the same phase as the through lanes was identified as having permissive left turns. For protected-permissive left turns two detectors were required; one to call the permissive phase and one to call the protected phase. In addition, only left turn lanes with detectors calling the opposing through lanes for the permissive phase were included since this would eliminate five-section signal heads from the list. For protected left turns a single detector which was not calling a through phase was required.

The detector database was also used to identify the number of opposing through lanes at each of the signals. One of the requirements for being included in the sample was the presence of count zones. Since count zones are set up lane-by-lane, this allowed for the determination of the number of lanes for each movement. This also allowed for the removal of any signal with dual left turn lanes from the list.

By cross-referencing these two lists, a list of potential sample signals was created. For ease of review this list was imported into Google Earth and several intersections for each of the configurations were selected. Each of the selected signals was then reviewed to ensure they met all requirements. For configurations where there were several potential signals, the priority was given to signals where multiple approaches could be used while also representing a variety of locations across the Wasatch Front.

3.2.2 Review with UDOT

Once the data was compiled and a preliminary list was created, two reviews were conducted. The first involved sending the list to various UDOT personnel to review and comment. The second was conducted at a Technical Advisory Committee (TAC) meeting where the list was discussed as a team to determine which locations should be included. Through this process additional requirements were established as follows:

- Limit intersection locations to Utah, Salt Lake, Davis, and Weber counties
- Approaches should be generally free of geometry curves which could limit sight distance
- Avoid intersections at or near construction sites
- Avoid intersections where changes are forthcoming (Evaluated based on information provided by region engineers)

- Prioritize intersections with two or more approaches that can be used in the study
- Intersection approaches with dedicated right turn lanes were preferred

3.2.3 Review with Data Collection Team

As a final step, the approaches were reviewed with the data collection team to confirm that the manual data equipment could be installed at or near the stop bar. As tube counters are not typically installed at the stop bar the following criteria were developed.

- Must be able to be anchored within 15 feet of the stop bar
- Must have a securing object on the roadside of pedestrian facilities
- Must be able to cross all target lanes without obstruction

3.3 Initial Location Selection

The initial selection using the automated categorization and filtering was coupled with preliminary feedback from UDOT personnel to produce a list of preliminary sample locations to be reviewed by the project team. These locations are listed in Table 3.2. Each of the approaches in the table was identified as a possible study intersection because they meet the lane configuration, left turn phasing, and detection needs of the study. As shown in the table, between seven and nine approaches were selected for further review. The table also shows that only 4 approaches were identified with a configuration of permissive only with three opposing through lanes. This is due in part to a limited number of intersections with this configuration and the detection requirements not being met at other locations with this configuration. This list represents intersections across all four counties filtered based on feedback from UDOT Region and TOC personnel. This initial list was then reviewed by the project team.

Table 3.2 Initial Data Collection Locations

LT Phasing	Single Opposing Thru		Two Opposing Thru's		Three Opposing Thru's	
	Intersection	# App	Intersection	# App	Intersection	# App
Permissive	*3000 N & Church St (#5155)*	2	Washington & 26th Street (#5017)	2	**Redwood Rd & 10610 S (#7407)**	**2**
	2200 W & 7800 S (#7010)	2	Wasatch Blvd & Bengal (#7829)	1	**400 S & 200 W (#7242)**	**2**
	Redwood Rd & 1575 N (#6081)	1	University Ave & 1450 N (#6416)	2		
	700 W & 9000 S (#7015)	2	2300 E & 9400 S (#7020)	1		
	University Ave & 3300 N (#6420)	2	Palisade & 800 N (#6307)	2		
Protected-Permissive	*Riverdale Rd & 1500 W (#5004)*	2	Washington & 400 N (#5059)	2	*Riverdale Rd & 1500 W (#5004)*	1
	700 E & 1700 S (#7186)	2	2200 W & 7800 S (#7010)	2	*700 E & 1700 S (#7186)*	2
	State St & 1720 N (#6448)	1	Redwood Rd & 1575 N (#6081)	1	**State St & 400 N (#6308)**	**2**
	Main St & Gentile (#5124)	2	Pioneer & 500 W (#6036)	2	*State St & 400 S (#6313)*	2
	State St & 400 S (#6313)	2	900 E & 5600 S (#7204)	2	*700 W & 9000 S (#7015)*	2
Protected Only	*Washington & 400 N (#5059)*	2	3000 N & Church St (#5155)	2	Riverdale Rd & 300 W (#5009)	1
	Van Winkle & Highland Dr (#7214)	1	Wasatch Blvd & 6200 S (#7003)	2	State St & 3300 S (#7155)	2
	Pioneer & Millpond Dr (#6035)	2	Redwood Rd & 1575 N (#6081)	1	*State St & 1720 N (#6448)*	2
	Antelope & 2000 W (#5393)	1	Bangerter & California (#7052)	1	*Pioneer & Millpond Dr (#6035)*	2
	State St & 1720 N (#6448)	1	Orem Blvd & Center St (#6516)	2	**Redwood Rd & 4100 S (#7104)**	**2**

Notes: **Bold –** Contains thru/right lane *Italics* – Intersection fits multiple categories

3.4 Final Location Consideration/Criteria

The list of approaches shown in Table 3.2 includes 72 approaches that were further filtered to arrive at the 44 total approaches included in the final sample. This additional filtering was provided during a review with UDOT personnel and included a discussion about the individual locations as well as additional items to be considered in the selection process. For example:

- Avoid using locations with thru-right turn lanes to eliminate confounding factors
- Interchanges were excluded as traffic patterns may be different from typical intersections
- Any known construction zones or intersections that will be in construction zones during the study were avoided
- Intersections where multiple approaches could be used in the study were prioritized, to provide efficiency. This includes intersections where approaches match different configuration criteria
- Traffic volumes were considered for each intersection. Selected locations required enough traffic to provide a range of gaps, including times with a limited number of gaps. The variation in traffic volume over a given day was also considered
- The posted speed limit was also considered as it may impact the analysis

Five approaches were needed for each of the lane configuration and left turn phasing categories. A total of 44 approaches at 17 intersections were selected for data collection. In addition, five intersections, including seven to nine approaches, were identified to provide backup if needed. The 17 selected intersections are located across the Wasatch Front in the counties as shown:

- Weber County – 3
- Davis County – 1
- Salt Lake County – 7
- Utah County – 6

And into the UDOT Regions:

- Region 1 – 4
- Region 2 – 7
- Region 3 – 6

Additional filtering was conducted on the list by the project team. As part of that review, two intersections were replaced based on the inability to install the equipment safely. The final locations are shown in Table 3.3 below. The table also shows the approaches selected at each intersection and if intersections were used for multiple configurations. Approaches from similar intersections are identified with similar colors. This final list of intersections was used to guide data collection for both the ATSPM and manual tube counter data for comparison in this study.

Table 3.3 Initial Data Collection Locations

Left Turn Phasing	Single Opposing Thru Lane		Two Opposing Thru Lanes		Three Opposing Thru Lanes	
	Intersection	Approach	Intersection	Approach	Intersection	Approach
Permissive	*3000 N & Church St (#5155)*	*NB, SB*	Palisade Drive & 800 N (#6037)	WB, EB	**Redwood Rd & 10610 S (#7407)**	**NB, SB**
	Redwood Rd & 1575 N (#6081)	*EB*	Wasatch Blvd & Bengal (#7829)	SN	**400 S & 200 W (#7242)**	**EB, WB**
	700 W & 9000 S (#7015)	*NB, SB*	University Ave & 1450 N (#6416)	NB, SB		
Protected-Permissive	*Riverdale Rd & 1500 W (#5004)*	*NB, SB*	*Washington & 400 N (#5059)*	*NB, SB*	*Riverdale Rd & 1500 W (#5004)*	*NEB, SWB*
	9000 S & 4000 W (#7421)	*NB*	*9000 S & 4000 W (#7421)*	*EB, WB*	*700 W & 9000 S (#7015)*	*EB*
	State St & 400 S (#6313)	*EB, WB*	*Redwood Rd & 1575 N (#6081)*	*NB*	*State St & 400 S (#6313)*	*NB, SB*
Protected Only	*Washington & 400 N (#5059)*	*EB, WB*	*3000 N & Church St (#5155)*	EB, WB	Riverdale Rd & 300 W (#5009)	NEB
	State St & 1720 N (#6448)	*NEB*	Wasatch Blvd & 6200 S (#7003)	NB, SB	State St & 3300 S (#7155)	NB, SB
	Pioneer & Millpond Dr (#6035)	NB, SB	*Redwood Rd & 1575 N (#6081)*	*SB*	*Pioneer & Millpond Dr (#6035)*	*EB, WB*

Notes: **Bold –** Contains thru/right lane *Italics* – Intersection fits multiple categories

4.0 DATA COLLECTION AND VALIDATION

4.1 Overview

This chapter discusses the data collection methodology for manual and high-resolution datasets for study locations. Additionally, information on observed data quality issues and a discussion on how the issues were addressed are included. As part of the scope of the study, a comparison between field-collected sample gap data and ATSPM high-resolution data was conducted. The field-collected gap data was processed and analyzed based on current gap analysis methods and was aggregated at the same level as the ATSPM data. Once both datasets were processed and aggregated, a complete analysis was performed to compare and validate the automated results against the manual results. The comparison was based on gap availability, duration, and acceptable count.

4.2 Data Collection Methodology

Both field and ATSPM high-resolution data were collected for this study. The methodology for each data collection process is outlined below.

4.2.1 Manual Data

The manual data were collected using Jamar tube counters for 24-hour periods on each of the sample approaches. Tubes were placed at or near the stop bar. This varies from typical placement of tube counters (outside the queuing area) but allows for the best comparison with raw data from ATSPM as the detection zones are generally at the stop bar. A single tube was laid across all lanes to best replicate the data collected lane-by-lane by radar detectors. The data collected was timestamped in seconds from initiation for each axle.

4.2.2 High-Resolution Data

High-resolution data for 48-hour periods on all sample approaches were obtained from the UDOT ATSPM servers. The ATSPM data collection requires one of two types of detection on each opposing approach. Lane-by-lane count detection is preferred, but lane-by-lane presence detection may be used. For this study, only locations with available lane-by-lane count detection were selected. The signal controller tracks all events using standard event codes. Communication from the signal controller to the ATSPM web server was used to automatically log the events to be processed upon request. The controller log events include timestamps for the beginning and end of green, timestamps for the arrival of a through or right-turning vehicle, and the signal ID. Although lane-by-lane count detectors were preferred and used whenever possible, data from both lane-by-lane count detectors and lane-by-lane presence detectors were compiled; the difference between the two is evaluated in later sections of this chapter.

4.3 Data Collection Issues and Corrections

The first stage of data collection using the manual method was conducted on June 16, 2020. For comparison purposes, ATSPM high-resolution data was collected for the same time period. Once data collection for both the automated and manual methods was completed, an initial comparison was conducted. The high-resolution data was consistent with the data collected manually for a majority of the approaches. However, some approaches showed large inconsistencies between the data from the two sources; these approaches were located at Riverdale Road at 1500 West (Signal ID 5004), 400 South at 200 West (Signal ID 6448), and State Street at 1720 North (Signal ID 6448). One common issue at these approaches included overcounting the number of larger gaps, which could potentially represent a problem with the detectors or tubes not capturing all vehicles. There could have been several possible causes for the discrepancies in counting or detecting the vehicles to determine the number of gaps. They include:

- Automated Signal Detection
    - Detection setup with the SmartSensor Matrix software
    - Channel assignment in Click 650 software
    - Channel assignment in ATSPM configuration
    - Intermittent communication between the signal and/or sensor
    - Sensor intermittent functionality
    - Data storage issues

- Manual Tube Detection
    - Loss of power
    - Faulty units
    - Faulty tubes
    - Obstruction to pressure

A review of each possible issue was conducted for all locations where there were inconsistencies between the two count methods. This was done for the automated signal detectors and in as much detail as possible for the pneumatic tubes. Additional information on issues at the individual intersections is discussed in the following subsections.

4.3.1 Riverdale Rd & 1500 West (Signal ID 5004) – Eastbound and Westbound

A comparison of the manual versus automated data indicated that the problem was most likely with the automated system, as the data was inconsistent and limited. A review of the ATSPM configuration showed that the channel allocation did not match that of the rest of the system. Methods for correcting the issues included the following:

- Detectors for both the eastbound and westbound were observed and compared to video but no major issues were found.
- Both detectors were rebooted, this did not show any changes in the Turning Movement Count (TMC) detection on the ATSPM website.
- Further inspection showed that the detector changes in the Click 650 and ATSPM setup were not the same. The detector changes in the Click 650 are shown in Table 4.1. The table shows settings for the original channels, and which channels they were changed to. Updating the detector channels in the ATSPM system corrected the data issues. Correct data was then download and used.

Table 4.1 Signal 5004 Corrections

Movement	Original Channel	Updated Channel
WBL	22	12
WBT Lane 1	23	13
WBT Lane 2	24	25
WBT Lane 3	25	15
WBR	26	16
EBL	36	28
EBT Lane 1	37	29
EBT Lane 2	38	30
EBT Lane 3	39	31
EBR	40	32
NBL	48	42
NBT	49	43
NBR	50	44
SBL	56	52
SBT	57	53
SBR	58	54

4.3.2 Pioneer Crossing & Millpond Dr (Signal ID 6035) – Eastbound

Comparisons of the manual and automated data indicated that the issue most likely was with the automated system as the data was inconsistent and limited. The following methods were used to correct the issues:

- Inspection of the detection showed issues with capturing all the eastbound vehicles.
- The detector was rebooted, and detection of vehicles improved. ATSPM TMC showed a significant increase in eastbound volume (see Figure 4.1). As the historical data was not available as the detectors were not collecting data, new counts for both the automated and manual methods were collected to rectify the data issues.

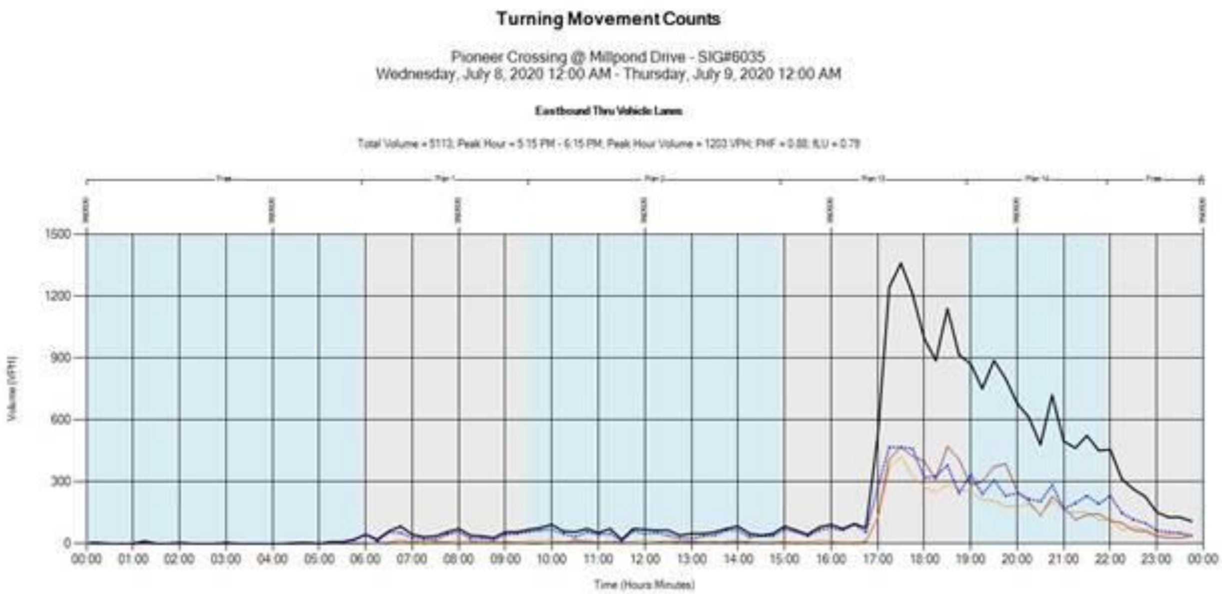


Figure 4.1 Signal data collection reboot

4.3.3 State Street & 400 South, Orem (Signal ID 6313) – Northbound

A comparison of the manual and automated data indicated that the issue most likely was with the manual tube collection, as the data was inconsistent and limited. The following methods were used to correct the issue:

- Detectors for both the eastbound and westbound were observed and compared to video but no major issues were found.
- The detector was rebooted, but this did not result in any major change in the TMC detection on the ATSPM website.
- A review with the data collection team revealed that a possible obstruction or positioning of the tubes could have caused the missing data. Data collection was repeated on site. Additional measures were taken to minimize data issues and provide additional validation:
    - Two tubes were laid covering all lanes with one covering all but one lane. This allowed for verification of obstructions or faulty tubes.
    - Video of the approach at the tube location was collected. This allowed for manual validation of the data collected.

4.3.4 State Street & 1720 North, Orem (Signal ID 6313) – Northbound

A comparison of the manual and automated data indicated that the issue was most likely with the manual tube collection, as the data was inconsistent and limited. The following methods were used to correct the issue:

- Detectors for both eastbound and westbound traffic were observed and compared to video, but no major issues were found.
- The detector was rebooted, this did not identify any major changes in the TMC detection on the ATSPM website.
- A review with the data collection team found possible obstructions or problems positioning the tubes which could have led to missing data. Data collection was repeated, and additional measures were taken to minimize data issues and provide additional validation:
    - Two tubes were laid covering all lanes with one tube covering all but one lane. This allowed for verification of obstructions or faulty tubes.
    - Video of the approach at the tube location was collected. This allowed for manual validation of the data collected.

After the issues were resolved, data collection was repeated for the above-mentioned intersections/approaches. The data collection dates for the finalized datasets are presented in Table 4.2.

Table 4.2 Dates of Data Collection

Intersection	Manual Data Collection Date	ATSPM High-Resolution Data Collection Date
400 South & 200 West	June 16, 2020	June 16-17, 2020
SR-193 (3000 N) & Church Street (Layton)	June 16, 2020	June 16-17, 2020
9000 South & 700 West	June 10, 2020	June 10-11, 2020
9000 South & 4000 West	June 10, 2020	June 10-11, 2020
Redwood Rd & 10610 S	June 10, 2020	June 10-11, 2020
Riverdale Road & 1500 West	June 16, 2020	June 16-17, 2020
Wasatch Blvd & 6200 South	June 16, 2020	June 16-17, 2020
Wasatch Blvd & Bengal	June 16, 2020	June 16-17, 2020
Washington Blvd & 400 North	June 16, 2020	June 16-17, 2020
Pioneer Crossing & Millpond Drive (Westbound, Northbound, and Southbound Approach)	June 18, 2020	June 18-17, 2020
Pioneer Crossing & Millpond Drive (Eastbound)	August 5, 2020	August 5-6, 2020
State Street & 400 S (Eastbound, Westbound and Southbound Approach)	June 18, 2020	June 17-18, 2020
State Street & 400 S (Northbound Approach)	August 6, 2020	August 6-7, 2020
State St & 1720 N (Northbound)	June 18, 2020	June 18-19, 2020
State St & 1720 N (Eastbound)	August 5, 2020	August 5-6, 2020
State St & 3300 S	June 18, 2020	June 18-19, 2020
University & 1450 N	June 18, 2020	June 18-19, 2020
Riverdale Road & 300 West	June 23, 2020	June 23-24, 2020
Palisade & 800 North	June 23, 2020	June 23-24, 2020
Redwood Rd & 1575 North (Northbound Approach)	June 23, 2020	June 23-24, 2020
Redwood Rd & 1575 North (Southbound and Eastbound Approach)	July 1, 2020	July 1-2, 2020

4.4 Analysis of Gap Data

The following subsections describe how the manual and high-resolution data were analyzed followed by a discussion comparing the two datasets using statistical methods and 24-hour distributions of plotted gap data.

4.4.1 Manual Data Analysis

An initial step of processing the tube-collected data, start times (baseline timestamp) of the tube counts on different approaches were adjusted to align with the closest detector on event (Event Code 82 on high-resolution data logger of traffic signal controllers) in the ATSPM high-resolution data. This step was required to accurately compare the manual data to the ATSPM data as the date/time is not collected with high enough accuracy to accurately match. This adjustment was only made for the first record of each approach so as to not affect the gap duration calculations. Timestamps were not used in the calculation for the manual data, but a "duration" field which include a time in seconds for the time of collection. The adjustment to the first timestamp was to eliminate inconsistencies in the "clock" from the various technology.

The high-resolution data was used to develop the start and end points of the "phase green time" by using the signal events for start of green and start of red, respectively. These start and end points were assigned a cycle number that could be used for processing both the manual and high-resolution records. The manual data was assigned to the correct phase number by matching the signal approach phase with the approach assigned by the data collection team. The manual event records were also filtered to only include axle events that occurred during phase green times.

Gaps were calculated for each phase of green time independent of the rest of the data. This process started by determining the difference in seconds from the start of the phase green time to the first axle record. Subsequent gaps were calculated using the difference between axle records assigned to the specific phase green time. Based on the use of axles and not vehicles it was expected that the number of very small gaps would not correlate; however, gaps greater than one second still represented gaps between axles of different vehicles. The last gap was identified by calculating the difference between the final axle record and the start of red. The process was completed for each of the sample approaches and each phase green time for that approach. Each gap was assigned an individual ID, including a signal ID, phase green time ID and gap ID, based on the sequence of occurrence within the green time.

The calculated gaps were aggregated and filtered for various analyses. In the existing online left turn gap analysis metric, the web server calculates the length of each gap and assigns it to one of four user-defined bins. The defaults for these bins are 1 to 3.3 seconds, 3.3 to 3.7 seconds, 3.7 to 7.4 seconds, and greater than 7.4 seconds. To keep the overall analysis consistent with the existing gap analysis tool, the same thresholds and bins were used for the analysis of the manual count data. The manual gaps were filtered and counted at the phase-cycle level based on the bin thresholds and the counts, and the average duration for datasets were then joined by cycle number.

An initial analysis was conducted to match the current ATSPM Left Turn Gap Measure. This included a sample of 6 approaches filtered by the default thresholds of 1, 3.3, 3.7, and 7.4 as set for the ATSPM measure. Filtering all gaps of less than 1 second helped minimize issues within the manual data which collected axle events and not vehicle events, as a large majority of gaps between axles of the same vehicle were shorter than 1 second. Figure 4.2 provides examples of field-collected data, represented similarly to the ATSPM Left Turn Gap Analysis chart. The chart includes counts of gaps within each range as well as the percentage of green time that include gaps of greater than or equal to 7.4 seconds. Similar charts were developed for 5 other approaches and are presented in Appendix A. The color schemes, bins, and thresholds are all the default values as outlined on the ATSPM website. Generally, the 24-hour trends of both the quantity and duration match expectations based on increases and decreases in approach volumes.

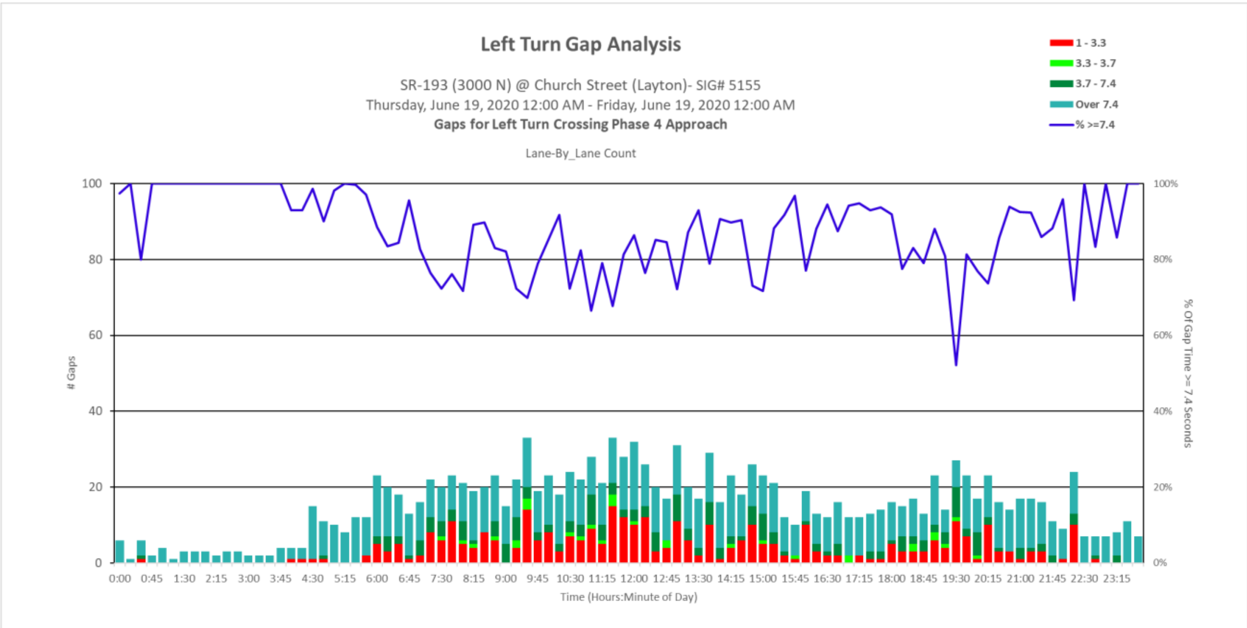


Figure 4.2 Gaps for northbound left turns at SR-193 and Church Street (Permissive/1 Opposing Thru)

4.4.1.1 Summary Statistics and Trends by Intersection Category

Additional analysis was completed to evaluate trends and variation between phase and lane number configuration categories. Using the nine previously defined categories, gaps were aggregated, and summary statistics were calculated. Table 4.3 and Table 4.4 present summary statistics for these nine intersection categories. Summary statistics include the number of gaps, the average duration of each gap, and the standard deviation of the gap length.

For the 24-hour (daily) period shown in Table 4.3, statistics are provided for gaps greater than or equal to 1 second, gaps greater than or equal to 3.7 seconds, and gaps greater than or equal to 7.4 seconds. The average gap duration does not substantially vary between configurations with each filter group, but the variation, as indicated by the standard deviation, has a greater range. This may indicate that location characteristics play a part in gap duration. Additionally, the table shows that average gap duration and standard deviation both increase as the filter threshold increases. This is to be expected as larger gaps are associated with lower volumes that generally arrive more randomly, rather than in the typical platoons.

For the AM peak, Mid-day (MD) peak, and PM peak periods (Table 4.4), the statistics are provided for gaps greater than or equal to 7.4 seconds. While the average gaps for permissive left turns grow with an increase in the number of opposing through lanes, average gaps for protected-permissive left turns stay consistent. The span of variance from 1 to 3 lanes is minimal with 2 lanes generally having the largest difference. This likely indicates that gaps are more consistent and predicable in peak periods.

Table 4.3 Daily Summary Statistics for Manual Gap Data

Approach Configuration	Gaps >=1 sec			Gaps >=3.7 sec			Gaps >=7.4 sec		
	Gap #	Avg	Std Dev	Gap #	Avg	Std Dev	Gap #	Avg	Std Dev
Permissive / 1 Opposing Thru'	9,673	6.1	5.6	5,027	9.7	5.6	3,095	12.4	5.6
Permissive / 2 Opposing Thru'	46,064	7.6	24.4	16,984	17.3	38.3	9,612	26.6	48.9
Permissive / 3 Opposing Thru'	25,693	9.6	21.6	11,708	18.7	29.6	7,259	26.9	35.1
Protected Only / 1 Opposing Thru'	9,871	11.0	28.6	4,709	20.8	39.1	3,271	27.5	45.3
Protected Only / 2 Opposing Thru'	37,012	7.8	27.0	14,879	16.3	41.1	8,503	24.6	52.9
Protected Only / 3 Opposing Thru'	27,567	8.0	14.8	10,549	17.9	20.3	7,132	24.0	22.3
Protected-Permissive / 1 Opposing Thru'	9,869	6.9	7.2	4,942	11.8	7.4	3,465	14.5	7.2
Protected-Permissive / 2 Opposing Thru'	39,794	6.7	14.0	14,550	14.9	20.7	8,558	21.7	24.8
Protected-Permissive / 3 Opposing Thru'	44,839	6.3	13.3	15,057	15.0	20.2	8,537	22.5	24.3

Table 4.4 Peak Period Summary Statistics for Manual Gap Data (Gaps>=7.4 seconds)

Approach Configuration	AM Peak (6:00 AM-9:00 AM)			MD Peak (9:00 AM-3:00 PM)			PM Peak (3:00 PM-6:00 PM)		
	Gap #	Avg	Std Dev	Gap #	Avg	Std Dev	Gap #	Avg	Std Dev
Permissive / 1 Opposing Thru'	1,472	13.9	9.1	3,856	12.7	5.1	1,808	13.1	5.6
Permissive / 2 Opposing Thru'	5,876	21.0	14.4	10,180	16.8	10.8	4,404	17.2	11.1
Permissive / 3 Opposing Thru'	4,000	25.5	19.5	7,812	19.1	13.7	3,988	17.6	11.4
Protected Only / 1 Opposing Thru'	1,568	28.3	28.0	3,496	23.9	20.9	1,684	25.4	20.2
Protected Only / 2 Opposing Thru'	5,228	18.8	11.1	8,964	15.2	7.6	3,888	14.0	6.2
Protected Only / 3 Opposing Thru'	4,032	18.6	10.3	5,388	19.5	11.1	2,128	18.6	9.2
Protected-Permissive / 1 Opposing Thru'	1,816	13.2	5.3	3,640	15.8	8.0	1,756	18.1	8.9
Protected-Permissive / 2 Opposing Thru'	4,520	16.0	9.0	7,056	14.1	7.0	2,692	14.5	7.4
Protected-Permissive / 3 Opposing Thru'	4,996	19.8	17.2	7,576	16.9	9.0	3,332	17.2	10.1

4.4.2 High-Resolution Data Analysis

The analysis of ATSPM high-resolution data involved review of the web-based measure that is available on ATSPM website as "Left Turn Gap Analysis", developing a Microsoft (MS) Access-based tool that replicates the same method of analyzing the data and furthermore, analyzing the trends of gap data based on different lane configuration.

4.4.2.1 Web-Based Measure (GDOT-Developed)

This step of analysis involved a thorough review of the source code of the "Left Turn Gap Analysis" measure developed by GDOT and Kimley-Horn. The research team also met with the GDOT and Kimley-Horn developer team to gain a better understanding of different components of the code. This section summarizes the findings from the review effort conducted by the research team.

The arrival of a through or right-turning vehicle is identified using the "Detector Off" events for the lane-by-lane or stop bar presence detectors. Detector Off events, which are Eventcode 81 on the high-resolution data logger of traffic signal controllers, were used instead of Detector On (Eventcode 82) events or upstream detection zones, because it was determined these would provide the closest timestamp to when each vehicle enters the intersection. By using the Detector Off event for each vehicle, the tool technically calculates headway instead of gap, but the terminology "gap" is used in place of "headway" in both the tool and this subsection.

As part of the existing online measure, the web server calculates the length of each gap and assigns it to one of four user-defined bins. The defaults for these bins are >= 1 <3.3 seconds, >= 3.3 < 3.7 seconds, >= 3.7 < 7.4 seconds, and >= 7.4 seconds. Gaps under 1 second were ignored to avoid cluttering the visual outputs (due to the high number of short gaps), but the user may change the bins to include these small gaps if they choose. The number of gaps per user-defined time period (which defaults to 15 minutes) is charted in a stacked bar chart format with smaller gaps on the bottom and larger gaps on the top. The web server also calculates the percent of green time that is part of a gap greater than or equal to a user-defined threshold. The default for this threshold is 7.4 seconds. This percentage is calculated for the same user-defined time period, as was the number of gaps, and is charted in a line graph format. The line graph is overlaid with the bar chart to create the final figure, an example of which is shown in Figure 4.3.

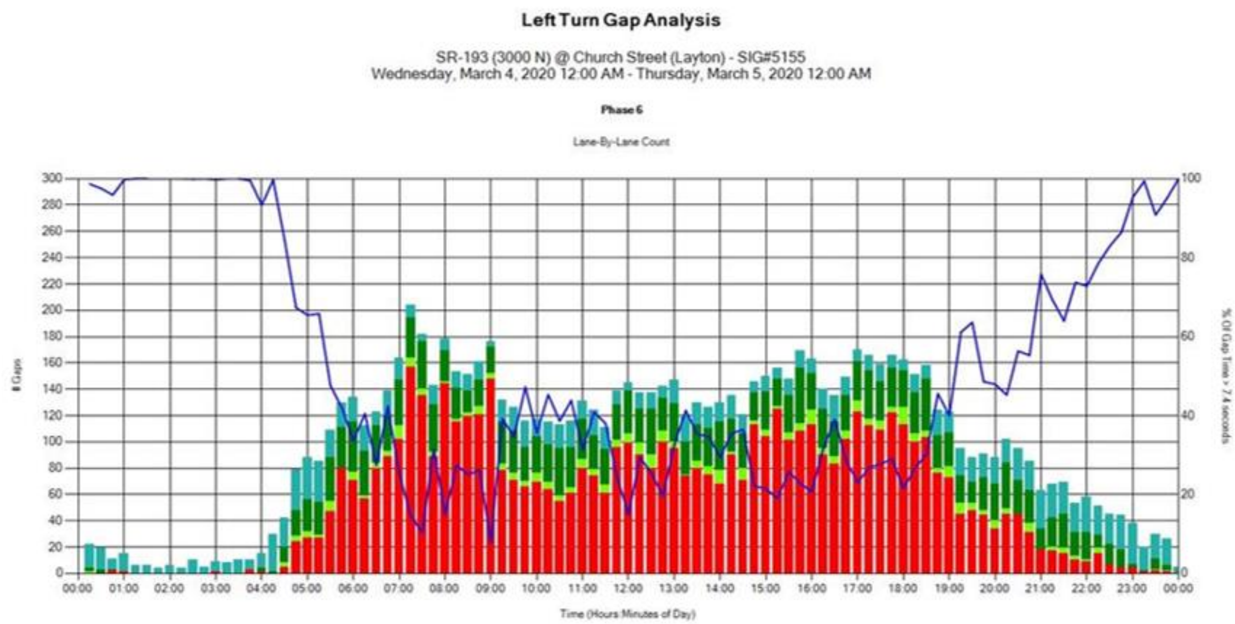


Figure 4.3 Example chart generated from ATSPM website

After examining the C#-based code used in the calculations for general understanding of methods and processes, the following additional information for the current web-based methods was noted.

- Converts the approach phase to opposing through phase to represent the left turn phasing.
- Through, right turn, through-right, and through-left lane types are used.
- The percent of green time displayed is the average of each cycle's percent of green time for large gaps.
- The current version creates a rolling 15-minute aggregate of gap counts based on user-set parameters.

4.4.2.2 MS Access-Based Replication

A replica of the Left Turn Gap Analysis ATSPM methodology was completed using MS Access. The data processes were carefully reviewed with members of the GDOT and Kimley-Horn team, who developed the original tool. The method used both Structured Query Language (SQL) and Visual Basic for Applications (VBA) coding to develop an offline replica of the measure chart.

The high-resolution data was used to develop a "phase green time" start and end point using the signal event for start of green and start of red, respectively. These start and end points were assigned a cycle number that could be used for processing both the manual and high-resolution records. The high-resolution data was assigned a phase by matching the signal approach phase to the detector channels for each movement. The detector event records were filtered to only include Detector Off events within the phase green time and were then assigned to that phase green time.

Gaps were calculated for each phase green time independent from the remainder of the data. This process began by determining the difference in seconds for the start of the phase green time to the first detector record. Subsequent gaps were calculated using the difference between detector records assigned to the specific phase green time. The last gap was calculated using the difference between the final detector record and the start of red. The process was completed for each of the sample approaches and each phase green time for that approach. Each gap was assigned both an individual ID (including the signal ID and phase green time ID) and a gap ID based on the sequence of occurrence within the green time. The gaps were aggregated and filtered for various analyses as described in the results section.

Figure 4.4 contains the same data as shown in Figure 4.3 but was created with the replica tool. Because the ATSPM website currently does not include actual counts, verification between the two figures can only be visual. In both Figure 4.3 and Figure 4.4, the default values for bins and thresholds are used: red bars represent gaps between 1 second and 3.3 seconds, light green bars represent gaps between 3.3 seconds and 3.7 seconds, dark green bars represent gaps between 3.7 seconds and 7.4 seconds, turquoise bars represent gaps greater than or equal to 7.4 seconds, and the dark blue line represents the percent of green time that is part of a gap 7.4 seconds or longer. As shown in the figures, the replicated offline methods were able to exactly duplicate the analysis developed as part of the web-based measure.

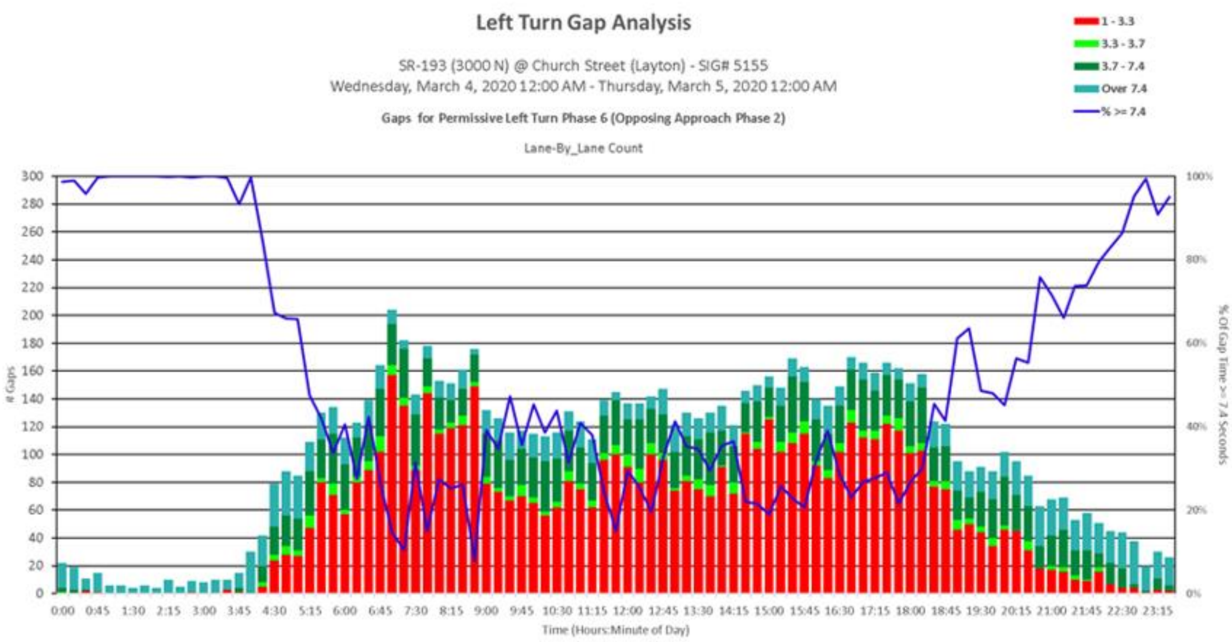


Figure 4.4 Chart generated from data processed with MS Access

Charts similar to Figure 4.4 were developed for 5 more approaches to have a good sample size for the verification of the MS Access-based tool and are included in Appendix B. Generally, the 24-hour distribution of both quantity and duration matched the expectations based on increases and decreases of approach volumes.

4.4.2.3 Summary Statistics and Trends by Intersection Category

Additional analyses were completed to evaluate trends and variation in different configuration categories. Using the nine categories mentioned in Table 3.1, gaps were aggregated, and summary statistics were calculated. Table 4.5 and Table 4.6 present summary statistics for these nine intersection categories. These summary statistics include the number of gaps, the average duration of a gap, and the standard deviation of the gap length.

For the 24-hour (daily) period of the data collection date (shown in Table 4.2), the statistics are provided for gaps greater than or equal to 1 second, gaps greater than or equal to 3.7 seconds, and gaps greater than or equal to 7.4 seconds. For large gaps (gaps greater than or equal to 7.4 seconds), the average gap sizes for approaches with only one opposing through lane were less than half of the average gap sizes for approaches with the same left turn phasing on segments with 2 or 3 opposing lanes. The standard deviations for approaches with only one opposing through lane is also smaller than the standard deviations for approaches with 2 or 3 opposing through lanes. Additionally, the table shows that average gap duration and standard deviation each increase as the filter threshold increases. This is to be expected as larger gaps are associated with lower volumes and arrivals outside the platoons which are more random.

For the AM peak, MD, and PM peak periods (Table 4.6), the statistics are provided for gaps greater than or equal to 7.4 seconds. In general, the gap data looks more similar during the two peak periods than the mid-day period. This indicates that gaps are more consistent and predicable in peak periods where typical analysis is performed. With a few exceptions, the average large gap length ranges between 12 and 17 seconds for all configurations and time periods in the table.

Table 4.5 Daily Summary Statistics for ATSPM Gap Data

Approach Configuration	Gaps >=1 sec			Gaps >=3.7 sec			Gaps >=7.4 sec		
	Gap #	Avg	Std Dev	Gap #	Avg	Std Dev	Gap #	Avg	Std Dev
Permissive / 1 Opposing Thru'	7,077	8.8	6.6	5,428	10.7	6.42	3,431	13.9	6.1
Permissive / 2 Opposing Thru'	50,239	7.3	22.5	19,154	15.8	34.8	9,513	26.5	47.0
Permissive / 3 Opposing Thru'	30,767	8.3	19.7	12,876	16.8	28.3	7,440	25.4	34.8
Protected Only / 1 Opposing Thru'	11,106	6.6	6.1	6,320	9.7	6.5	3,219	14.1	6.6
Protected Only / 2 Opposing Thru'	47,385	5.7	11.5	15,956	13.0	17.6	7,735	21.4	22.4
Protected Only / 3 Opposing Thru'	57,651	5.1	11.5	17,482	12.4	18.9	7,930	21.2	25.4
Protected-Permissive / 1 Opposing Thru'	11,609	5.3	5.4	5,563	8.4	6.5	2,082	14.0	7.9
Protected-Permissive / 2 Opposing Thru'	44,521	6.73	20.4	17,411	13.9	31.3	8,169	23.8	43.6
Protected-Permissive / 3 Opposing Thru'	33,391	7.03	22.9	11,603	16.6	37.1	5,893	27.7	49.6

Table 4.6 Peak Period Summary Statistics for ATSPM Gap Data (Gaps>=7.4 seconds)

Approach Configuration	AM Peak (6:00 AM-9:00 AM)			MD Peak (9:00 AM-3:00 PM)			PM Peak (3:00 PM-6:00 PM)		
	Gap #	Avg	Std Dev	Gap #	Avg	Std Dev	Gap #	Avg	Std Dev
Permissive / 1 Opposing Thru'	477	14.1	5.4	1,159	14.7	6.4	488	15.2	7.4
Permissive / 2 Opposing Thru'	1,527	20.3	15.3	2,588	16.4	10.7	1,078	15.1	9.6
Permissive / 3 Opposing Thru'	1,024	24.9	17.1	2,024	17.3	10.5	953	16.7	8.8
Protected Only / 1 Opposing Thru'	400	12.9	5.3	881	14.7	6.9	428	15.4	7.3
Protected Only / 2 Opposing Thru'	1,056	16.4	10.2	1,634	14.0	7.5	468	14.7	8.3
Protected Only / 3 Opposing Thru'	1,381	15.5	8.7	1,435	12.3	5.0	644	11.9	4.9
Protected-Permissive / 1 Opposing Thru'	273	14.0	6.4	575	15.3	9.6	196	13.4	5.7
Protected-Permissive / 2 Opposing Thru'	1,350	17.2	12.1	1,984	13.4	6.6	909	13.2	5.7
Protected-Permissive / 3 Opposing Thru'	918	24.6	23.3	991	15.8	10.1	498	14.2	8.9

4.5 Comparison of Gap Data

A comparison between field-collected sample gap data and ATSPM high-resolution data was conducted. Although lane-by-lane count detectors were preferred and used for further tool development, data from both lane-by-lane count detectors and lane-by-lane presence detectors were collected for evaluation and comparison of high-resolution data with manual gap data. As mentioned in the previous sections, the field-collected gap data was processed and analyzed based on current gap analysis methods and was aggregated at the same level as the ATSPM data. Once all three datasets were processed and aggregated, a statistical analysis was performed to compare and validate the automated results against the manual results. The comparison was based on gap availability, duration, and acceptable count. The following subsections describe methods used to evaluate any differences in the manual and high-resolution gap data and the results.

4.5.1 Observational Analysis Methodology

In the existing online left turn gap analysis measure, the web server calculates the length of each gap and assigns it to one of four user-defined bins. The defaults for these bins are 1 to 3.3 seconds, 3.3 to 3.7 seconds, 3.7 to 7.4 seconds, and greater than or equal to 7.4 seconds. To keep the overall analysis consistent with the existing gap analysis tool, the default thresholds and bins are maintained throughout different data sources. Gap data collected from three data sources were processed at a Phase Cycle level based on timestamp and each gap was evaluated for duration. The gaps were filtered and counted based on similar thresholds as ATSPM, and the counts and average duration for datasets were then joined by cycle number. For further comparison, standard statistical software and analysis tools (e.g., SPSS, R/RStudio and MS Access) were used to perform a statistical analysis.

4.5.2 Statistical Analysis Methodology

Two statistical tests were used to evaluate the gaps data: a paired samples t-test and analysis of variance (ANOVA). Having a basic knowledge of these tests will aid in understanding the results of the statistical evaluation of the differences in the gaps data.

Paired samples t-tests typically consist of a sample of matched pairs of similar units, or one group of units that has been tested twice (a "repeated measures" t-test). In this case, the pairs are the measurements of each gap collected manually and collected with the high-resolution data. A t-test looks at the t-statistic, the t-distribution, and degrees of freedom to determine the probability of difference between populations (e.g., manual vs ATSPM data collection). The formula used to calculate the test is the ratio shown in Equation 4-1 [11].

$$t = \frac{\bar{X}_D - \mu_0}{s_D/\sqrt{n}} \tag{4-1}$$

Where: $\bar{X}_D$ is the average of the differences between all pairs,

s_D is the standard deviation of the differences between all pairs,

μ_0 is a constant that is zero for this test because the null hypothesis is that the averages of the paired gap measurements are equal, *n* is the number of pairs (the degrees of freedom is equal to *n* – 1), and

t indicates whether a significant difference between the two samples exists (if $t > 1.8$, then a significant difference exists).

The significance value (also known as p) of the test indicates to what level of confidence the significant difference exists. If the p-value is ≤ 0.05, then the difference between the pairs is "significant" with 95% confidence; any *p*-value smaller than 0.05 represents higher confidence in the significance of the test.

ANOVA is a statistical technique that assesses whether the means of several groups are equal. A one-way ANOVA analyzes just one independent variable (e.g., gap duration). The null hypothesis for an ANOVA is that there is no significant difference in the means of the groups. The alternative hypothesis assumes that there is at least one significant difference among the groups. After cleaning the data, the researcher must test the assumptions of ANOVA, then calculate the *F*-ratio and the associated probability value (*p*-value). The one-way ANOVA model is given in Equation 4-2 [11].

$$Y = \mu_i + \varepsilon \tag{4-2}$$

Where: *Y* is the quantitative dependent variable (usually called the response variable in ANOVA)

μ_i is the true mean value of the dependent variable for the i^{th} population, where there are *k* populations.

ε is the random error in the response not attributable to the independent variable. Like in regression models, the error is assumed to be normally distributed with constant variance.

4.6 Manual vs High-Resolution Data Comparison Results

4.6.1 Observation Comparison Analysis

Different observation comparison methods and results are presented in this subsection.

4.6.1.1 Approach 24-Hour Distribution Results

24-hour distributions were prepared to replicate the threshold gaps that are used to display the percent of green time (the line graph) in the current ATSPM left turn gap analysis tool. The default for this threshold is gaps greater than or equal to 7.4 seconds. For each method (i.e., manual tube count, ATSPM count detector, ATSPM presence detector) the number of gaps greater than or equal to 7.4 seconds were summed by hour for all study approaches and plotted against time. Figure 4.5 shows the comparison 24-hour distribution for the eastbound approach at 700 West and 9000 South. The distribution plots show that gaps collected from all data sources follow similar trends throughout the day with ATSPM (both presence and count detector) showing slightly higher values than the manual gap counts. The highest differences are observed during the peak periods when the volumes are higher. Similar comparison was performed on 5 other approaches. Resulting charts are presented in Appendix C. For all the approaches, the manually-collected gap data is closer in value to the lane-by-lane counts than the presence detector.

A few of the approaches seem to have a larger difference in the number of gaps detected by presence detectors, including:

- Redwood Rd & 1575 North (Signal ID 6081)
- 700 West & 9000 South (Signal ID 7015)
- Washington Blvd & 400 North (Signal ID 5059)

This validates the assumption that the lane-by-lane count detectors are more suited for gap analysis than the presence detectors.

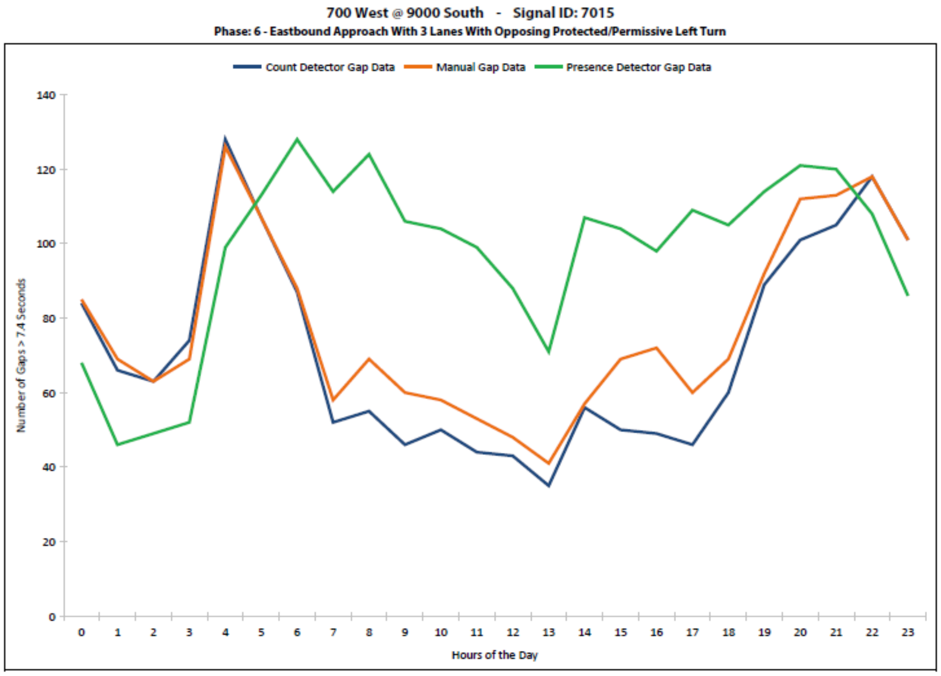


Figure 4.5 Eastbound 700 West @9000 South 24-hour gap count comparison (gap counts >=7.4 seconds)

4.6.1.2 Summary Trends by Intersection Category

Additional analysis was completed to evaluate trends and variation in different configuration categories. For this comparison, only the ATSPM gap values from count detectors were used. Using the nine categories defined previously in Table 3.3, the gaps were aggregated by Cycle ID and the difference between the duration and number of gaps were calculated. Summary statistics include the daily and peak period average of differences in gap counts and duration of gaps, and daily and peak period standard deviation of differences in gap counts and duration of gaps. Figure 4.6 through Figure 4.9 show the plots for daily averages and standard deviations of gaps and gap durations for each approach configuration. The following general trends were observed:

- The average differences in counts decreases as the duration filter increases from 1 to 7.4 seconds, while the duration shows the opposite trend.
- The span of variance of duration from 1 to 3 lanes is minimal with 2 lanes generally having the largest difference.

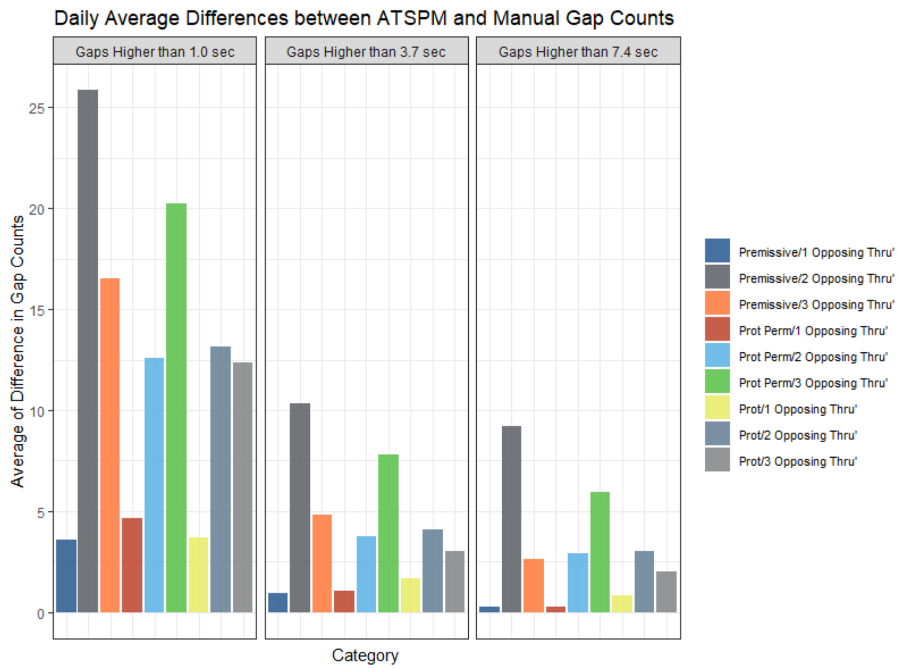


Figure 4.6 Daily average of differences in gap counts

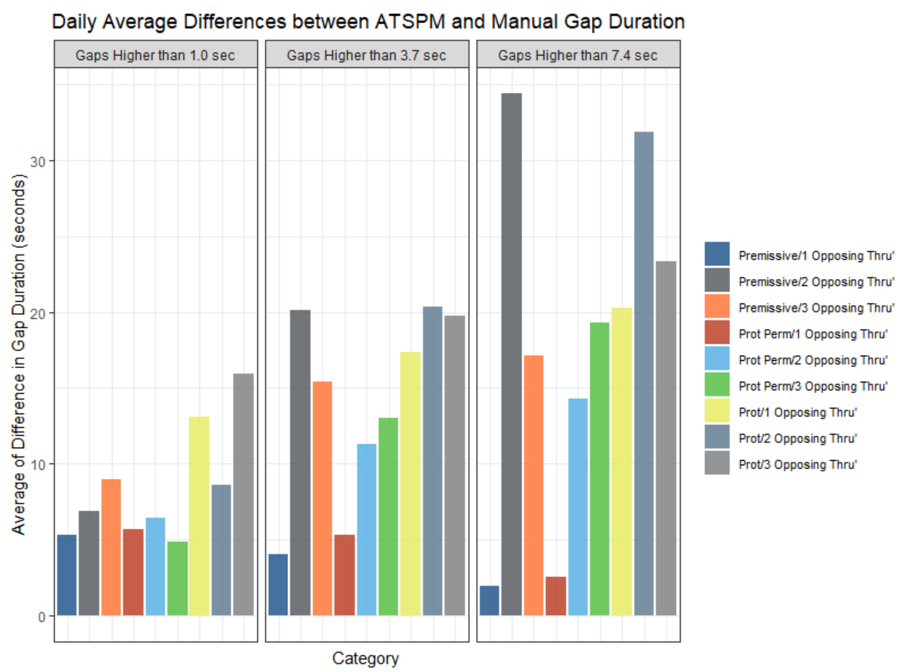


Figure 4.7 Daily average of differences in gap duration (seconds)

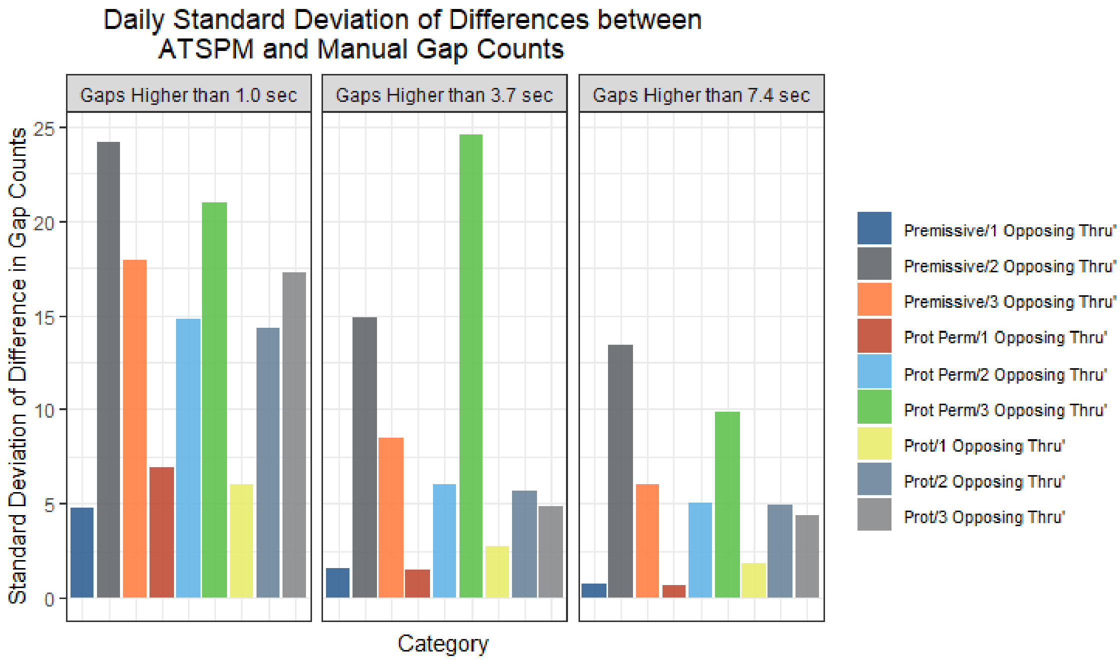


Figure 4.8 Daily standard deviation of differences in gap counts

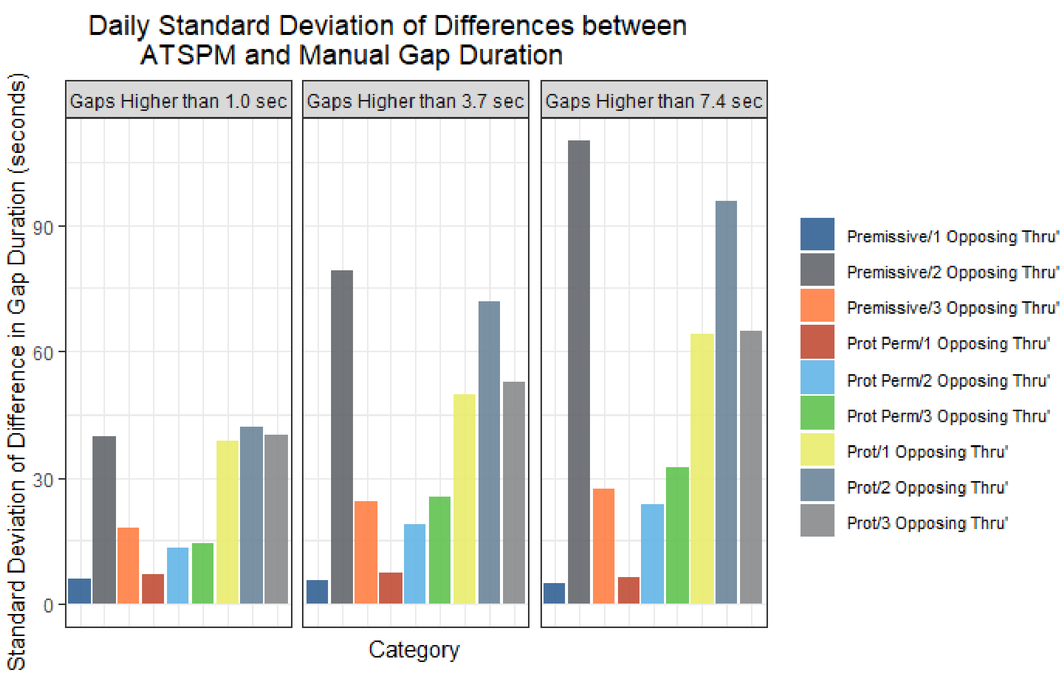


Figure 4.9 Daily standard deviation of differences in gap duration (seconds)

Summary statistics plot for different peak periods were also developed and are included in Appendix D.

4.6.2 Statistical Analysis

Using an independent samples t-test, the duration of gaps was compared between those identified with manual data collection and high-resolution data. The comparison was done for data collected by both presence detector and count detectors. As shown in Table 4.7, overall gap lengths collected manually were significantly shorter than those collected with count detectors (3 seconds). Very short gaps (<1 second) collected manually are significantly shorter (by 0.17 seconds) than those collected with count detectors. Short gaps (1-3.3 seconds) collected manually are significantly shorter (by 0.93 seconds) than those collected with count detectors. Medium gaps (3.3-7.4 seconds) collected manually are significantly longer (by 0.12 seconds) than those collected with count detectors. Realistically these differences, while statistically significant, will not make a substantial difference in any analysis as they are all small fractions of a second. The very small gaps (less than 1 second) are the only gaps that could meaningfully change based on data collection method. Because of this, the analysis described in the following section omits gaps less than 1 second to better identify potential differences in methods without including a large group of gaps that could skew the data.

Table 4.7 Gap Lengths by Data Collection Method: Manual vs ATSPM (Count)

Variable	**Manual**	**ATSPM**	***t***	**Sig.**	**Mean Diff.**	**N**
Gap length (all)	2.90	5.90	-2.23	0.026	-3.00	1,330,996
Gap length (≥1 second)	9.25	8.29	0.32	0.746	0.96	569,831
Gap length (<1 second)	0.22	0.40	-247.00	0.000	-0.17	761,135
Gap length (1-3.3 seconds)	1.80	1.90	-42.60	0.000	-0.93	339,336
Gap length (3.3-7.4 seconds)	4.94	4.81	18.67	0.000	0.12	111,029
Gap length (>7.4 seconds)	32.49	33.19	-0.05	0.962	-0.70	115,466

Table 4.8 Gap Lengths by Data Collection Method: Manual vs ATSPM (Presence)

Variable	Manual	ATSPM	*t*	Sig.	Mean Diff.	N
Gap length (all)	2.23	6.80	-166.90	0.000	-4.56	1,174,218
Gap length (≥1 second)	7.31	8.13	-14.90	0.000	-0.82	393,943
Gap length (<1 second)	0.22	0.41	-182.60	0.000	-0.19	679,275
Gap length (1-3.3 seconds)	1.87	2.06	-73.98	0.000	-0.19	249,024
Gap length (3.3-7.4 seconds)	4.97	5.00	-5.13	0.000	-0.03	121,780
Gap length (>7.4 seconds)	22.71	21.82	7.25	0.000	1.43	124,139

Gap lengths less than 7.4 seconds collected manually are calculated as significantly shorter (by 0.03-0.82 seconds) than those collected with presence detectors. Alternatively, gap lengths over 7.4 seconds collected manually are calculated as significantly longer (by 1.43 seconds) than those collected with presence detectors.

Table 4.9 shows the mean gap duration collected with count detectors for each of the approach configurations (all gaps >1 second). A fixed-effects ANOVA determined that there is a significant difference in mean gap length of the nine approach configuration types (f=189.69, sig.=0.000). The figure below shows these differences visually.

Table 4.9 Gap Duration by Configuration (seconds)

Left Turn Phasing	1 Lane	2 Lanes	3 Lanes
Permissive	7.11	7.24	8.54
Protected-Permissive	6.62	5.93	5.43
Protected Only	5.61	6.96	6.82

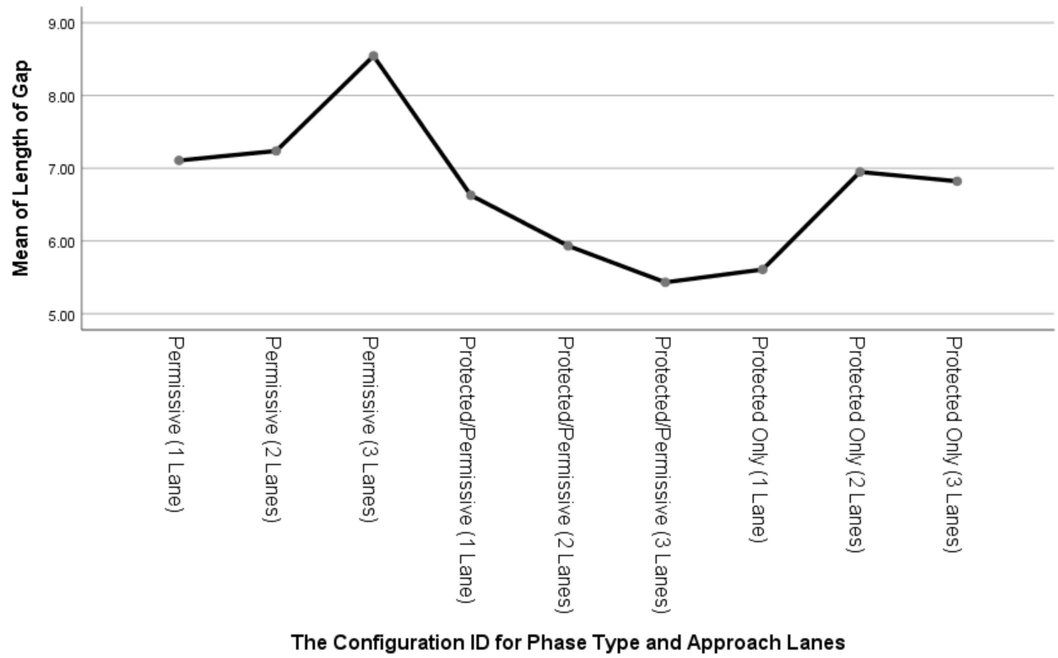


Figure 4.10 Gap duration (seconds) by configuration.

Next, a breakdown was run to determine the percentage of gaps occurring in each category for each configuration type. As the table shows, the majority of gaps were less than 1 second. For most configurations, a majority of measurable gaps were less than 3.3 seconds. However, for permissive one lane approaches gaps were evenly split between 1-3.3 seconds and greater than 7.4 seconds.

Table 4.10 Gaps Lengths by Configuration Type (%)

Gaps (seconds)	1	2	3	4	5	6	7	8	9
<1	36.9	51.2	53.0	52.8	59.0	60.2	54.5	58.3	63.5
1-3.3	22.3	29.3	25.7	20.4	25.8	26.6	22.5	24.1	23.2
3.3-7.4	16.4	10.1	9.5	11.9	7.7	7.2	12.3	9.2	6.2
7.4+	24.3	9.4	11.9	14.9	7.4	6.0	10.6	8.3	7.2
n =	27,143	204,443	125,159	45,264	222,823	271,481	46,680	20,600	184,373

Key: 1- Permissive 1 lane, 2- Permissive 2 lanes, 3- Permissive 3 lanes, 4- Protected-Permissive 1 lane, 5- Protected-Permissive 2 lanes, 6- Protected-Permissive 3 lanes, 7-Protected Only 1 lane, 8- Protected Only 2 lanes, 9- Protected Only 3 lanes

Next, data collection efficacy was examined by time of day. The table below shows results from an independent samples t-test comparing manually collected and gap data from count detectors for each time period. Data collected manually during the mid-day period, PM peak and evening showed gaps that were on average 0.46 seconds longer than gaps identified by ATSPM. A fixed effects ANOVA determined that there is a significant difference in mean gap length by time of day.

Table 4.11 Gaps Lengths by Time of Day (in seconds): Manual vs ATSPM (Count)

Time of Day	Manual	Automated	*t*	Sig.	Mean Diff.	N	
						Manual	ATSPM
Early Morning	29.57	28.58	1.539	0.124	0.987	17,861	18,209
AM Peak	6.20	6.13	1.128	0.259	0.074	37,760	40,464
Mid-Day	4.61	4.14	18.097	0.000	0.474	90,818	109,223
PM Peak	3.98	3.52	15.274	0.000	0.458	51,520	63,794
Evening	7.05	6.59	8.608	0.000	0.459	66,265	73,915

A follow-up independent samples t-test found that gap data collected manually identified significantly shorter gaps than those identified through presence data. The difference in mean measured gap length ranged from 3.7-14.6 seconds.

Table 4.12 Gaps Lengths by Time of Day (seconds): Manual vs ATSPM (Presence)

Time of Day	Manual	Presence	*t*	Sig.	Mean Diff.	N	
						Manual	ATSPM
Early Morning	14.318	28.938	-31.949	0.000	-14.620	37,144	18,495
AM Peak	1.991	6.597	-118.21	0.000	-4.606	127,518	38,582
Mid-Day	1.448	4.724	-202.19	0.000	-3.277	326,270	100,058
PM Peak	1.191	3.933	-151.47	0.000	-2.777	200,535	60,858
Evening	2.467	6.517	-124.39	0.000	-4.049	201,071	76,222

Ratio-based t-tests were utilized to identify any significant difference in the number of manual gap counts versus the number of automated gap counts or presence gap counts for a given scenario. For all measurements, there was a significant difference in the number of gaps identified by manual and automated counters. As shown below, manual counters detected significantly more gaps less than 1 second in length (33% more) and gaps over 7.4 seconds (1.4% more). Alternatively, the manual counters detected significantly fewer gaps 1-7.4 seconds in length (3-10%). For all gaps over 1 second in length, manual counters detected significantly fewer (3.6%) than the automated counters. Overall, manual counters identified approximately 17% more gaps than automated counters.

Table 4.13 Number of Gaps by Gap Length in Seconds: Manual vs ATSPM (Count)

Gap Duration (seconds)	Manual	Automated	*t*	Sig.	Mean Diff.	N Total
<1	82.5%	17.5%	748.2	0.000	0.325	761,135
≥1	46.4%	53.6%	-54.96	0.000	-0.036	569,829
1-3.3	46.7%	53.3%	-38.79	0.000	-0.033	339,336
3.3-7.4	40.4%	59.6%	-66.60	0.000	-0.096	115,029
7.4+	51.4%	48.6%	9.79	0.000	0.014	115,464
All gaps	67.1%	32.9%	418.75	0.000	0.171	1,330,964
N =	892,538	438,426				1,330,964

For all measurements, there was a significant difference in the number of gaps identified by manual and presence counters, with manual counters identifying more gaps. As shown in Table 4.14, manual counters detected significantly more gaps less than 1 second in length (42%

more) and gaps 1-3.3 seconds in length (8.6% more). For critical gaps (3.3 seconds or longer) manual counters detected significantly fewer gaps (2.7-11.3%). For all gaps over 1 second in length, manual counters detected significantly although negligibly fewer (0.1%) gaps than the automated counters. Overall, manual counters identified approximately 17% more gaps than automated counters.

Table 4.14 Number of Gaps by Gap Duration in Seconds: Manual vs ATSPM (Presence)

Gap Duration (seconds)	Manual	ATSPM (Presence)	*t*	Sig.	Mean Diff.	N Total
<1	92.5%	7.5%	1329.62	0.000	0.425	679,275
≥1	50.9%	49.1%	11.991	0.000	0.009	494,943
1-3.3	58.6%	41.4%	86.849	0.000	0.086	249,024
3.3-7.4	38.7%	61.3%	-81.240	0.000	-0.113	121,780
7.4+	47.3%	52.7%	-18.904	0.000	-0.027	124,139
All gaps	75.2%	24.8%	635.975	0.000	0.252	1,186,753
n=	892,538	294,215				1,186,753

Table 4.15 Number of Gaps by Approach Configuration: Manual vs ATSPM (Count)

Time of Day	Manual	ATSPM (Count)	*t*	Sig.	Mean Diff.
Permissive – 1 lane	58.4%	41.6%	22.346	0.000	0.084
Permissive – 2 lanes	48.1%	51.9%	-12.308	0.000	-0.019
Permissive - 3 lanes	45.6%	54.4%	-21.409	0.000	-0.044
Protected-Permissive – 1 lane	47.5%	52.5%	-7.181	0.000	-0.025
Protected-Permissive – 2 lanes	45.9%	54.1%	-24.636	0.000	-0.041
Protected-Permissive – 3 lanes	43.6%	56.4%	-42.472	0.000	-0.064
Protected Only – 1 lane	44.9%	55.1%	-14.933	0.000	-0.051
Protected Only – 2 lanes	45.6%	54.4%	-25.891	0.000	-0.044
Protected Only – 3 lanes	47.6%	52.4%	-12.415	0.000	-0.024

*Excluding gaps less than 1 second.

Evaluating manual versus lane-by-lane count detector gap identification by approach configuration determined that manual counters identify significantly fewer gaps than lane-by-lane count detectors for all approach types except permissive controlled with 1 lane. As shown in Table 4.15, this difference ranges from approximately 2.0%-6.5%.

Evaluating manual versus presence gap identification by approach configuration determined that manual counters identify significantly more gaps than automated counters for all approach types. This difference ranges from approximately 20.4%-34.3%.

Table 4.16 Number of Gaps by Approach Configuration: Manual vs ATSPM (Presence)

Time of Day	Manual	ATSPM (Presence)	*t*	Sig.	Mean Diff.
Permissive – 1 lane	77.5%	22.5%	104.814	0.000	0.275
Permissive – 2 lanes	71.4%	28.6%	206.911	0.000	0.214
Permissive - 3 lanes	70.4%	29.6%	152.530	0.000	0.204
Protected-Permissive – 1 lane	83.3%	16.7%	172.28	0.000	0.333
Protected-Permissive – 2 lanes	81.0%	19.0%	346.138	0.000	0.310
Protected-Permissive – 3 lanes	72.4%	27.6%	238.648	0.000	0.224
Protected Only – 1 lane	84.3%	15.7%	187.935	0.000	0.343
Protected Only – 2 lanes	73.1%	26.9%	231.520	0.000	0.231
Protected Only – 3 lanes	78.3%	21.7%	275.798	0.000	0.283

An examination of manual versus automated gap identification by time of day determined that manual counters identify significantly fewer gaps than automated counters for all time periods except early morning. This difference is up to 5% during the PM peak.

Table 4.17 Number of Gaps by Time of Day: Manual vs ATSPM (Count)

Time of Day	Manual	ATSPM (Count)	*t*	Sig.	Mean Diff.	N	
						Manual	ATSPM (Count)
Early Morning	49.5%	50.5%	-1.832	0.067	-0.005	17,861	182,209
AM Peak	48.3%	51.7%	-9.674	0.000	-0.017	37,760	40,464
Mid-Day	45.4%	54.6%	-41.326	0.000	-0.046	90,818	109,223
PM Peak	44.7%	55.3%	-36.351	0.000	-0.053	51,520	63,794
Evening	47.3%	52.7%	-20.463	0.000	-0.027	66,265	73,915

*Excluding gaps less than 1 second.

An examination of manual versus presence gap identification by time of day, determined that manual counters identify significantly more gaps than automated counters for all time periods. This difference ranges from 16.8%-26.8%.

Table 4.18 Number of Gaps by Time of Day: Manual vs ATSPM (Presence)

Time of Day	Manual	ATSPM (Presence)	*t*	Sig.	Mean Diff.	N	
						Manual	ATSPM (Presence)
Early Morning	66.8%	33.2%	83.915	0.000	0.168	37,144	18,495
AM Peak	76.8%	23.2%	258.376	0.000	0.268	127,518	38,582
Mid-Day	76.5%	23.5%	408.736	0.000	0.265	326,328	100,058
PM Peak	76.7%	23.3%	323.212	0.000	0.267	200,535	60,858
Evening	72.5%	27.5%	265.527	0.000	0.225	201,071	76,222

*Excluding gaps less than 1 second.

Overall, while the differences in gap estimation for the length of gaps is not operationally impactful, the number of gaps identified by each method differs significantly. It warrants exploration to determine why the number of identified gaps differs so widely between the manual, automated, and presence data collection methods.

4.7 Summary

A comparison between field-collected sample gap data and ATSPM high-resolution data was conducted to validate the accuracy of the left turn gap analysis measure in the ATSPM website. To keep overall analysis consistent with the existing gap analysis tool, the field-collected gap data was processed and analyzed based on current gap analysis methods and was aggregated at the same level as the ATSPM data. Once both datasets were processed and aggregated, a complete analysis was performed to compare and validate the automated results against the manual results. The comparison was based on gap availability, duration, and acceptable count. The following list summarizes the findings:

- For both the manual and high-resolution data, generally, the 24-hour distribution of both quantity and duration matched the expectations based on increases and decreases of approach volumes. Although the number of gaps varied between manually collected data and ATSPM high-resolution data, the general trend of gap duration across different configurations remained the same. A 24-hour trend analysis of gap data (both manual and high-resolution) showed a steady average gap duration between different lane configurations. The variation, as indicated by the standard deviation, had a greater range for manual data than for high-resolution data.

- The observational comparison between different datasets show that gaps collected from all data sources follow similar trends throughout the day with ATSPM (both presence and count detector) showing slightly higher values than the manual gap counts. The highest differences are observed during the peak periods when the volumes are higher.

- Detailed statistical analysis indicated that overall, gap lengths collected manually were significantly shorter (by 3 seconds) than those collected with count detectors. Very short gaps (<1 second) collected manually are significantly shorter (by 0.17 seconds) than those collected with count detectors. Short gaps (1-3.3 seconds) collected manually are significantly shorter (by 0.93 seconds) than those collected with count detectors. Medium gaps (3.3-7.4 seconds) collected manually are significantly longer (by 0.12 seconds) than those collected with count detectors. Realistically these differences, while statistically significant, will not make a substantial difference in any analysis as they are all small fractions of a second.

5.0 GAP DATA EVALUATION: POTENTIAL AUTOMATED MEASURES

5.1 Overview

As part of the study, an evaluation was completed examining several automated measures that could potentially be used in conjunction with the gap analysis to determine needs for left turn phasing. Three criteria were used to determine if each measure warranted further review: (1) Can it be developed using high-resolution signal controller data; (2) Does it provide data to highlight potential left turn phasing issues; and (3) Can it provide data or decision criteria for left turn phasing? As these are designed to be automated measures with minimal or no additional data collection, the capacity to be developed from the high-resolution data was evaluated as pass or fail. If either of the other criteria was then met, they were considered for further review. Nine measures were evaluated for their potential application for left turn phasing analysis:

- Critical Headway (Gap)
- Green Time Usage Distribution
- Phase Gap Out Rate
- Vehicle Approach Speeds
- Split Fail
- Turning Movement Counts (Left and Opposing)
- Saturation Flowrate
- Pedestrian Actuations
- Queue Discharge

This chapter provides an evaluation of each of the nine measures. Each evaluation includes a brief description, the methodology to create the measure, example outputs, and any potential applications. The final section in this chapter includes a summary of the results.

5.2 Potential Automated Measures

The preliminary evaluations found that all nine measures could be developed from the high-resolution data except for critical headway, which required some additional data. Even though a measure could be developed, some of the measures did not warrant further evaluation in this study based on their projected use in evaluating the need for left turn phasing. Following this section will be a summary of the findings and a table consolidating the results.

5.2.1 Critical Headway

One measure that will be essential in determining left turn phasing needs at signalized intersections is the amount of time required for left turn vehicles to perform a left turn maneuver, also called the critical gap. This measure was developed for each approach of each study intersection and shows the minimum gaps/headways between oncoming traffic at which permissive left turns can safely complete their turning movement.

Part of identifying a methodology for calculating the critical gap at a study intersection included reviewing gap thresholds determined by research at BYU [7] and calculated values. For the calculated values, three methods were reviewed: gap calculations provided by the American Association for State Highway and Transportation Officials (AASHTO), gap calculations provided in the *Highway Capacity Manual* (HCM), and values calculated using vehicle acceleration rates and the distance vehicles must travel.

The research study by BYU [7] focused on evaluating the safety and operational differences between three left turn treatments: permissive, protected, and protected-permissive left turn phasing. The safety analysis involved using VISSIM traffic modeling software to analyze conflicts and determine what value of accepted gap time best approximates actual driving conditions. Derived safe time gaps for different intersection types and signal configurations from the simulation runs are presented in Table 5.1. The values in the table show little variation in the safe time gaps at different intersection configurations. It is important to note that the simulations in the study were conducted for a limited combination of left turn and through volumes. Moreover, the approaches in the model were all configured to operate at a speed of 35 MPH, and the cycle lengths were the same for all signals. In a real-life scenario, the variation in vehicle speed and the aggressiveness of drivers not captured by the simulation could have a major influence on safe left turn decision-making.

Table 5.1 Safe Time Gaps (in seconds) Based on Simulation

Configuration		Time Gap (seconds)
1-Lane	Permissive	3.3
	Protected-Permissive	3.5
2-Lane	Permissive	3.6
	Protected-Permissive	3.5
3-Lane	Permissive	3.7
	Protected-Permissive	3.7

The first of three methods of calculating the critical gap were based on tables and equations in the HCM [12]. For each study approach, the intersection and traffic characteristics were used alongside some adjustments to the equations to make them pertinent to signalized intersections. For example, the grade factor and intersection geometry were removed because they are only applicable to minor movements at unsignalized intersections. The adapted HCM equation for the left turn critical gap is given in Equation 5-1.

$$t_{c,x} = t_{c,base} + t_{c,HV} P_{HV} \tag{5-1}$$

Where: $t_{c,x}$ is the critical headway for left turns (in seconds),

$t_{c,base}$ is the base critical headway found in Exhibit 20-12 [12],

$t_{c,HV}$ is the adjustment factor for heavy vehicles (1.0 for major streets with one lane in each direction; 2.0 for major streets with two or three lanes in each direction, and

P_{HV} is the proportion of heavy vehicles.

The second of the three methods involved extracting time gaps from Table 9-13 in the 2011 AASHTO Green Book [13].These gaps are used for developing intersection sight distances for left turns at signalized intersections. The time gaps (in seconds) for passenger cars, single unit trucks, and combination trucks were derived based on the number of opposing lanes at the intersection.

The third of the three methods used the Unguren equation [14]. This equation is generally used as a starting point for developing signal timing plans for continuous flow intersections (CFI). The equation is an estimate of potential split time (green time plus yellow time plus all-red time) for CFI left turns based on distances and roadway speeds. The portion of the equation that was particularly helpful was the travel time required for the left turns to clear the intersection based on the crossing distance. The adapted equation for the critical gap for left turns is given in Equation 5-2:

$$Critical\ Gap = \sqrt{\frac{2d_1}{a}} + PRT \quad (5\text{-}2)$$

Where d_1 is the left turn crossing distance (in feet),

a is the acceleration (usually around 7 ft^2/sec), and

PRT is the driver perception reaction time (usually 2.0 seconds)

Overall, the critical gap values from the different methods are similar to each other for the various intersection configurations. Four example calculations are given in Table 5.2. In general, the values calculated using the HCM are the lowest in the group and range from 4.1 to 5.7 seconds for the study approaches. Values calculated based on the Green Book are the highest (ranging from 5.5 to 6.5 seconds for passenger cars). These results are intuitive considering that the values are coming from a design manual where guidelines are expected to be more conservative. The values calculated with the Unguren equation fall between the values from the HCM and the Green Book. In any case, the maximum difference between the highest and lowest values for the critical gap for any given approach was found to be 2.2 seconds.

Table 5.2 Example Critical Headway Calculations

Signal ID	Approach Name	# of Lanes	Speed (mph)	Critical Headway (seconds)				
				HCM	Unguren Equation	Green Book		
						Passenger Car	Single Truck	Combo Truck
7242	Eastbound	3	30	5.5	5.9	6.5	7.9	8.9
7242	Westbound	3	30	5.5	5.9	6.5	7.9	8.9
5155	Eastbound	3	55	4.3	5.2	6.5	7.9	8.9
5155	Westbound	1	55	4.3	5.2	5.5	6.5	7.5

Although this measure requires data not provided by ATSPMs, it is very useful since it defines what conditions are necessary for a vehicle to make a permissive left turn. If there are not enough critical gaps to serve the left turn demand, then that approach can be flagged as needing left turn phasing adjustments.

5.2.2 Green Time Usage

Another potentially useful measure related to determining left turn phasing needs is the green time usage. Green time usage refers to the distribution of vehicles over time served during a green phase. This measure uses the count detectors and green and yellow duration of the phase cycles to determine how many seconds after the green phase began each vehicle was served. Cycles in a given time period (e.g., AM, mid-day, PM) can be combined to show the average trends of a timing plan. For example, Figure 5.1 shows the distribution of vehicles served in 1-second bins in the PM periods for the signal at State Street and 400 South in Orem.

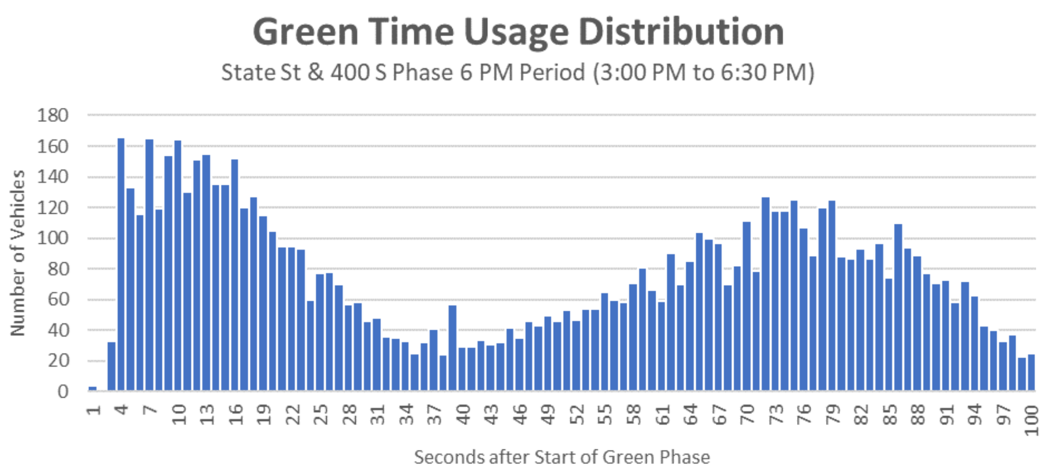


Figure 5.1 Example green time distribution

This measure can provide better understanding of how vehicles are served in the opposing through phase and can provide insights into complaints related to left turns. For example, the PM period shown in Figure 5.1 may have enough total gaps to serve the entire left turn demand, but only if the left-turning vehicles arrive at the beginning or early middle of green. If most left-turning vehicles approach the signal near the end of the green phase, there may not be enough gaps at that point to serve them all. This measure can be reviewed to see if further investigation into vehicle arrival times at the intersections should be performed before considering left turn phasing.

5.2.3 Phase Gap Out Rate

The phase gap out rate is the percent of phases in a given period that end with a gap out. For example, Figure 5.2 shows the results of the Split Monitor measure on the ATSPM website for the signal at State Street and 400 South including the phase gap out rate which is displayed in green text for each timing plan shown. The phase gap out rate could be helpful in determining left turn phasing needs. The signal controller at an intersection records the method of each phase termination—phases end with either a gap out or a force off (or a max out when the signal is running free), and gap outs occur when a phase does not receive a detector call for a specified length of time (usually between 1 to 2 seconds) which triggers the start of yellow.

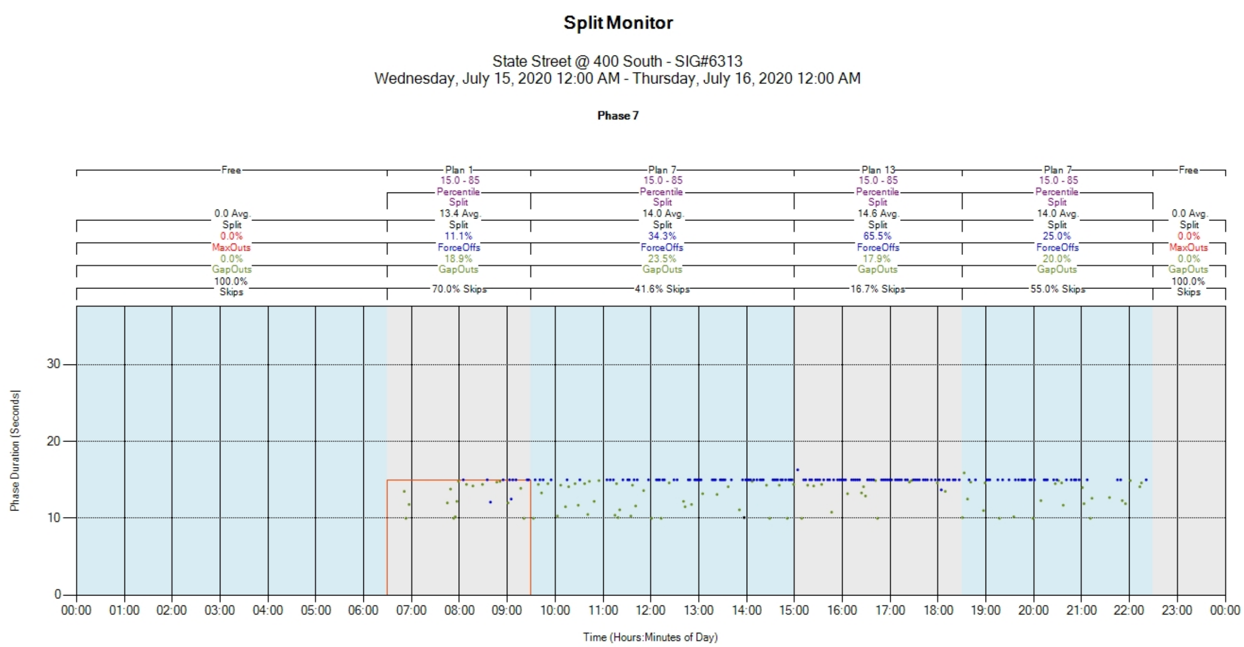


Figure 5.2 Example phase gap out results in ATSPM split monitor measure

Reviewing the phase gap out rate can provide two options for further insight. If complaints are received about protected left turn movements being cut short, the gap out rate of that phase can be reviewed to see if perhaps there is a detection issue at the intersection that does not detect vehicles in the left turn queue. On the other hand, if complaints are received about permissive left turns, the gap out rate of the opposing through movement can be reviewed to see if a lack of through volume triggers the phase to end prematurely. This can be useful information and may lead to a longer minimum split time or a dedicated left turn phase.

5.2.4 Vehicle Approach Speed

Another potentially helpful measure is the vehicle approach speed. At intersections equipped with radar advanced detection, the detector records and reports the speeds of approaching vehicles that arrive on green. The Approach Speed measure on the ATSPM website can then display a graph of the 85th percentile, average, and 15th percentile speeds over a selected time period. For example, the blue line in Figure 5.3 shows the 85th percentile speed of vehicles on the eastbound through approach at Pioneer Crossing and Millpond Drive.

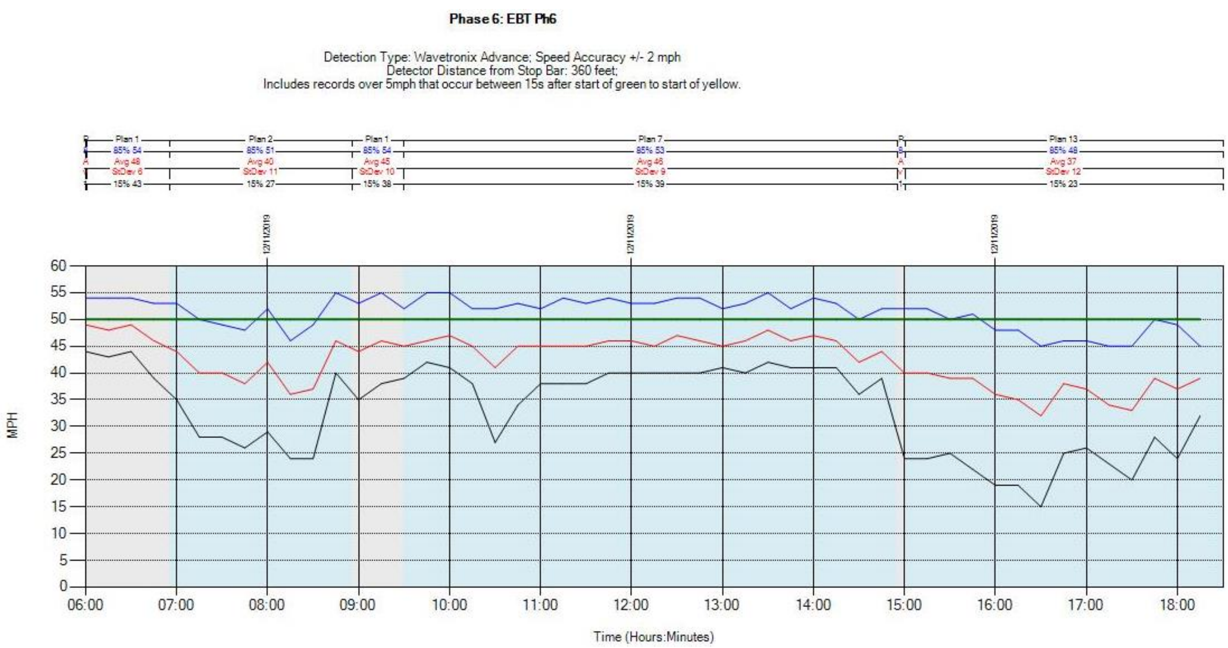


Figure 5.3 Example of approach speed measure in ATSPM .

This measure is helpful because the vehicle speeds of the opposing through movement are considered in the current UDOT left turn guidelines, particularly to flag locations where higher speeds might make it advisable to consider protected only left turn phasing. In addition, the speeds collected could be used to calculate required sight distance and the critical headway for the left turn movement.

5.2.5 Split Failures

The split failure rate may also be helpful in determining left turn phasing needs. At signalized intersections, split failures occur when the provided green time is not enough to serve all vehicles in the queue, thus causing one or more vehicles to wait until the next green phase before being served. The Purdue Split Failure tool on the ATSPM website uses the occupancy ratios of the stop bar detectors to determine whether a split failure occurred. A high occupancy ratio during the green phase indicates that there was a queue of vehicles in the lane for the duration of the phase. A high occupancy ratio during the first five seconds of red indicates that there were vehicles waiting at or near the stop bar when the light turned red. If the occupancy ratios of both the green phase and the first five seconds of red are high (i.e., 80% or greater per the current accepted methodology developed by Purdue University), then that phase is flagged as having a split failure. For example, the green and red lines in Figure 5.4 indicate the occupancy ratios for the green and red phases, respectively, while the yellow lines indicate split failures that occurred on the eastbound left permissive phase at Redwood Road and 1575 North.

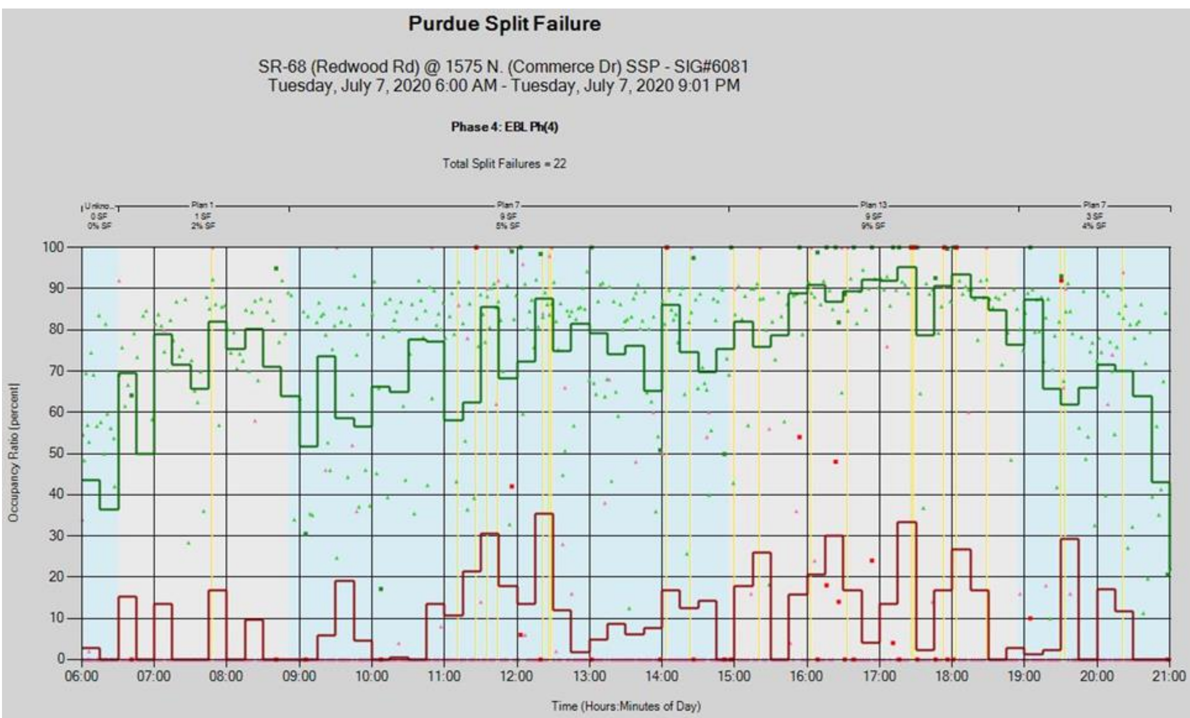


Figure 5.4 Example of Purdue split failure measure

This measure is helpful because a high proportion of split failures at a permissive left turn phase may indicate that there are not enough acceptable gaps in the opposing through traffic. It may also indicate a high volume of left-turning vehicles which might benefit from introducing (or lengthening) a protected phase.

5.2.6 Turning Movement Count (TMC)

Another potentially helpful measure is the Turning Movement Count (TMC). The number of vehicles entering the intersection is collected with lane-by-lane detectors located a few feet beyond the stop bar. These counts are then summed by 15-minute periods. The TMC measure on the ATSPM website provides the exact volumes per movement in a table, some columns of which can be combined to create charts comparing left turn volume versus opposing volume. For example, Figure 5.5 shows a chart of the northbound through and right-turning volume compared to that of the southbound left-turning volume over a 24-hour period at Washington Blvd and 400 North.

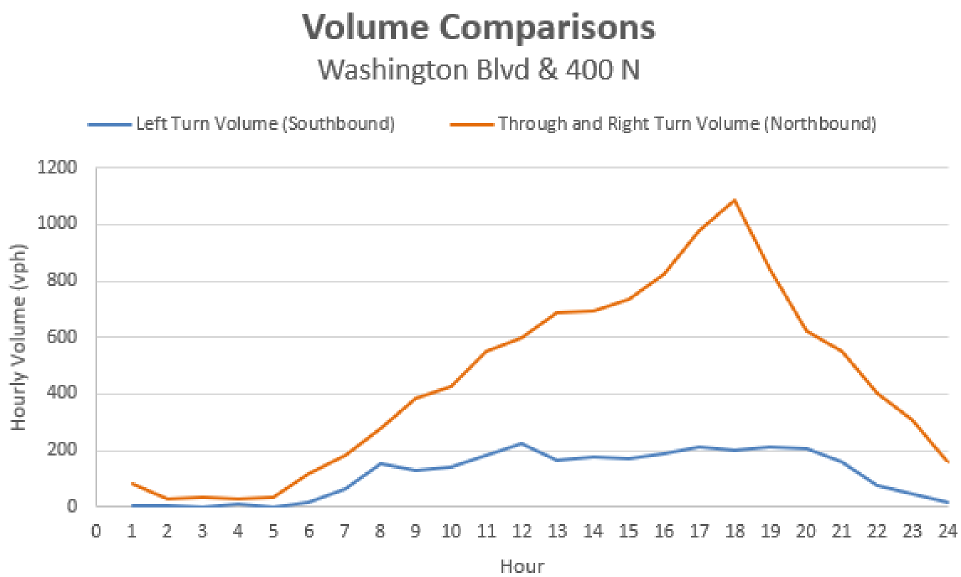


Figure 5.5 Example of turning movement count comparison

This measure is helpful because the number of vehicles making left turn movements is a key measure when determining the need for left turn phasing at an intersection. Moreover, the current main measures in the UDOT guidelines for left turn phases at signalized intersections require knowledge of the left turn volume. The left turn volumes that come from this measure can be compared to the opposing through volume and also to the number of available gaps, thus providing insights into when protected left turn phasing should be introduced or lengthened.

5.2.7 Saturation Flow Rate

The saturation flow rate may also be helpful in understanding left turn phasing needs. At a signalized intersection, the saturation flow rate is a measure of the maximum volume of vehicles that could drive through the intersection assuming each lane could flow without interruption. It is typically expressed as the number of vehicles per hour green per lane. For a true saturation flow rate to be calculated, it is necessary to know how many vehicles were in the queue at the start of green so that only flow rates while the queue is dissipating are considered. Currently, the number of vehicles in the queue at the start of green cannot be determined using the data provided by ATSPMs. However, the saturation flow rate can be estimated using the vehicle headways in the ATSPM high-resolution data. For this estimate, the headways in each lane during a given time period are rounded down to the nearest integer and tallied for each headway duration. The cumulative count for each possible headway duration is calculated along with the cumulative percent. The relative slope between increasing headway durations is then calculated (slope units are percent per second), and an average headway duration is calculated using all the headway durations with a slope greater than 3 percent per second. This average headway is inverted to get the frequency and is then multiplied by 3600 sec/hr to get the number of vehicles per hour green for each lane (the saturation flow rate estimate). For example, the headway duration counts, cumulative percent, and slope calculations for phase 2 at State Street and 400 South are given in Table 5.3. The lowest slope value exceeding 3.0 is highlighted for each lane. For lane one, all headways 6 seconds or shorter are used to calculate the saturation flow rate given in Table 5.4.

Table 5.3 Example Calculations for Saturation Flow Rate Estimate

	Headway Length (sec)	0	1	2	3	4	5	6	7	8	9	10
Lane 1	Count	158	988	2,357	1,576	890	540	263	234	180	119	94
	Cumulative	158	1,146	3,503	5,079	5,969	6,509	6,772	7,006	7,186	7,305	7,399
	%	2%	14%	42%	62%	72%	79%	82%	85%	87%	89%	90%
	Slope	-	12	28.6	19.1	10.8	6.6	3.2	2.8	2.2	1.4	1.1
Lane 2	Count	19	589	1,303	1,038	652	452	271	267	163	128	113
	Cumulative	19	608	1,911	2,949	3,601	4,053	4,324	4,591	4,754	4,882	4,995
	%	0%	10%	32%	49%	60%	68%	72%	77%	79%	82%	83%
	Slope	-	9.8	21.8	17.4	10.9	7.6	4.5	4.5	2.7	2.1	1.9
Lane 3	Count	19	378	1,366	1,078	668	456	317	216	177	133	103
	Cumulative	19	397	1,763	2,841	3,509	3,965	4,282	4,498	4,675	4,808	4,911
	%	0%	7%	30%	49%	60%	68%	74%	77%	80%	83%	84%
	Slope	-	6.5	23.5	18.5	11.5	7.8	5.4	3.7	3	2.3	1.8

Table 5.4 Example Results of Saturation Flow Rate Estimate

State Street & Orem 400 South (SigID 6313)					
		Lane 1	Lane 2	Lane 3	Total
Phase 2	Cutoff (sec)	6	7	8	-
	Average Headway after cutoff (sec)	2.70	3.20	3.45	-
	Saturation Flow Rate (vphg)	1,335	1,126	1,044	3,504

Time periods with a higher saturation flow rate indicate heavier traffic flow at the intersection opposing left-turning traffic. Moreover, high saturation flow rates can be linked with intersections or time periods where little to no acceptable gaps are available for left-turning vehicles during a permissive phase. However, this measure is complex compared to the other measures and may not provide additional value beyond TMC.

5.2.8 Pedestrian Actuation

Another potentially useful measure is pedestrian actuations. During permissive phases, left-turning vehicles must yield not only to vehicles in the oncoming through lanes, but also to pedestrians in the crosswalk. Because of this, gaps in the opposing through vehicle traffic may not be useable by left-turning vehicles. The signal controller records which cycles had an actuation of the pedestrian pushbutton. This measure compares the green time from cycles with a pedestrian actuation versus the total green time in a given time period. It would be ideal to use the time when the crosswalk is occupied by a pedestrian as the measure of time; however, pedestrian count detectors are not installed in crosswalks which means the exact time a pedestrian is crossing is impossible to determine without on-site video or in person surveillance. An example output of this measure is given in Table 5.5 which presents the percent of green time in the given period that had pedestrian activity on the east leg crosswalk (phase 2) at State Street and 400 South. Another way to use the output of this measure is shown in Figure 5.6. In this chart, the number of gaps in opposing through traffic is overlaid with the pedestrian actuation data to show the number of gaps in the PM peak period potentially affected by pedestrian activity.

Table 5.5 Example of Pedestrian Actuations Results

Peak Period	**Total Green Time (minutes)**	**Green Time with Ped Actuation (minutes)**	**% of Green Time with Ped Actuations**
AM Period (6:30 AM- 9:15 AM)	2,863	86	3.0%
MD Period (9:15 AM- 3:00 PM)	10,235	450	4.4%
PM Period (3:00 PM- 6:00 PM)	9,071	856	9.4%

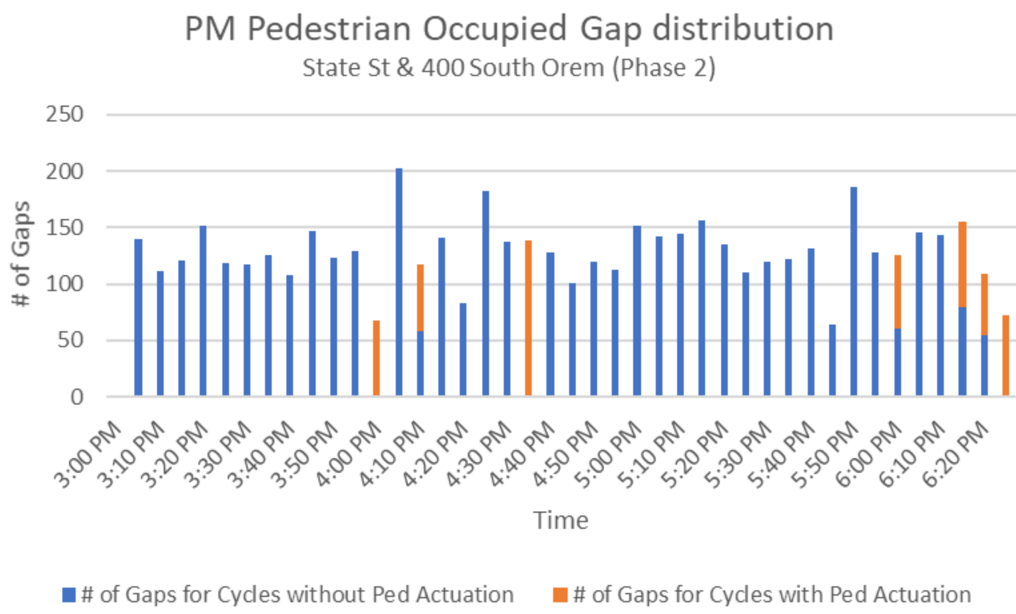


Figure 5.6 Example comparison of available gaps versus pedestrian actuations

This measure is helpful because an understanding of when pedestrians are using the crosswalk can provide insights into limitations on left turn gap acceptance. In conjunction with the number of acceptable gaps and left turn volumes, understanding if complaints about left turns are related to pedestrian activity can help to identify locations where changes to the left turn phasing may be appropriate.

5.2.9 Queue Discharge

One last measure that could be useful in determining left turn phasing needs is the queue discharge. This measure identifies changes to the headway during the process of discharging the queue, or moving vehicles through the intersection. There are two potential ways of analyzing the headways during the queue discharge. The first method is to average the headways (in seconds) based on their position in the queue. An example of the results from this method is given in Figure 5.7 where the headways found in phase 2 at State Street and 400 South are plotted against their position in the queue. The second method is to average the headways based on the number of seconds that have passed since the start of the green phase. An example of the results from this second method is given in Figure 5.8 where headways occurring within 5-second bins are grouped together.

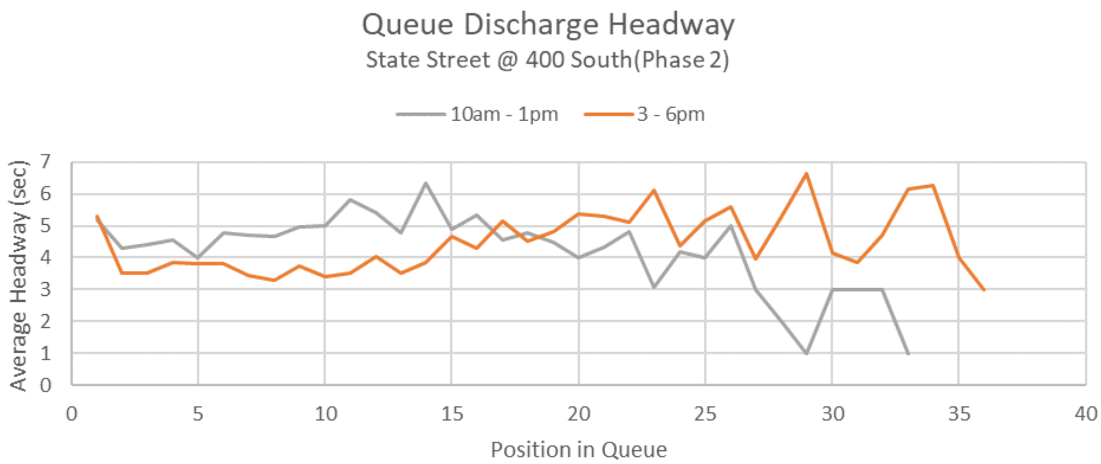


Figure 5.7 Example queue discharge results based on vehicle position in queue

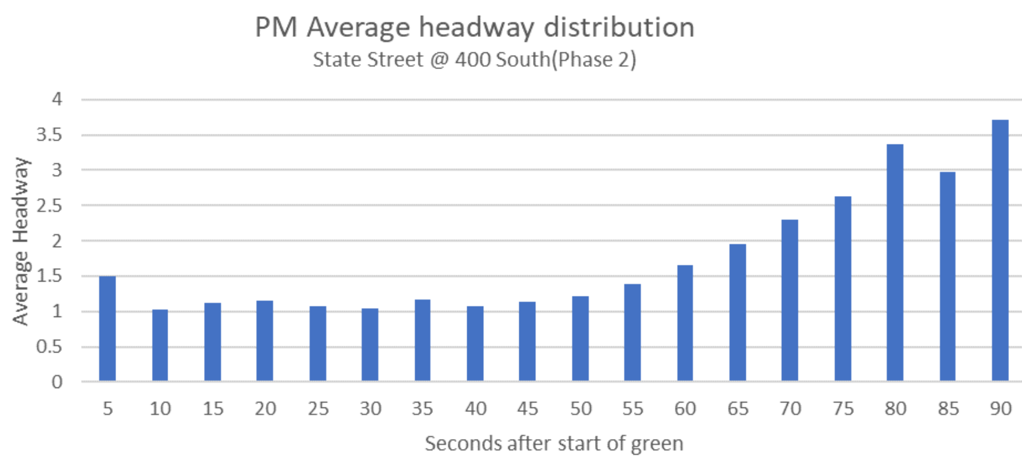


Figure 5.8 Example queue discharge results based on seconds after start of green

This measure can be helpful in determining how the through movement opposing a left turn is performing. Moreover, acceptable gaps are less likely to occur at times when the average headway is lower than the critical gap. However, this measure may not provide additional value beyond that of green time usage.

5.2.10 Conclusions of the Potential Measures Exploration

The evaluation results of the nine measures based on the three criteria are shown in Table 5.6. Six measures pass without reservations, one passes despite requiring data outside of ATSPM, one passes the criteria but with the acknowledgement that another measure explored may provide at least as much value, and one passes the criteria but fails because it is too complex.

Table 5.6 Pass/Fail Results of the Potential Measures

Measure	Can Use Only ATSPM Data?	Can Highlight Potential LT Issues?	Can Provide Criteria for LT Phasing?	Pass/Fail
Critical Headway	No	Yes		Pass[1]
Green Time Usage	Yes	Yes		Pass
Phase Gap Out Rate	Yes	Yes		Pass
Approach Speed	Yes		Yes	Pass
Split Failures	Yes	Yes		Pass
TMC	Yes		Yes	Pass
Saturation Flowrate	Yes (but complex)			Fail[2]
Pedestrian Actuations	Yes	Yes		Pass
Queue Discharge	Yes	Yes		Pass[3]

[1] This measure is critical enough that is passes while needing data outside of ATSPM.
[2] This measure fails because it is too complex and may not provide value beyond that of TMC.
[3] This measure passes but may not provide value beyond that of the green time usage measure.

5.3 Summary

The preliminary evaluations found that all nine measures could be developed from the high-resolution data except for critical headway, which required some additional data. Even though a measure could be developed, some of the measures did not warrant further evaluation in this study based on their projected use in evaluating the need for left turn phasing. A summary of the findings is listed in this section.

Critical Headway: While this measure did require some additional input beyond the high-resolution data provide by the signal, it was determined to be essential in the filtering of gaps in the approach vehicles and was thus selected for further review. Three different methods were evaluated for critical headway; previous research, developed equations (HCM equation, and CFI equation) and the AASHTO Greenbook. Although all the methods had merit and validity, it was determined that the HCM-based equation should be used based on its direct application to traffic analysis and left turn gap acceptance.

Green Time Usage Distribution: This measure held potential for determining when during the green time gaps might be available, by displaying when vehicles are served during the green phase. However, it did not have a direct correlation to gap acceptance and left turn phasing. This measure's potential lies more in evaluating signal timing changes, such as an evaluation of split length, and could be used as part of a signal review prior to left turn phase study. However, a review of timing changes is outside the scope of this study and is not recommended for further review.

Phase Gap Out Rate: The rate of gap outs can potentially reveal if the left turn phasing type may need to be reviewed, by helping to review the current performance of the signal and determining if other steps should be taken to remedy any identified issues before left turn phasing is considered. The evaluation showed that it has potential as part of a flagging tool for left turn phasing analysis and is recommended for further review.

Vehicle Approach Speeds: The speed of incoming vehicles can only be acquired if advanced detection is available for the intersection approach. Currently this measure is not widely available. As part of the evaluation of the critical headways, it was determined that approach speed influences gap acceptance and therefore this data will need to be gathered. However, due to the current limited availability of data it is not recommended for further review as an automated measure. Where available, it could be used to provide added accuracy to the analysis in addition to using the existing speed limit, which should be within 5 mph of the 85th percentile speed.

Split Fail: As with gap outs, split fail is a measure of how volumes are being served. It can also provide direct data regarding if the current phasing configuration is functioning or if other types should be considered. Based on these data, it is recommended that split fail be considered as both a potential flag for left turn phasing studies as well as a decision criterion within a study.

Turning Movement Counts (Left and Opposing): There are some known quality issues with the turning movement counts (TMC) data, particularly with locations that are over capacity since this data is only counting capacity. Therefore, it can provide valuable insight into the need to left turn phasing by using the TMC data as a flag for further analysis. Those data limitations can then be minimized by not basing the entire analysis solely on volume thresholds. The TMC can be used with both the cross-product calculations and BYU's recommended volume comparisons. It is recommended that this measure be included and reviewed as part of the flagging tool and as possible decision criterion for left turn phasing.

Saturation Flowrate: This measure could not be developed using high-resolution data by the same methodology as would be determined by an engineer in the field. However, two methods to estimate saturated flow rate from the high-resolution data were developed as a proof of concept that requires further validation and statistical analysis. The measure is very important in many types of traffic analysis, but a clear connection to left turn phasing in addition to what TMC cannot provide was not found. Based on the need for further validation and limited additional data, this measure is not recommended for further review. However, saturation flow rate is essential to traffic analysis and signal timing projects which may warrant future investigation and development.

Pedestrian Actuations: While this measure is not a direct correlation to the pedestrian volumes at an intersection, it can provide insight into the magnitude of signal cycles affected by pedestrian traffic. As pedestrians can limit the number of acceptable gaps, it was determined to be an important measure. Based on its ability to provide insight regarding pedestrian traffic volumes and frequency, it is recommended that this measure is reviewed further as a flag on whether pedestrian traffic should be considered in a left turn phasing study.

Queue Discharge: This measure of how and when the vehicles in the queue cross the intersection provides value in understanding and evaluating traffic operations and signal timing. However, for left turn analysis it does not provide additional data that is not already provided by volume and gap measures. Although this method is not recommended for further review, it could be useful for other signal timing and traffic analysis and may warrant review outside this study.

6.0 METHODOLOGY AND TOOL DEVELOPMENT

6.1 Overview

The left turn gap analysis tool provides a bridge between a UDOT-received complaint about a left turn and the identification of solutions for improvement at those locations. This chapter discusses the methodology of the left turn gap analysis tool. First a discussion is provided describing the flagging flowchart, next a description of the tool is included, and then finally a summary on the migration of the tool from MS Access to the ATSPM website is provided.

6.2 Left Turn Gap Flagging Flowchart

The left turn gap flagging flowchart shown in Appendix E has three main components: i) initial processing and checks, ii) left turn gap analysis, and iii) additional measures. The evaluation of potential measures discussed in the previous chapter was valuable to the development of this flowchart, as will be evident in the following discussions of each component. Portions of the flowchart are included as figures in this section, while the full flowchart is provided in Appendix E. All thresholds mentioned in the description of the flowchart are defaults only and should be user-defined while adhering to engineering judgment.

The initial processing and checks component shown in Figure 6.1 is meant to catch any flaws and issues with the detection system as well as identify any possible complications with high pedestrian volumes. The flowchart path begins by a user inputting the approach information of a left turn complaint location, as well as selecting an appropriate time period for analysis (such as the PM peak period). Three checks are then performed: the percent of cycles that ended in a gap out, the volume of left turning vehicles, and the percent of cycles with pedestrian calls. If the percent of cycles that end in a gap out is 70% or higher or if the volume of left-turning vehicles is less than 60 vph, then the flowchart directs the user to check the detectors at that approach to determine if faulty detectors are causing issues at the intersection. If the percent of cycles with pedestrian calls is greater than 30%, then the flowchart directs the user to review the left turn crash history at that location. Additionally, the flowchart directs the user to review possible changes in split patterns of the signal timing even if less than 70% of cycles gap out in case there are improvements that could be made to the operation of the intersection with a simple adjustment in split times.

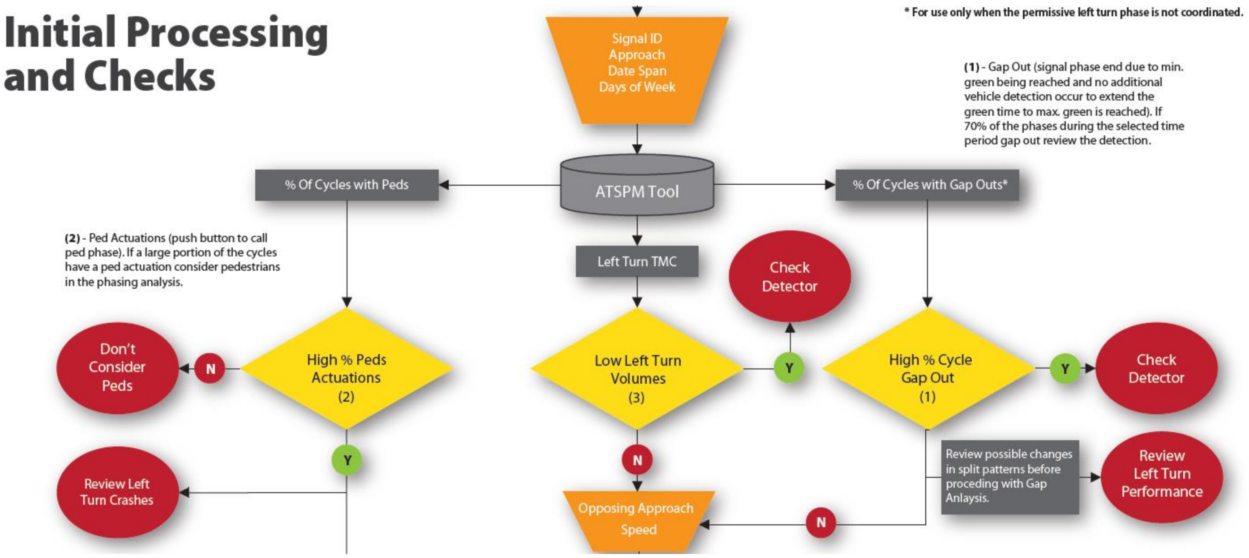


Figure 6.1 Initial checks portion of the flowchart

Once any detector issues have been resolved at the intersection, the flowchart directs the user to the left turn gap analysis process as shown in Figure 6.2. The flowchart identifies four steps for this analysis. First, the critical headway (as discussed in section 5.2.1) needs to be calculated. Second, the gap analysis tool should be used to make a count of the number of acceptable gaps and the total duration of these gaps during the permissive left turn phase. Third, approaching vehicle data should be used to determine the number of vehicles wanting to turn left at the approach. Fourth, the left-turning capacity (the total duration of the acceptable gaps) should be compared to the demand (the number of vehicles multiplied by the critical gap time). If the demand exceeds 70% of the capacity, the flowchart directs the user to flag that left turn approach and consider it for further study.

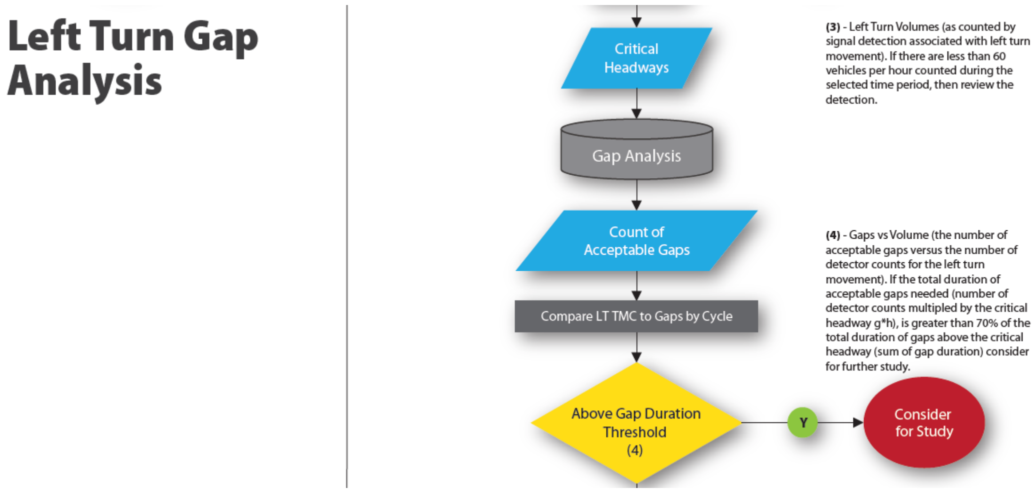


Figure 6.2 Left turn gap analysis portion of the flowchart

If the approach has not been flagged for further study in the left turn gap analysis process, the flowchart then directs the user to consider three additional measures pertaining to the left turn movement: split failures, pedestrian calls, and conflicting volumes as shown in Figure 6.3. In the split failure analysis, the flowchart directs the user to flag a left turn approach for further study if 50% or more of the cycles fail to clear out the left turn queue. In the pedestrian call analysis, a left turn approach is flagged for further study if more than 30% of the cycles have a pedestrian actuation. In the conflicting volumes analysis, two sets of thresholds are considered. The first set of thresholds, presented in Table 6.1, should be compared against the left turn hourly volume, multiplied by the opposing through hourly volume. The second set of thresholds uses decision boundaries and is presented in Table 6.2. The flowchart directs the user to flag the left turn approach for further study if the appropriate threshold in either set is exceeded.

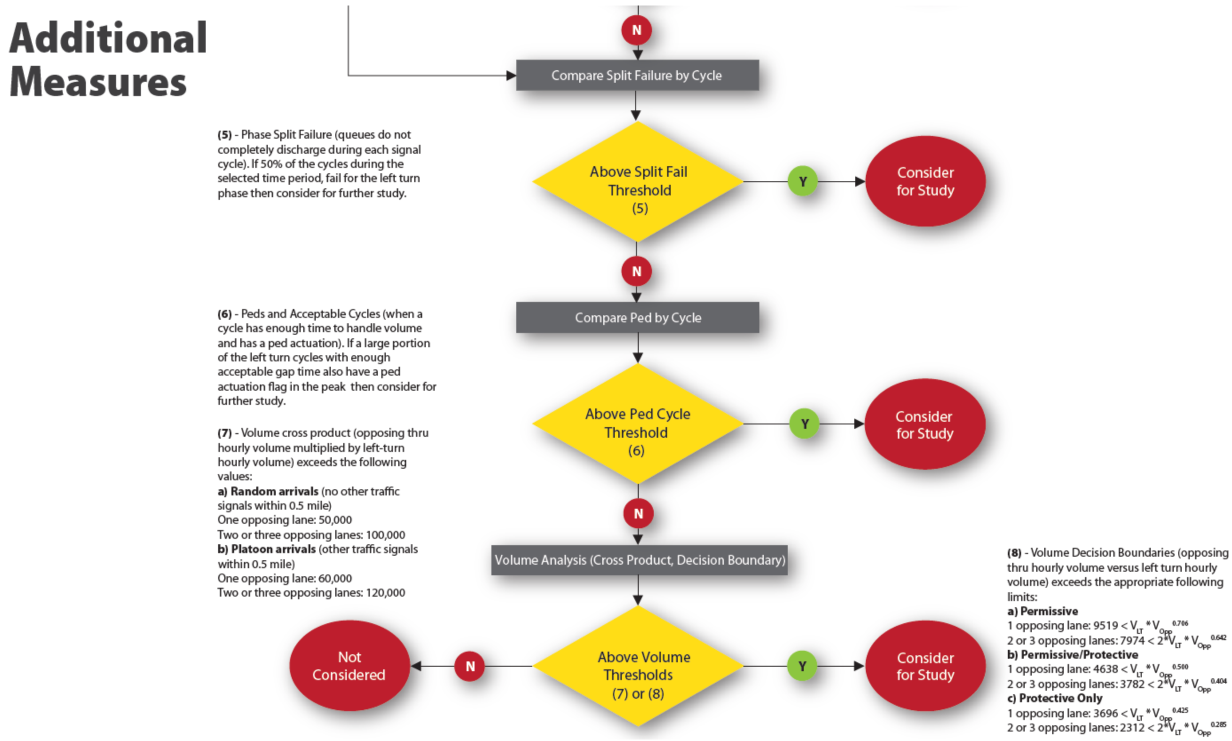


Figure 6.3 Additional measures portion of the flowchart

Table 6.1 Volume Cross Product Thresholds [15]

	Random Arrivals *(no other traffic signals within 0.5 mile)*	**Platoon Arrivals** *(other traffic signal(s) within 0.5 mile)*
1 Opposing Lane	50,000	60,000
2 or 3 Opposing Lanes	100,000	120,000
Updated November 13, 2014		

Table 6.2 Volume Boundary Thresholds [7]

		1 Opposing Lane	**2 or 3 Opposing Lanes**
Permissive	*Equation*	$V_{LT} * V_{Opp}^{0.706}$	$2 * V_{LT} * V_{Opp}^{0.642}$
	Threshold	9,519	7,974
Protected-Permissive	*Equation*	$V_{LT} * V_{Opp}^{0.500}$	$2 * V_{LT} * V_{Opp}^{0.404}$
	Threshold	4,638	3,782
Protected Only	*Equation*	$V_{LT} * V_{Opp}^{0.425}$	$2 * V_{LT} * V_{Opp}^{0.285}$
	Threshold	3,696	2,312

6.3 Left Turn Gap Flagging GUI Concept

The steps of the flowchart were integrated into a GUI concept for ease of making necessary queries and calculations on the data. This GUI was created using MS Access and guides the user through entering needed information, selecting the desired approach(es), and reviewing the results of the left turn gap analysis flowchart. On the main page of the GUI, the user is prompted to select at least one signal from a drop-down list and add it to a table for analysis by clicking a button. The user is then directed to indicate which approaches are to be analyzed by changing "No" values to read as "Yes" for any available permissive phases as shown in Figure 6.4. The user must also select a date range for the analysis using a built-in calendar tool as well as the day(s) of the week using checkboxes and the time period using a set of option controls. Once all these inputs have been entered, the user may initiate the initial checks process previously described.

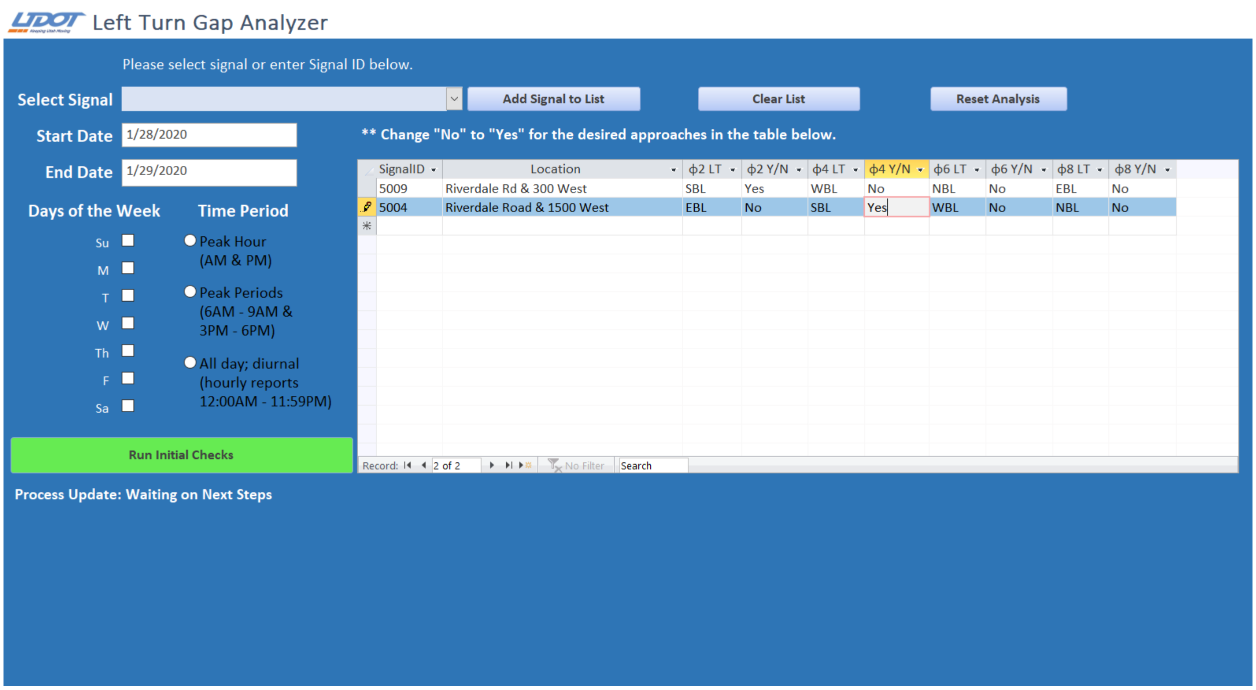


Figure 6.4 **Entering data into the GUI prior to running the initial checks process**

The initial checks process is begun by clicking a labeled button on the form. This button is linked to visual basic code that systematically runs SQL queries and calculations on data downloaded from the ATSPM database. As described previously, this process considers the number of left-turning vehicles, gap outs, and pedestrian calls. Once this process has finished running, the GUI displays simplified results with either a green checkmark or a warning message (depending on whether the approach passes or fails the checks) as shown in Figure 6.5. The possible warning messages are listed in Table 6.3. Detailed results that include numeric evaluations of the measures are given in a PDF report (example in Appendix E), accessed by clicking on the labeled button in the GUI.

Table 6.3 Initial Checks Possible Warning Messages

Measure	Warning Message	Displayed If…
Left Turn Volume	"Check Detector"	Volumes < 60 vph
Gap Outs	"Check Detector"	Gaps Outs ≥ 70% of cycles
Pedestrian Calls	"Include Ped Analysis"	Pedestrian Calls > 30% of cycles
Other	"Review Split Pattern Performance"	N/A (always displayed)

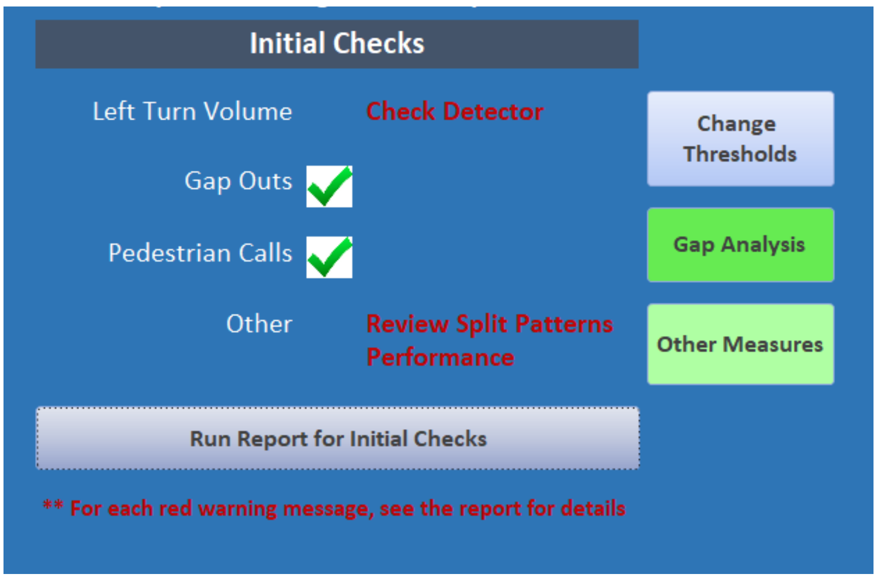


Figure 6.5 Initial checks results section of the GUI

Following a review of the initial checks, the user may continue with the analysis via the three stacked buttons shown in Figure 6.5. The first button takes the user to a separate form where they may view and edit the thresholds used in the left turn gap and additional measures. The second and third buttons commence the processes for those two analyses. It is recommended but not required that the user run the gap analysis process before running the additional measures process.

Like the initial checks process, the gap analysis and additional measures processes are run with visual basic code and SQL code. Once either of the processes has finished, the GUI will display new items: analysis results messages for whichever process had been run and a button that opens the detailed report displaying results from both processes. As shown in Figure 6.6, the results message will either display “Consider for Study” or “Not Recommended for Study” depending on whether the measures were flagged as outlined in the flowchart. The detailed report includes the calculated demand and capacity from the gap analysis, the number and percent of cycles with a split failure, the number and percent of cycles with a pedestrian call, and values of the conflicting volumes and their resultant cross product and boundary values.

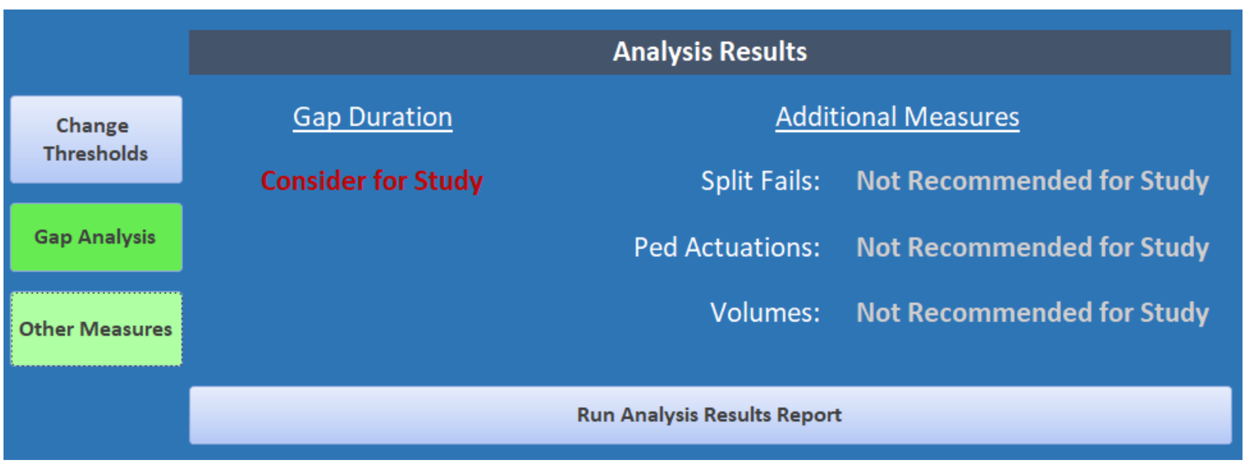


Figure 6.6 Left turn gap analysis and additional measures section of the GUI

6.4 Migration to ATSPM

After meeting with UDOT and discussing the tool, it was determined that the tool should be moved from Microsoft Access to a more universal platform and be converted to a report available on the ATSPM website. Plans to create this report were developed in meetings with UDOT and the Utah Department of Technology Services (DTS). The following sections discuss the ATSPM GUI concept for the tool, modifications to the data to make it compatible with the aggregation system, and a status update of the ATSPM measure.

6.4.1 ATSPM GUI Concept

Through meetings with UDOT and DTS, a concept for the tool in the ATSPM website was developed. Unlike the Access GUI, the ATSPM GUI requires the user to make all decisions up front instead of along the way. This reduces the number of times the user must interact with the tool once the code processes have begun running. The GUI concept is shown in Figure 6.7. In the left section, the user inputs the Signal ID of the intersection they want to analyze. The Region, Measure Type, Area, and Agency drop-down boxes as well as the map may be used to help find a specific signal. The top middle section is where the user selects which left turns are to be analyzed as well as the specific analyses to be run. The options for left turns are specific to the intersection and will be populated after the Signal ID is selected. The Signal Data Check and Final Gap Analysis Report options are selected by default. In the top right section, the user can edit any threshold values used in the analyses. The default thresholds are 30% cycles with pedestrian calls, 50% cycles with gap outs, 60% left-turning vehicles per hour, 70% acceptable gaps to left turn demand, and 50% cycles with split failures. The bottom right section is where the user inputs date and time information. The start and end dates can be typed or selected on the calendar tool and the range may span more than one day. The times are selected using drop-down lists in 15-minute increments. By default, Monday through Friday are selected in the Days of the Weeks subsection. In the Analysis Time Period subsection, the user selects one of four options for the analysis period on the days selected: peak hour (calculated when the code begins running), peak periods (predefined as 6 AM-9 AM and 3 PM-6 PM), 24-hour period, or custom (times are available in 15-minute increments). Once all the required information has been entered, the user can click the Create Report button and the code will begin running.

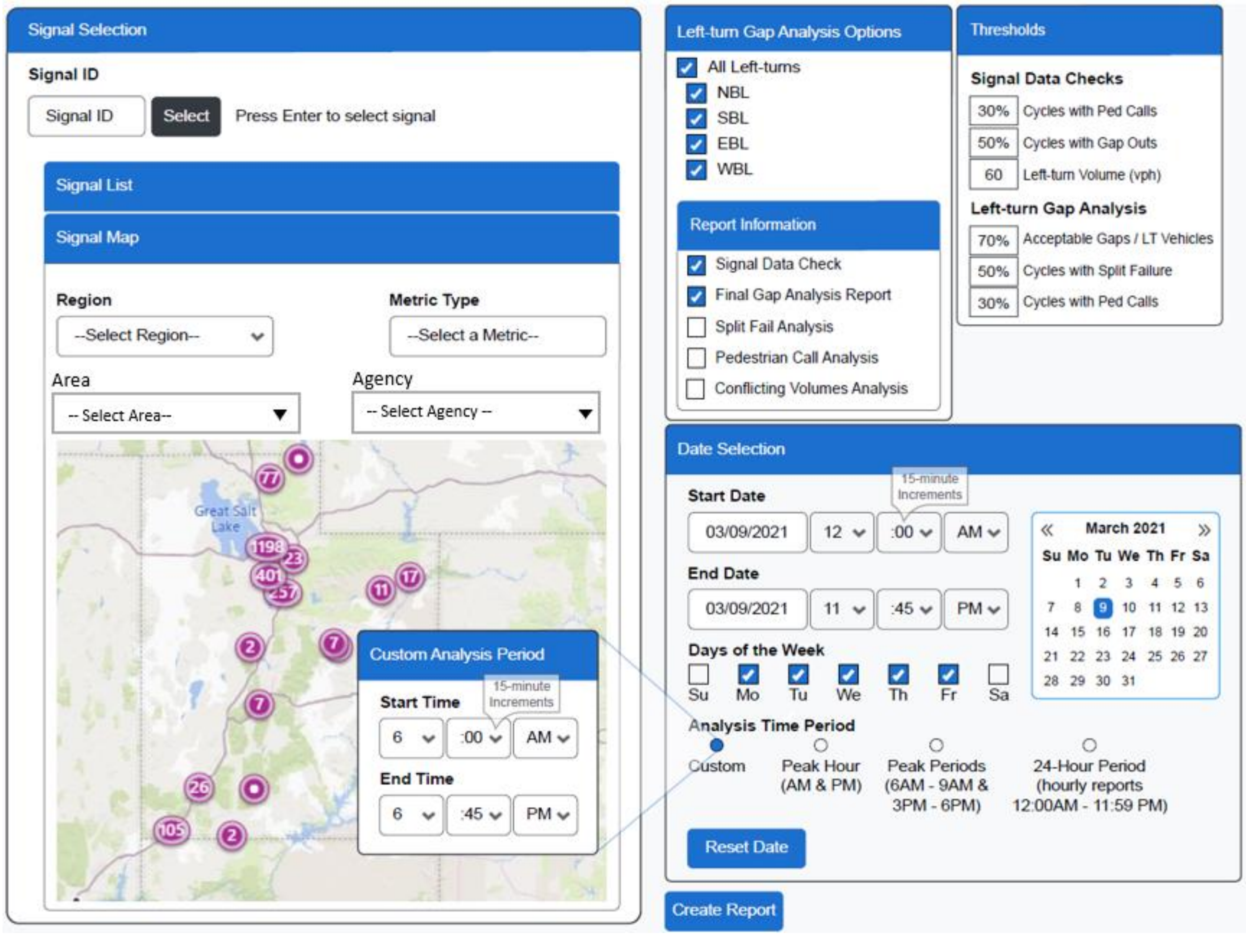


Figure 6.7 Concept of the left turn gap tool in ATSPM

The code runs the same analyses as described previously, but only the ones checked in the GUI. Upon completion of the code, a results page that contains information about the selected analyses is displayed. An example of the results for a peak hour analysis is shown in Figure 6.8. Near the top of the page is a description of the location and left turn movement analyzed, the phase type (protected only, protected-permissive, or permissive only), the number of through lanes, the signal type (protected only, permissive only, FYA, or 5-head), and the speed limit on the opposing through approach.

Wednesday, February 17, 2021
5:03:02 PM

Left Turn Phase Analysis Results

UDOT Keeping Utah Moving

Signal ID: **5009** **Riverdale Rd & 300 West**

Left Turn Appproach: **WBL**	Phase Type: **Protected Only**	Signal Type: **Protected Only**	
Opposing Approach: **EBT**	Number of Thru Lanes: **1**	Speed Limit: 35mph	

Peak Period: AM Start: **7:30:00 AM** End: **8:30:00 AM** Start Date: **1/29/2020** End Date: **1/29/2020**

Left Turn Gap Analysis Results

Capacity: **96** Demand: **359** V/C Ratio: **3.7396** Phase: **Protected Only**

Consider for Study

Alternative Measures Analysis Results

Split Failure and Pedestrians			Volume Cross Product and Boundaries		
Cycles With Split Failure:	5 ,	15.62%	Left Turn Movement Volume:	359	
Not Considered			Opposing Through Movement Vol:	28	
Cycles With Pedestrian Calls	0 ,		Cross Product Value:	10,052	Not Considered
Ped Analysis not Recommended			Calculated Volume Boundary:	1,479.57	Not Considered

Left Turn Gap Analysis Results

Capacity: **96** Demand: V/C Ratio: Phase: **Permissive**

Don't Consider for Study

Alternative Measures Analysis Results

Split Failure and Pedestrians			Volume Cross Product and Boundaries		
Cycles With Split Failure:	5 ,	15.62%	Left Turn Movement Volume:	359	
Not Considered			Opposing Through Movement Vol:	28	
Cycles With Pedestrian Calls	0 ,		Cross Product Value:	10,052	Not Considered
Ped Analysis not Recommended			Calculated Volume Boundary:	1,479.57	Not Considered

Peak Period: PM Start: **2:30:00 PM** End: **3:30:00 PM** Start Date: **1/29/2020** End Date: **1/29/2020**

Left Turn Gap Analysis Results

Capacity: **67** Demand: V/C Ratio: Phase: **Permissive**

Don't Consider for Study

Alternative Measures Analysis Results

Split Failure and Pedestrians			Volume Cross Product and Boundaries		
Cycles With Split Failure:	8 ,	29.63%	Left Turn Movement Volume:	406	
Not Considered			Opposing Through Movement Vol:	124	
Cycles With Pedestrian Calls	0 ,		Cross Product Value:	50,344	Not Considered
Ped Analysis not Recommended			Calculated Volume Boundary:	3,149.42	Consider for Study

Page 1 of 1(

Figure 6.8 Example report for a peak hour analysis

6.4.2 Data Aggregation

Recent UDOT efforts to improve the ATSPMs website have included aggregating data at the 15-minute level to reduce in-the-moment calculation delays. It was desired that the left turn gap analysis measure also be aggregated.

The aggregation technique used, performs three sets of calculations on the gap data. The first set of calculations counts the gaps found in each 15-minute time period and separates them into bins based on their duration. Eleven bins are used in the aggregation; the upper and lower bounds are listed in Table 6.4. The second set of calculations sums all of the gap durations above three thresholds for each 15-minute period. The three thresholds used are 4.1 seconds, 5.3 seconds, and 7.4 seconds, for a total of three gap duration sums. The third set of calculations calculates the total time in each 15-minute period that the phase indicator for the approach is green or yellow. After all the calculations are performed, the output aggregate table for the left turn gap analysis tool has 19 columns: one each for the 15-minute period start time, signal ID, phase number, and approach number; 11 for the gap duration counts; three for the gap duration sums; and one for the sum of the green/yellow indication durations.

Table 6.4 Bin Thresholds for the 15-Minute Aggregation

Bin Number	Lower Bound (exclusive)	Upper Bound (inclusive)
1	0 sec	1 sec
2	1 sec	3.3 sec
3	3.3 sec	3.7 sec
4	3.7 sec	3.9 sec
5	3.9 sec	4.1 sec
6	4.1 sec	5.3 sec
7	5.3 sec	5.5 sec
8	5.5 sec	6.5 sec
9	6.5 sec	6.9 sec
10	6.9 sec	7.4 sec
11	7.4 sec	N/A

The aggregation results were validated by taking the high-resolution data and performing manual counts and sums in MS Excel. After a few rounds of debugging, the aggregation results adequately matched the manual calculations and the aggregation code was approved.

6.4.3 Development Status

The ATSPM left turn gap analysis measure is still in the development phase but well on its way to becoming available online. Because this measure is an engineering-level tool and not intended for public use, the online tool will be password-protected on the ATSPM website when it is published.

6.5 Summary

Several tools were created for the left turn gap analysis. First, a flowchart of the decision-making and flagging process was developed. Second, a GUI in MS Access was created to guide a user through the steps of the analysis and perform automated calculations. Third, a concept for converting the GUI to be available as a measure on the ATSPM website was developed and its implementation is underway. The measure will perform calculations on data aggregated at the 15-minute level which have been verified for accuracy.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

The purpose of this study was to develop an automated method of flagging signalized intersection approaches in need of left turn phasing changes based on the availability (or unavailability) of gaps in traffic conflicting with a left turn movement. 44 approaches representing a total of nine intersection configurations were selected for study, and manual counts were used to verify the accuracy of the high-resolution counts collected by the signal controllers and used on the ATSPM website. Furthermore, the validated dataset was used to evaluate potential measures that could be used in the development of the left turn gap flagging tool. Several of these measures were found useful, especially the critical gap calculation and TMC. With the help of the identified measures, a flowchart process for flagging left turns for phasing changes was developed. This process was integrated into a new left turn gap analysis tool built in MS Access. When the MS Access tool was determined useful, UDOT began the process of migrating it to the ATSPM website; this process is still underway. This chapter will review the results of this study (the flowchart and tool) and the recommendations.

7.2 Findings

The evaluation of potential measures discussed in Chapter 5 of this report was valuable to the development of the left turn gap flagging flowchart and tool. Five of the eight passing measures (critical headway, phase gap out rate, split failures, TMC, and pedestrian actuations) are used in the flowchart as decision-making points. The process directed by the flowchart steps through warnings to check the detectors if any issues are found with the data, an analysis that compares the left turn demand to the number of acceptable gaps present, and three additional measures that could give further insight into how the left turn movement might benefit from phasing changes.

The tool automates the steps and calculations referred to in the flowchart. It can be applied to approaches with lane-by-lane count detectors, representing approximately 64% of all approaches in the ATSPM website. All types of left turn phasing found in Utah were represented in the data collection, with the exception of doghouse signal head types—protected-permissive approaches were instead studied by collecting data at approaches that use FYA.

7.3 Recommendations

Based on the results of this research, it is recommended that the left turn gap analyzer tool be integrated into the ATSPM aggregate system. The left turn gap flagging flowchart, as applied in the tool, should be used to aid UDOT in selecting approaches in need of left turn phasing changes. There should be steady progress made by UDOT to integrate the tool into the ATSPM website. Because the target audiences of this tool are engineers and consultants, it is recommended that the tool be password-protected on the website.

The research group also identified the following improvements to the original left turn gap analysis measure on the UDOT ATSPM website for clarity and consistency:

- It is recommended that the title of the output figures be changed to show the number of the phase in which the gaps are found (i.e., "Left Turn Crossing Phase X" where X is the opposing through phase number). Currently, the phase number shown is the permissive phase of the left turn which can vary for the same direction of approach depending on the type of signal head used.

- It is recommended that the label on the secondary Y-axis of the output figure be rephrased to say "% of Green Time where Gaps ≥7.4 seconds" with the legend updated to match. Currently, the label on the secondary Y-axis says "% of Gap Time > 7.4 seconds" and the legend says "% Green Time > 7.4 seconds." The new phrasing clarifies the meaning. Figure 7.1 and Figure 7.2 depict the existing output (with annotations) and proposed output, respectively, based on this recommendation and the one previous.

- It is recommended that the analysis includes all gaps that occur during the evaluation period, even if the full cycle is not included in that period. Currently, the analysis calculations only include gaps in cycles that both start and end in the evaluation period; consequently, the number of gaps in a given 15-minute period can vary depending on where those 15 minutes fall in the evaluation period as shown in the examples in Figure 7.3.

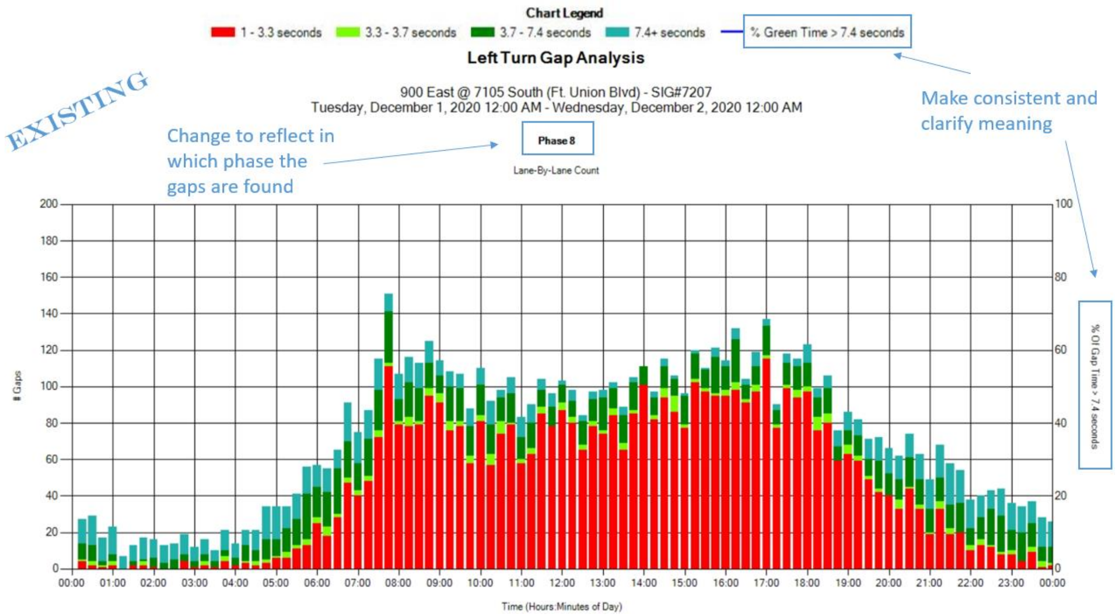


Figure 7.1 Annotated existing measure output

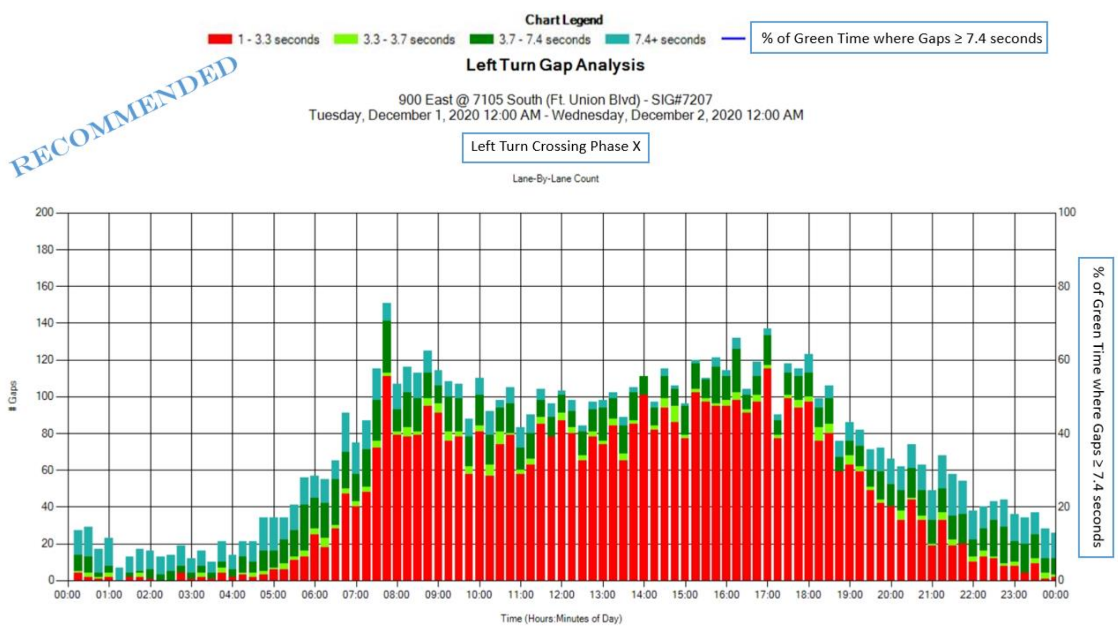
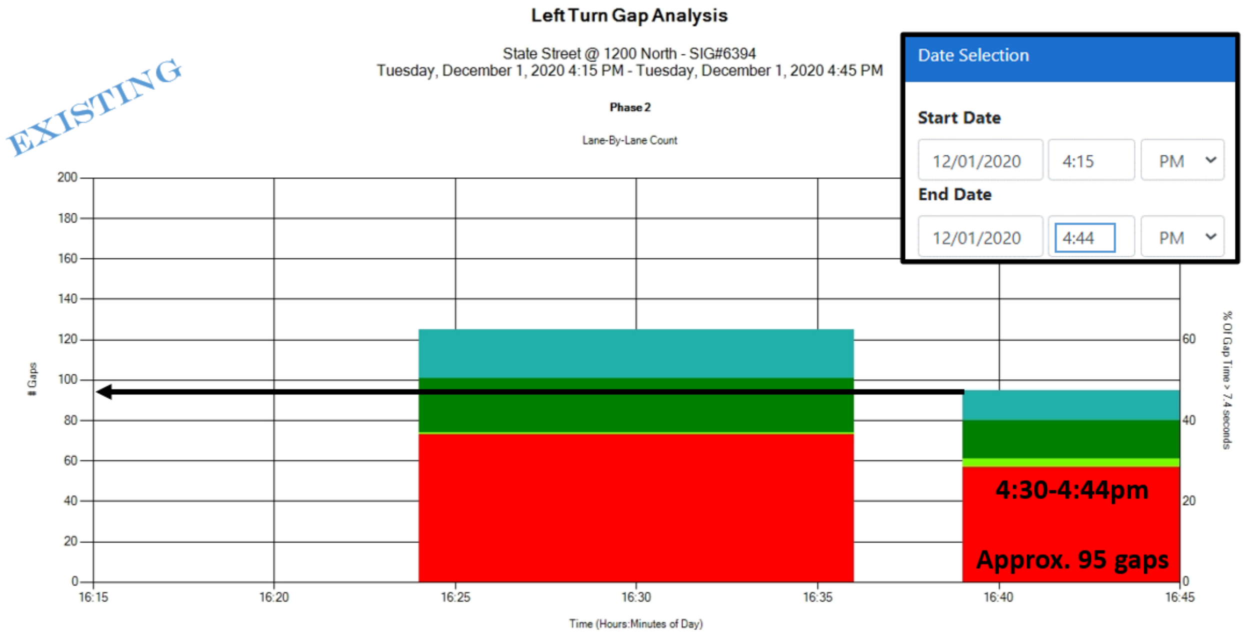
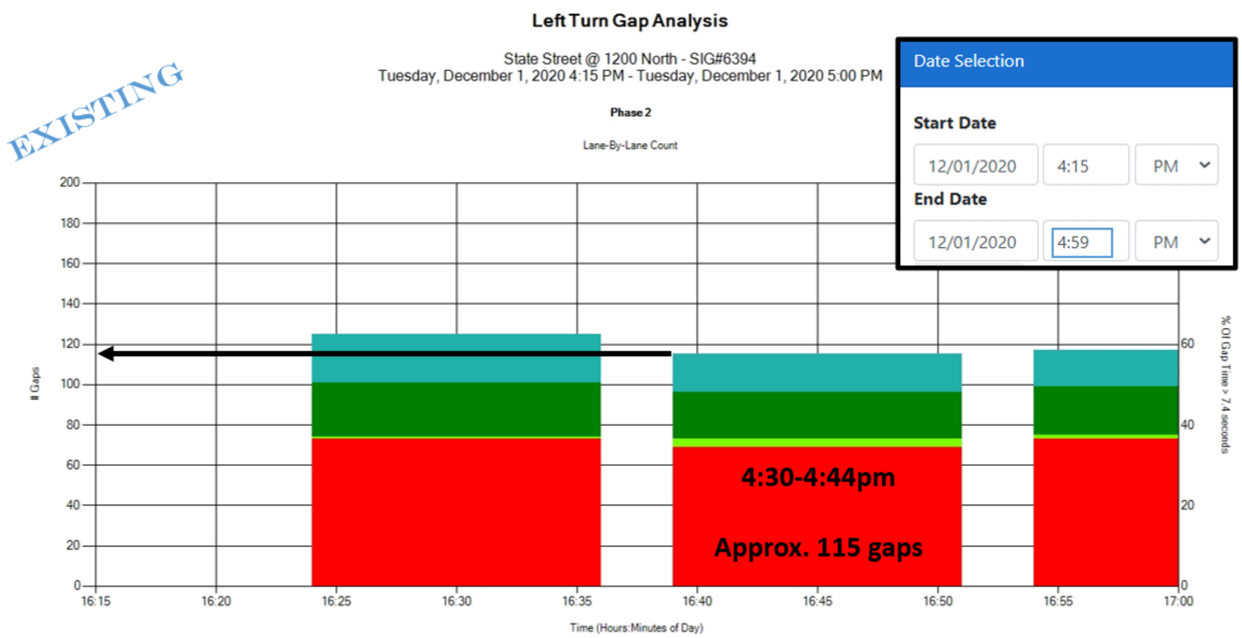


Figure 7.2 Recommended measure output



(a)



(b)

Figure 7.3 Example of difference in number of gaps in the same 15-minute period

7.4 Conclusions

This study found that the ATSPM gap analysis data can be used to regulate the need for and potential impacts of left turn phasing at signalized intersections. In addition, the high-resolution data was used to provide additional measures of gap availability and acceptance for left turns. These measures and the gap analysis data were integrated together and presented as a methodology flowchart and tool that automate the analysis process and provide engineers with data-driven recommendations to improve signalized left turn movements. The implementation of the tool on the ATSPM website will aid UDOT in being more responsive to left turn phasing needs throughout the state.

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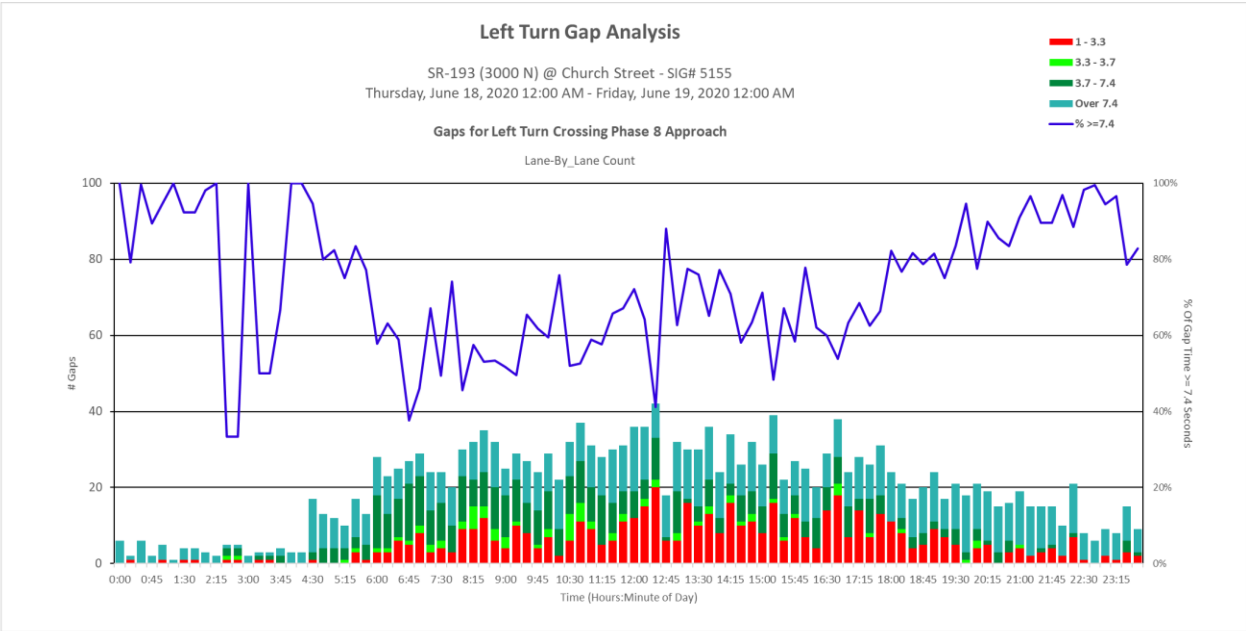
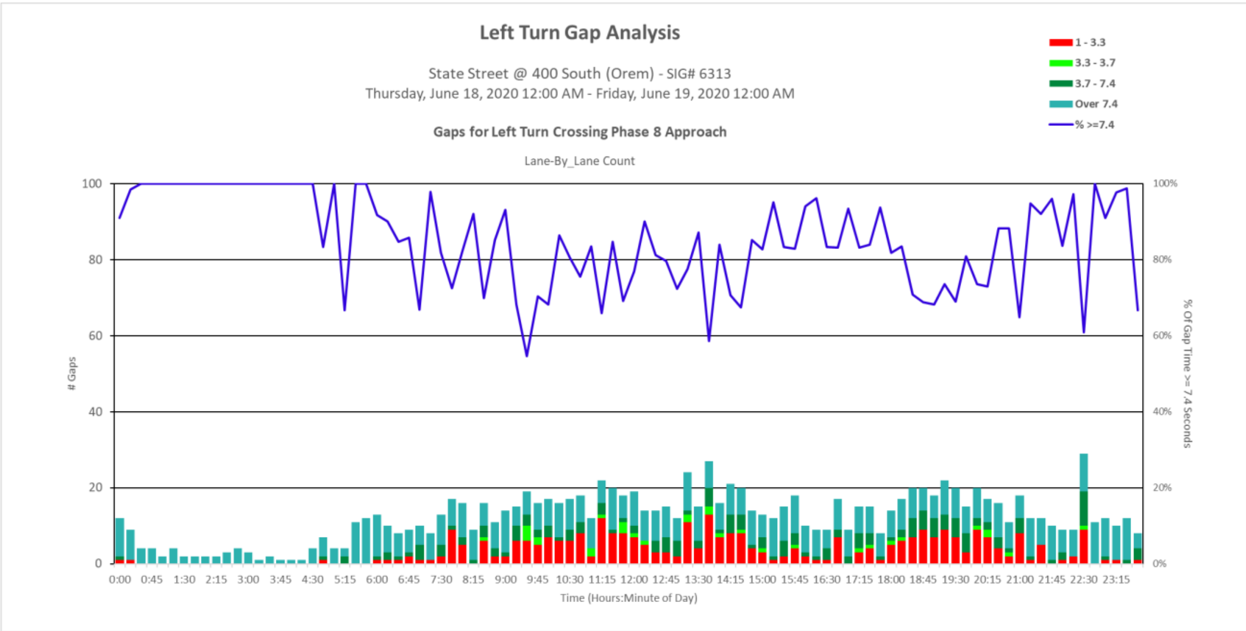
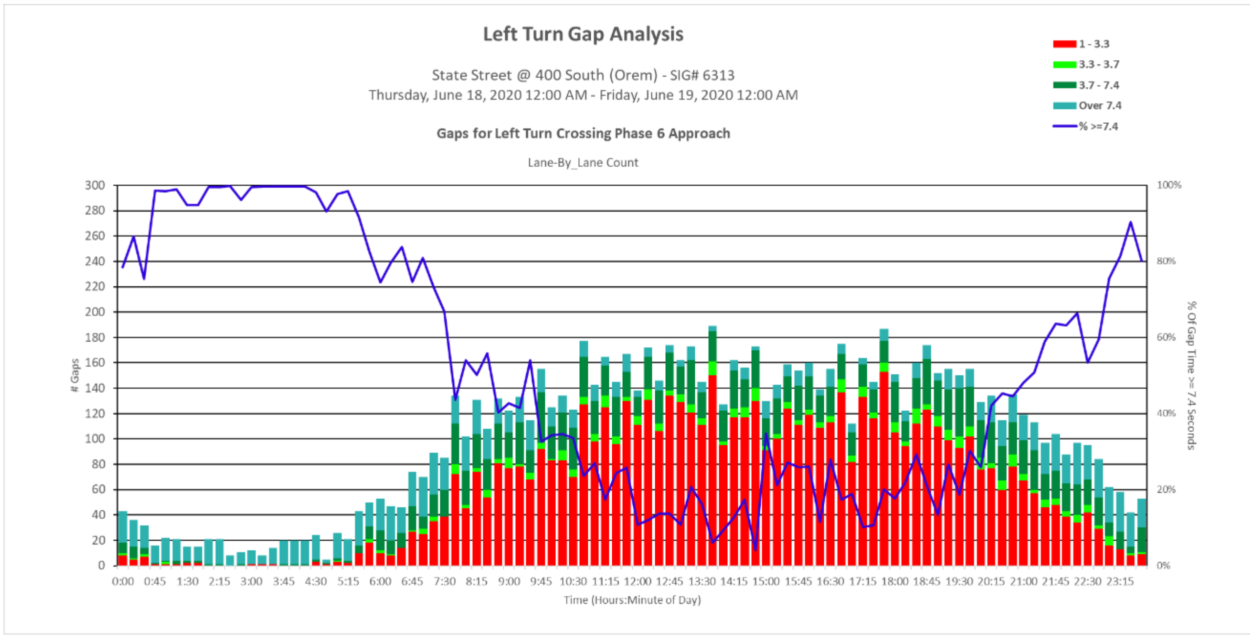
APPENDIX A: ATSPM LEFT TURN GAP REPLICATION FOR MANUAL DATA

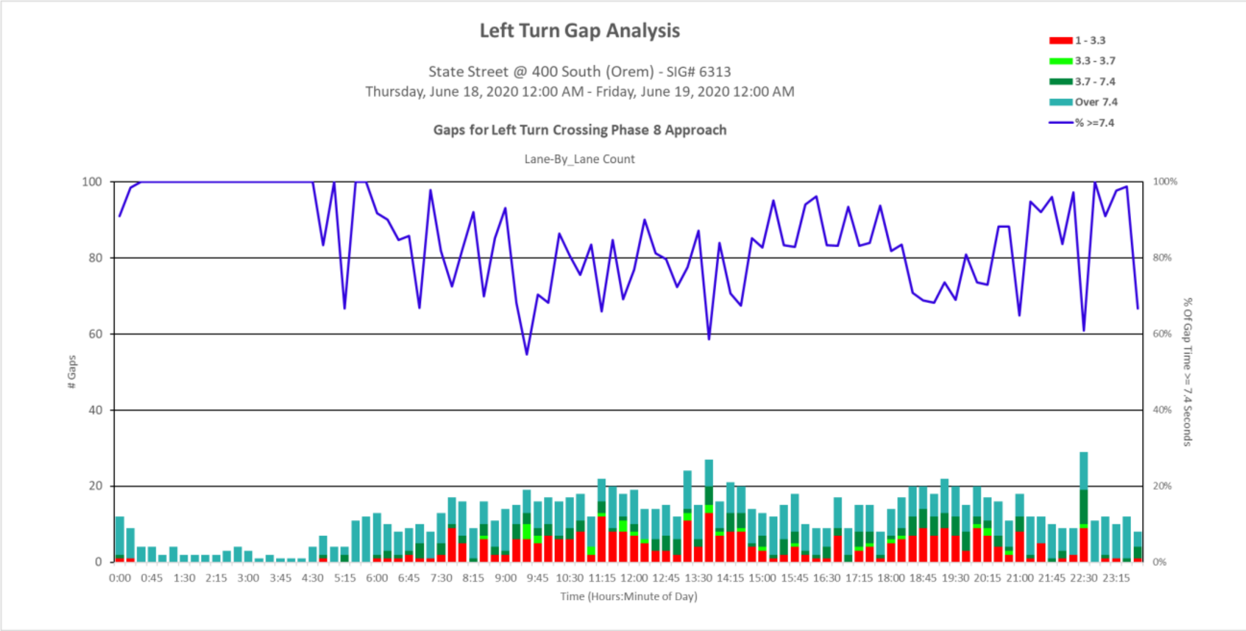
This appendix provides examples of field-collected data, represented similarly to the ATSPM Left Turn Gap chart.



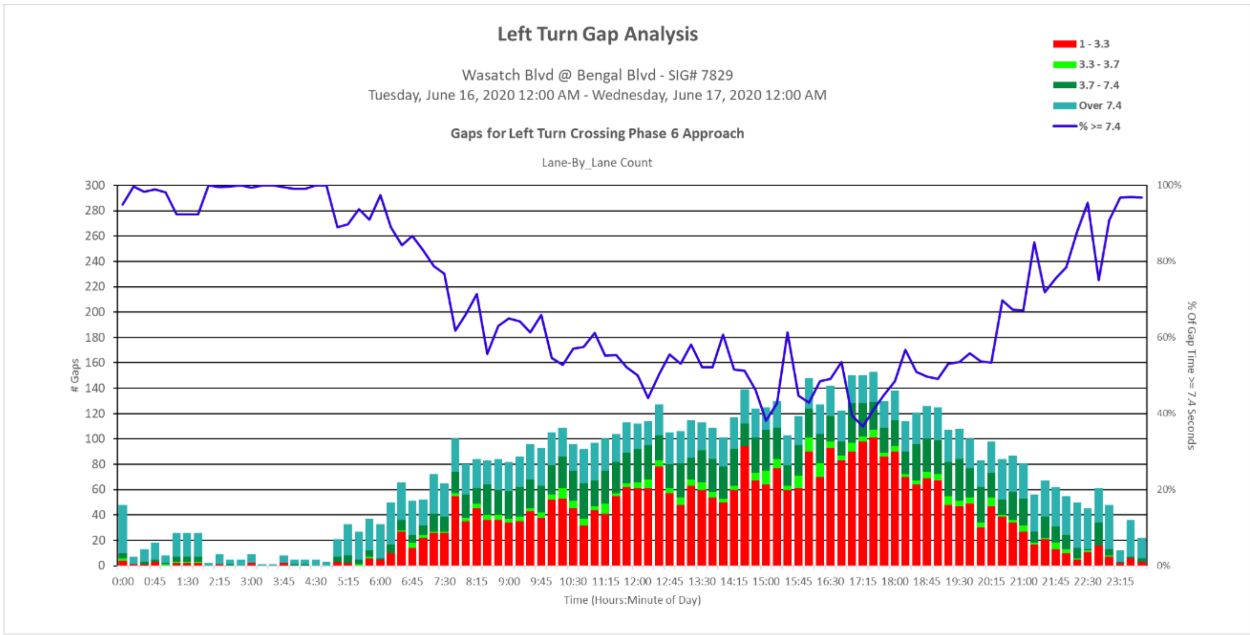




Left Turn Gap Analysis
State Street @ 400 South (Orem) - SIG# 6313
Thursday, June 18, 2020 12:00 AM - Friday, June 19, 2020 12:00 AM
Gaps for Left Turn Crossing Phase 6 Approach
Lane-By_Lane Count
1 - 3.3
3.3 - 3.7
3.7 - 7.4
Over 7.4
% >=7.4
# Gaps
% Of Gap Time >= 7.4 Seconds
Time (Hours:Minute of Day)

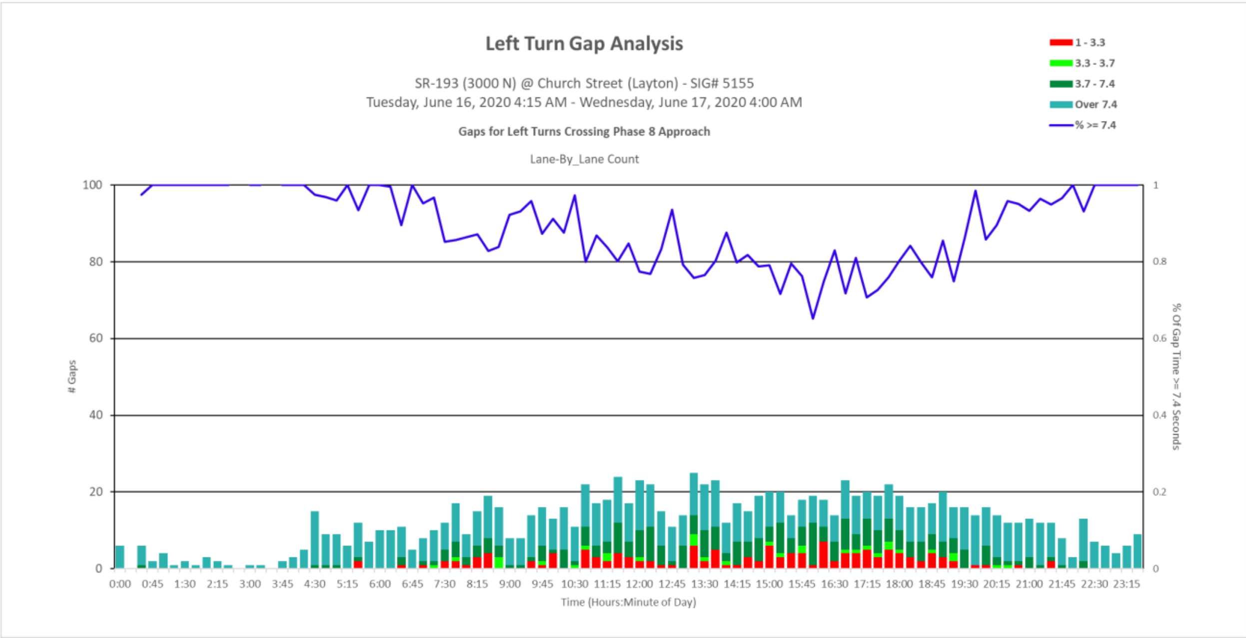


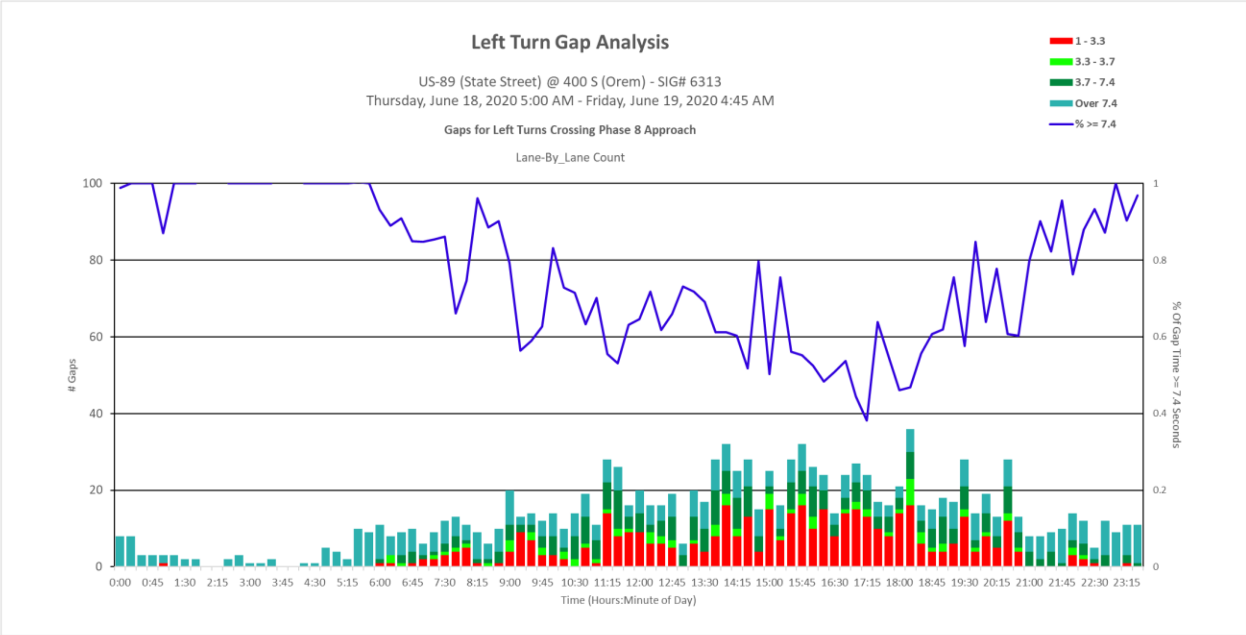
Left Turn Gap Analysis
State Street @ 400 South (Orem) - SIG# 6313
Thursday, June 18, 2020 12:00 AM - Friday, June 19, 2020 12:00 AM
Gaps for Left Turn Crossing Phase 8 Approach
Lane-By_Lane Count
1 - 3.3
3.3 - 3.7
3.7 - 7.4
Over 7.4
% >=7.4
# Gaps
% Of Gap Time >= 7.4 Seconds
Time (Hours:Minute of Day)

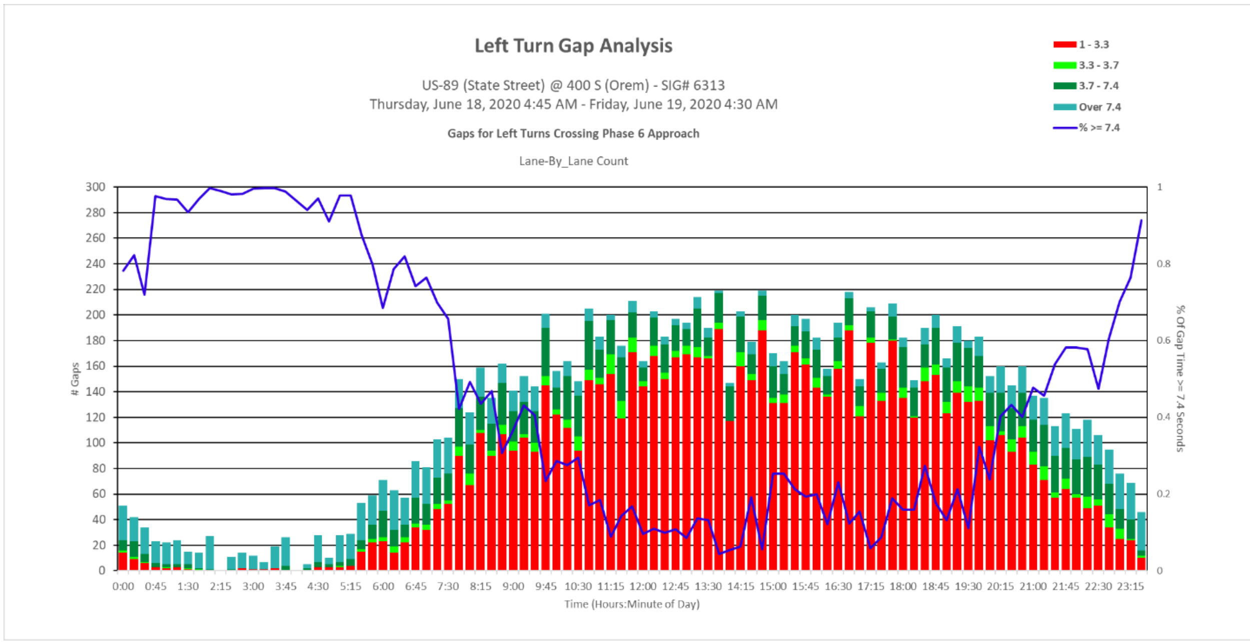

Left Turn Gap Analysis
Wasatch Blvd @ Bengal Blvd - SIG# 7829
Tuesday, June 16, 2020 12:00 AM - Wednesday, June 17, 2020 12:00 AM
Gaps for Left Turn Crossing Phase 6 Approach
Lane-By_Lane Count
1 - 3.3
3.3 - 3.7
3.7 - 7.4
Over 7.4
% >= 7.4
# Gaps
% Of Gap Time >= 7.4 Seconds
Time (Hours:Minute of Day)

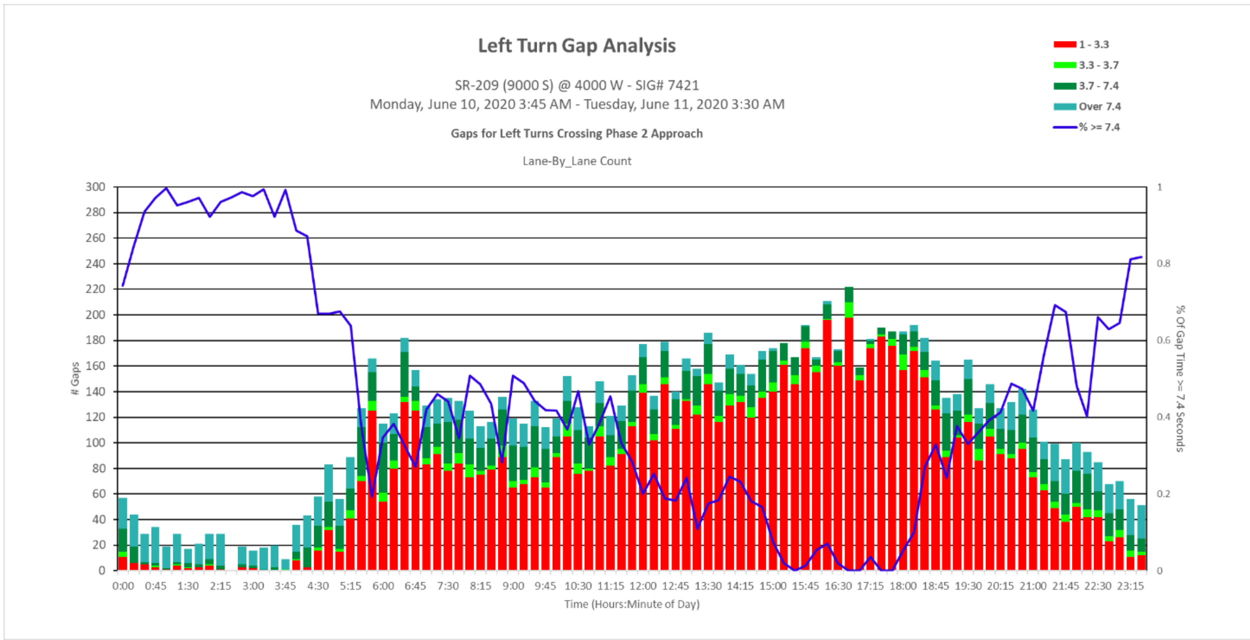
APPENDIX B: ATSPM LEFT TURN GAP REPLICATION FOR MANUAL DATA

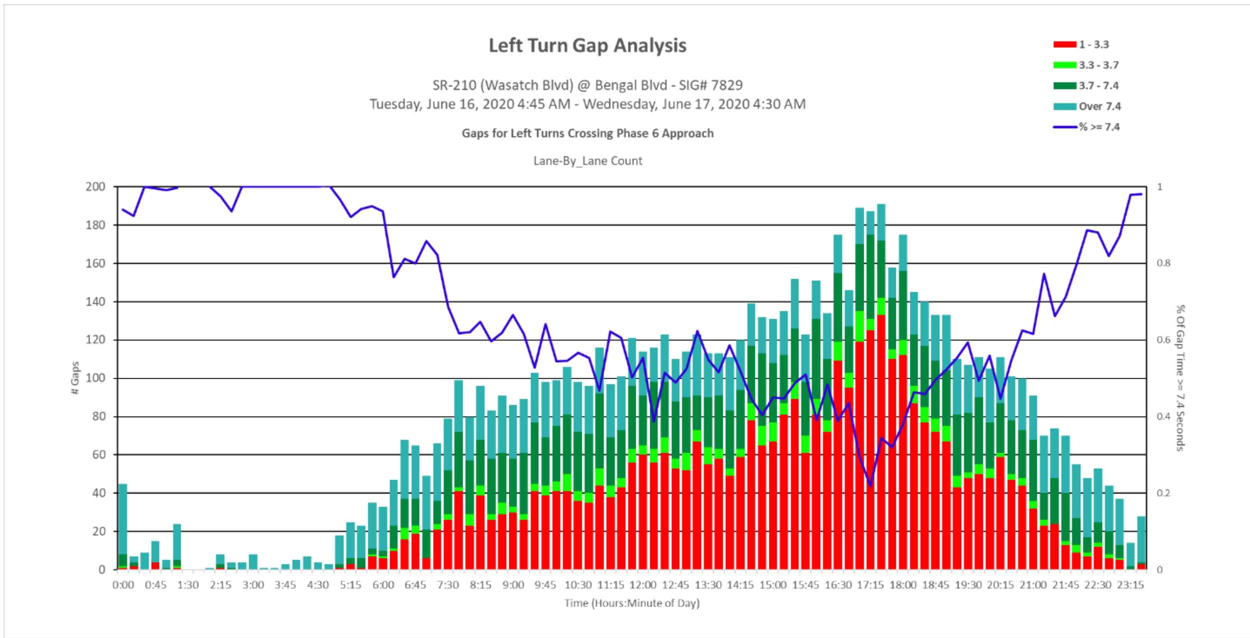
This appendix provides examples of ATSPM high-resolution data, represented similarly to the ATSPM Left Turn Gap chart.





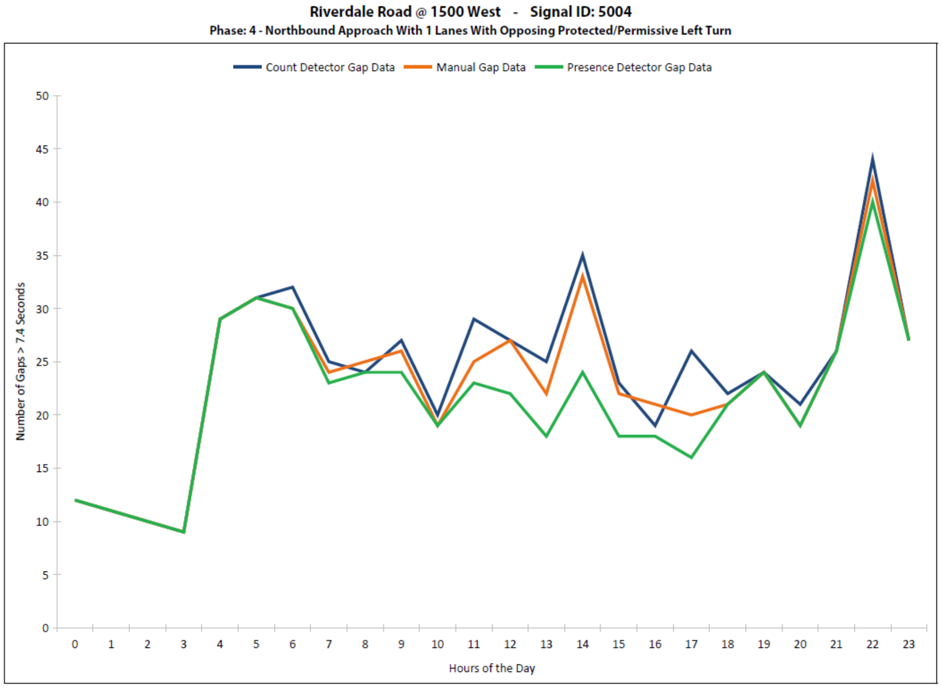

Left Turn Gap Analysis
US-89 (State Street) @ 400 S (Orem) - SIG# 6313
Thursday, June 18, 2020 4:45 AM - Friday, June 19, 2020 4:30 AM
Gaps for Left Turns Crossing Phase 6 Approach
Lane-By_Lane Count
1 - 3.3
3.3 - 3.7
3.7 - 7.4
Over 7.4
% >= 7.4
# Gaps
% Of Gap Time >= 7.4 Seconds
Time (Hours:Minute of Day)


Left Turn Gap Analysis
SR-209 (9000 S) @ 4000 W - SIG# 7421
Monday, June 10, 2020 3:45 AM - Tuesday, June 11, 2020 3:30 AM
Gaps for Left Turns Crossing Phase 2 Approach
Lane-By_Lane Count
1 - 3.3
3.3 - 3.7
3.7 - 7.4
Over 7.4
% >= 7.4
# Gaps
% Of Gap Time >= 7.4 Seconds
Time (Hours:Minute of Day)

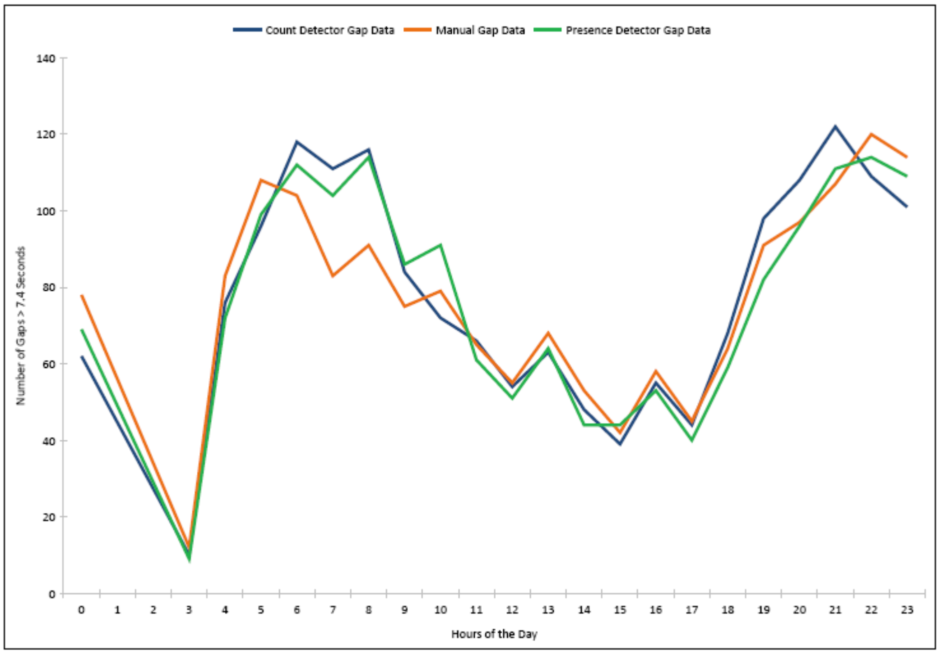

Left Turn Gap Analysis
SR-210 (Wasatch Blvd) @ Bengal Blvd - SIG# 7829
Tuesday, June 16, 2020 4:45 AM - Wednesday, June 17, 2020 4:30 AM
Gaps for Left Turns Crossing Phase 6 Approach
Lane-By_Lane Count
1 - 3.3
3.3 - 3.7
3.7 - 7.4
Over 7.4
% >= 7.4
# Gaps
% Of Gap Time >= 7.4 Seconds
Time (Hours:Minute of Day)

APPENDIX C: COMPARISON OF 24-HOUR DISTRIBUTION PLOT BETWEEN DIFFERENT DATA SOURCES

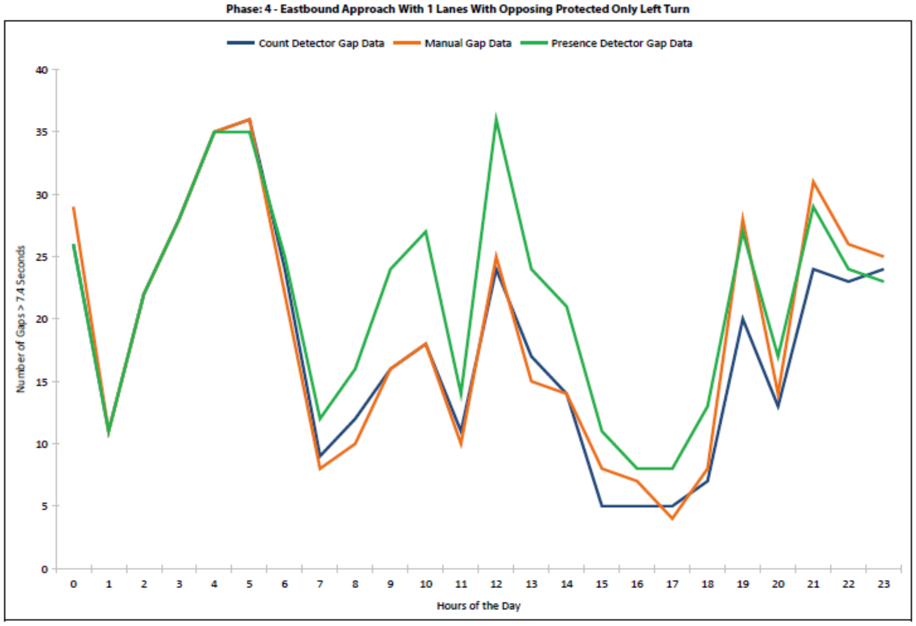
This appendix shows the comparison of 24-hour distribution plots for different approaches with gaps collected from all data sources - manual data, high-resolution data (both presence and count detector).



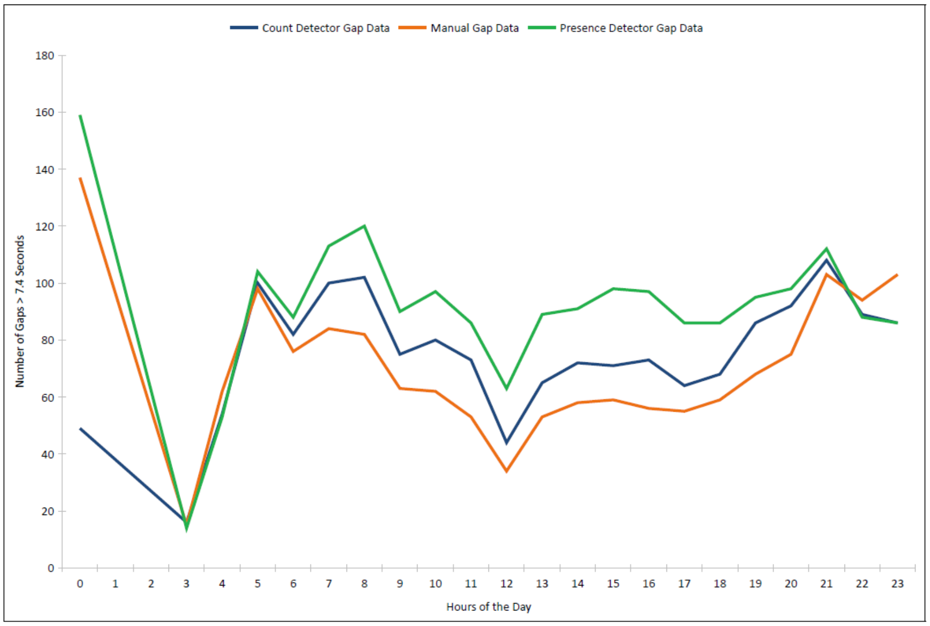
Riverdale Road @ 1500 West - Signal ID: 5004
Phase: 2 - Westbound Approach With 3 Lanes With Opposing Protected/Permissive Left Turn



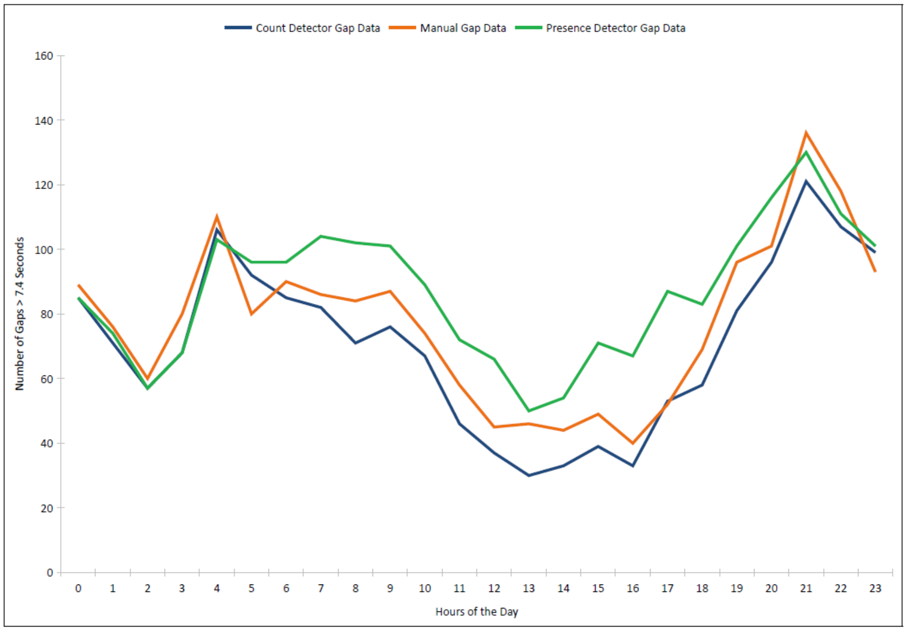
Washington @ 400 North - Signal ID: 5059
Phase: 4 - Eastbound Approach With 1 Lanes With Opposing Protected Only Left Turn



SR-68 (Redwood Rd) @ 1575 N. (Commerce Dr) SSP - Signal ID: 6081
Phase: 2 - Northbound Approach With 2 Lanes With Opposing Protected/Permissive Left Turn

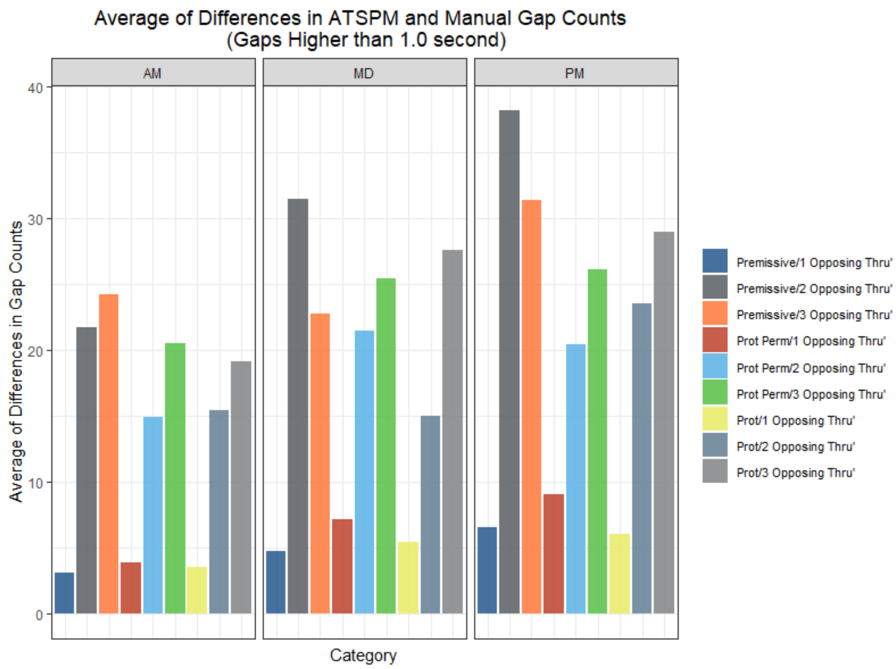


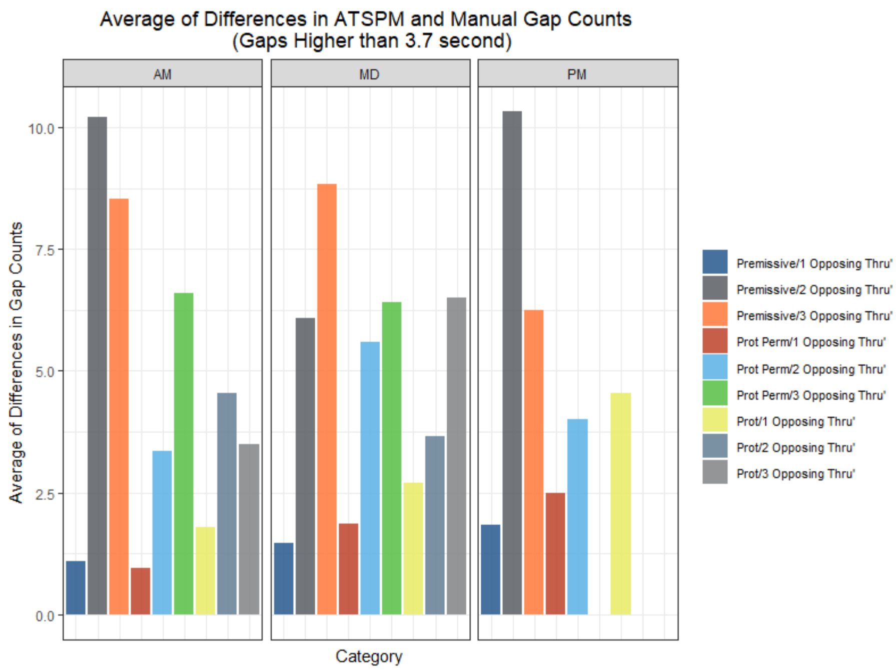
Washington @ 400 North - Signal ID: 5059
Phase: 6 - Southbound Approach With 2 Lanes With Opposing Protected/Permissive Left Turn

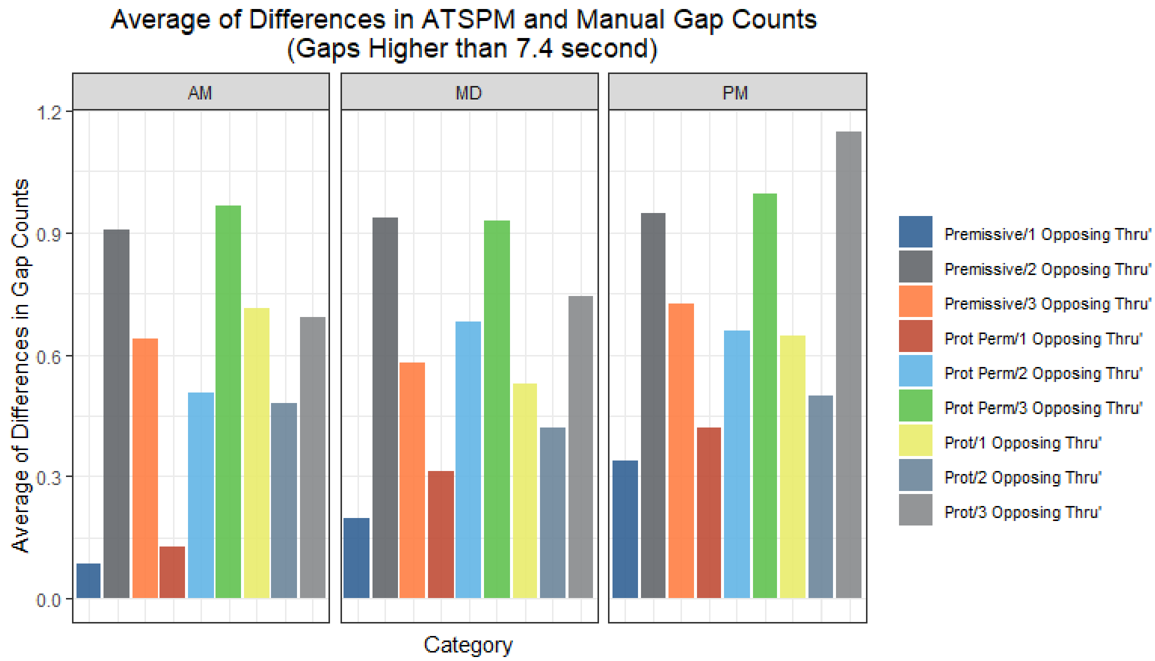


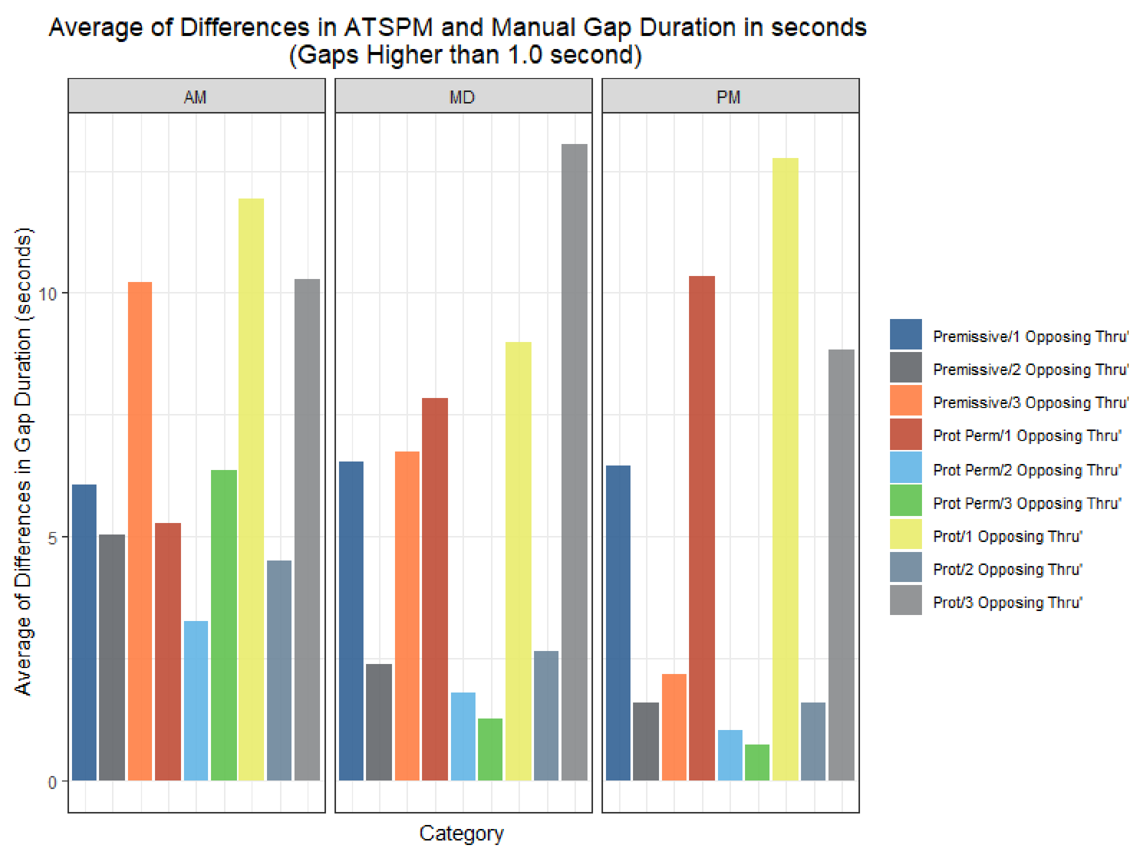
APPENDIX D: LEFT TURN FLAGGING FLOWCHART

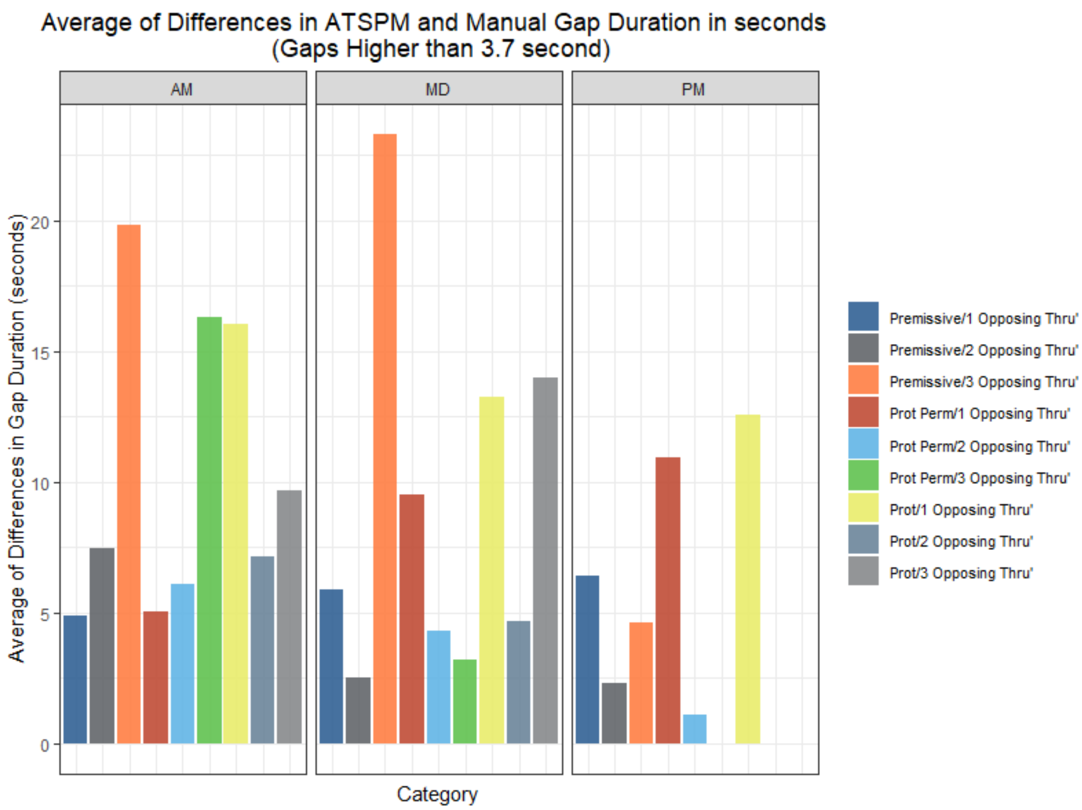
This appendix shows the plots for peak period (AM, Mid-day, and PM peak) averages and standard deviations of gaps and gap durations for each approach configuration.



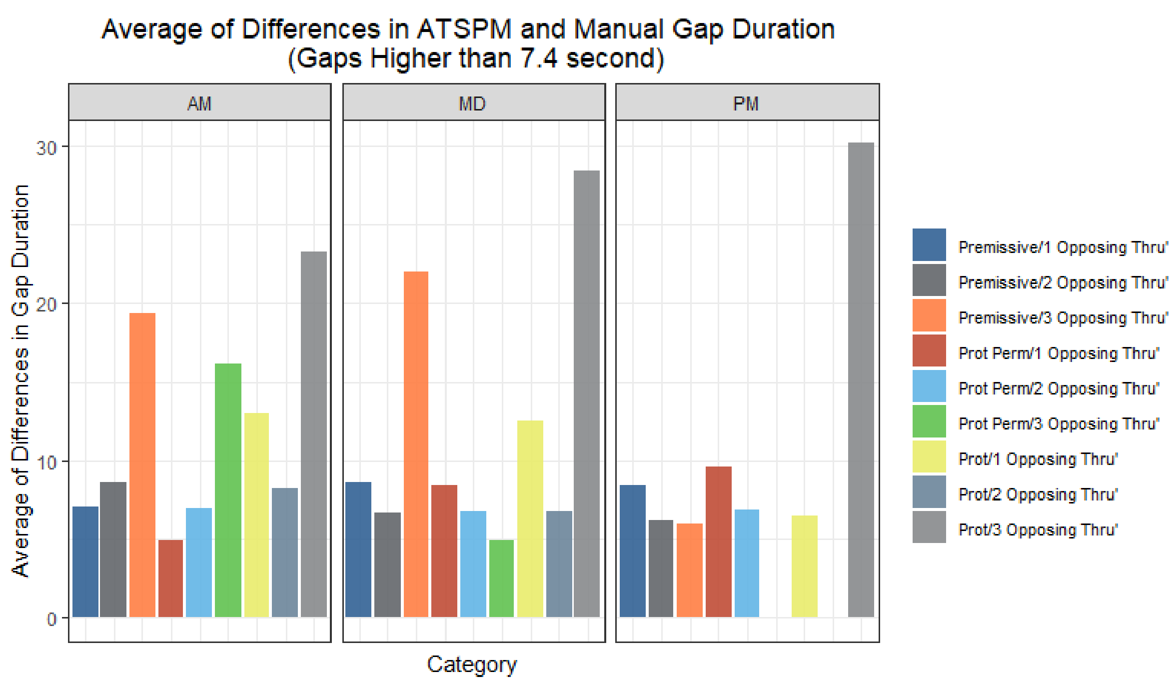



Average of Differences in ATSPM and Manual Gap Counts
(Gaps Higher than 7.4 second)
AM
MD
PM
Average of Differences in Gap Counts
1.2
0.9
0.6
0.3
0.0
Category
Premissive/1 Opposing Thru'
Premissive/2 Opposing Thru'
Premissive/3 Opposing Thru'
Prot Perm/1 Opposing Thru'
Prot Perm/2 Opposing Thru'
Prot Perm/3 Opposing Thru'
Prot/1 Opposing Thru'
Prot/2 Opposing Thru'
Prot/3 Opposing Thru'

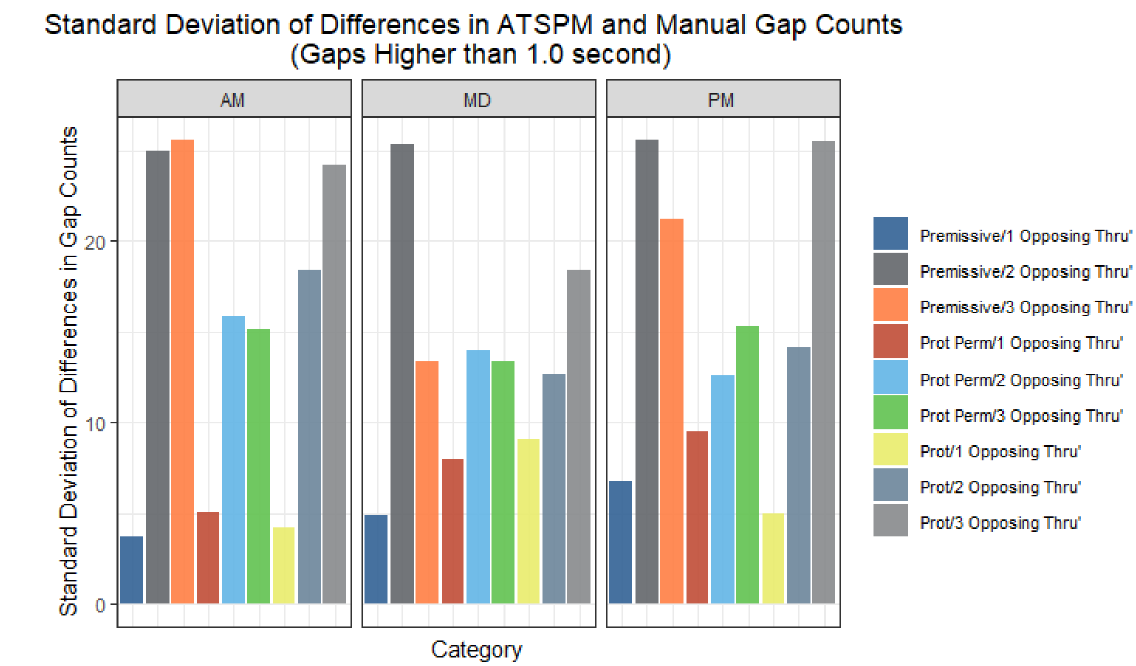

Average of Differences in ATSPM and Manual Gap Duration in seconds
(Gaps Higher than 1.0 second)
AM
MD
PM
Average of Differences in Gap Duration (seconds)
10
5
0
Category
Premissive/1 Opposing Thru'
Premissive/2 Opposing Thru'
Premissive/3 Opposing Thru'
Prot Perm/1 Opposing Thru'
Prot Perm/2 Opposing Thru'
Prot Perm/3 Opposing Thru'
Prot/1 Opposing Thru'
Prot/2 Opposing Thru'
Prot/3 Opposing Thru'

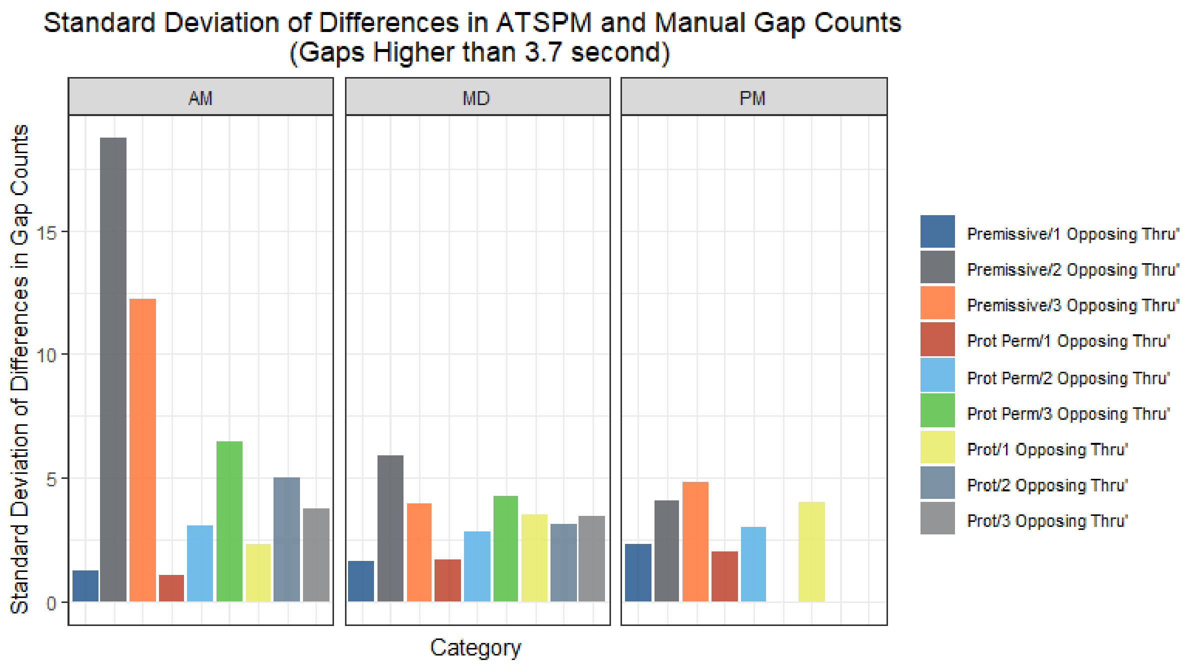


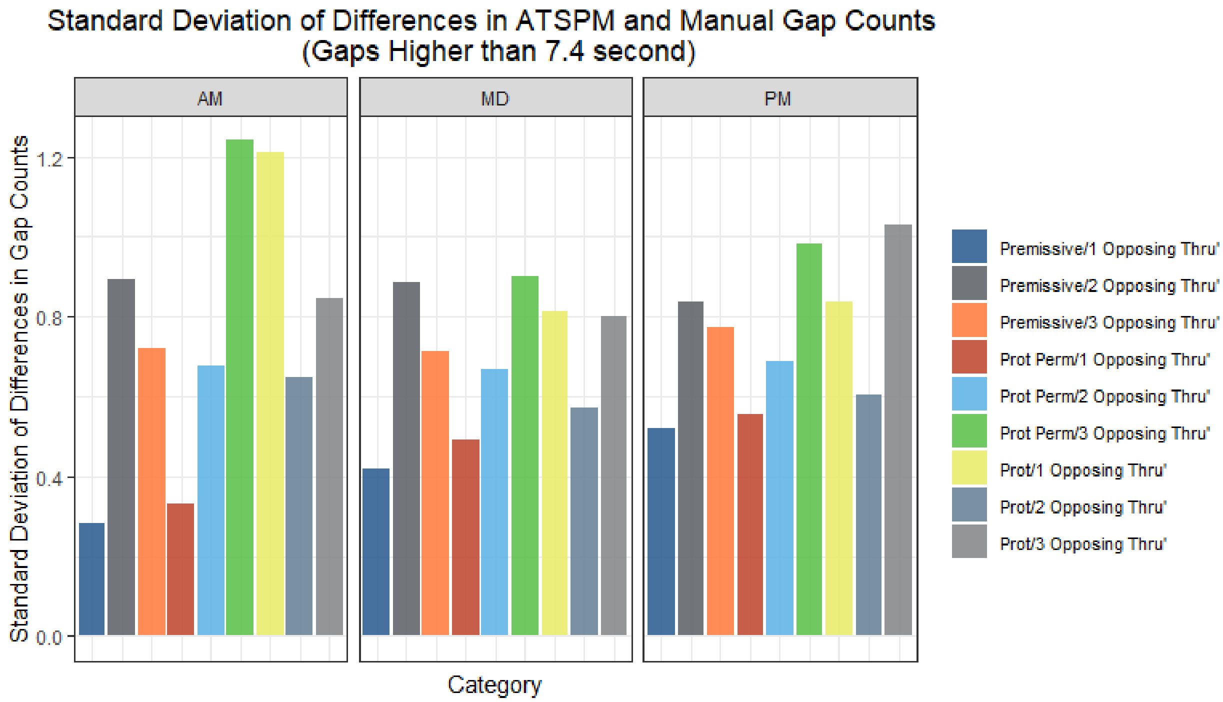
Average of Differences in ATSPM and Manual Gap Duration in seconds
(Gaps Higher than 3.7 second)
AM
MD
PM
Average of Differences in Gap Duration (seconds)
0
5
10
15
20
Category
Premissive/1 Opposing Thru'
Premissive/2 Opposing Thru'
Premissive/3 Opposing Thru'
Prot Perm/1 Opposing Thru'
Prot Perm/2 Opposing Thru'
Prot Perm/3 Opposing Thru'
Prot/1 Opposing Thru'
Prot/2 Opposing Thru'
Prot/3 Opposing Thru'

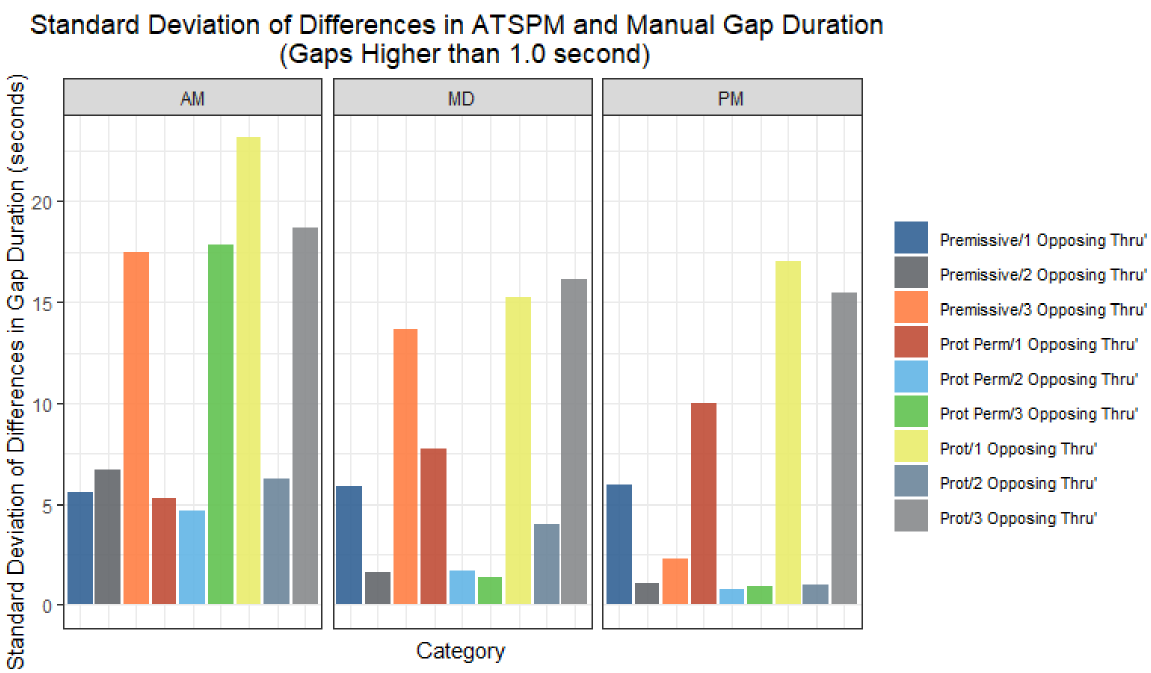


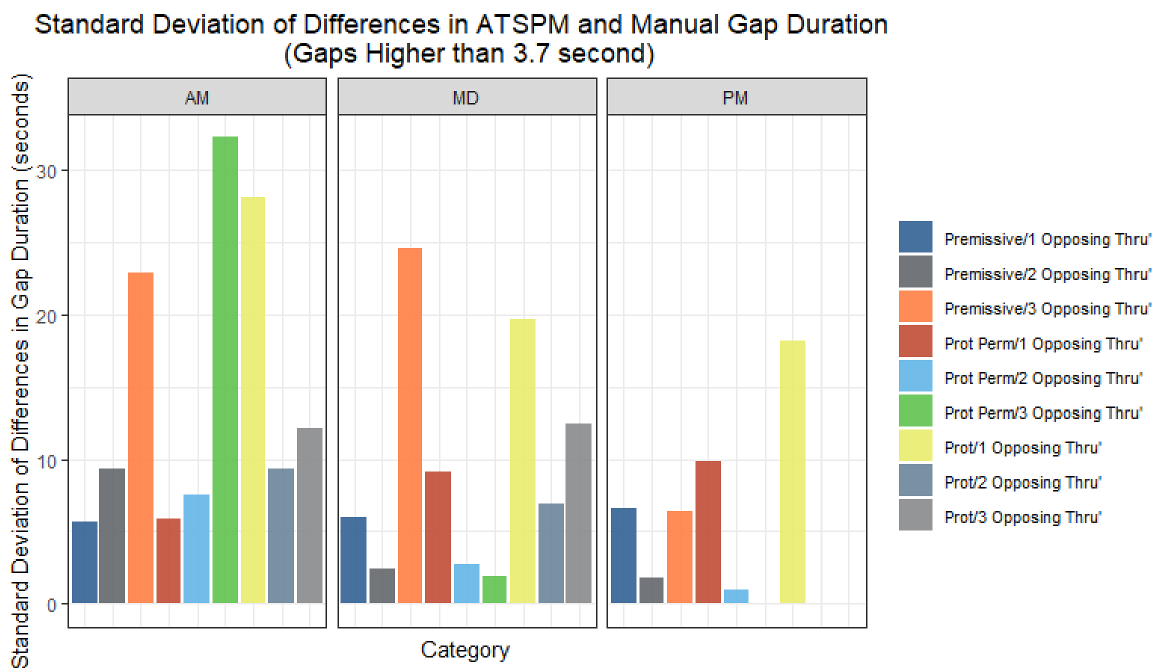
Average of Differences in ATSPM and Manual Gap Duration
(Gaps Higher than 7.4 second)
AM
MD
PM
Average of Differences in Gap Duration
0
10
20
30
Category
Premissive/1 Opposing Thru'
Premissive/2 Opposing Thru'
Premissive/3 Opposing Thru'
Prot Perm/1 Opposing Thru'
Prot Perm/2 Opposing Thru'
Prot Perm/3 Opposing Thru'
Prot/1 Opposing Thru'
Prot/2 Opposing Thru'
Prot/3 Opposing Thru'

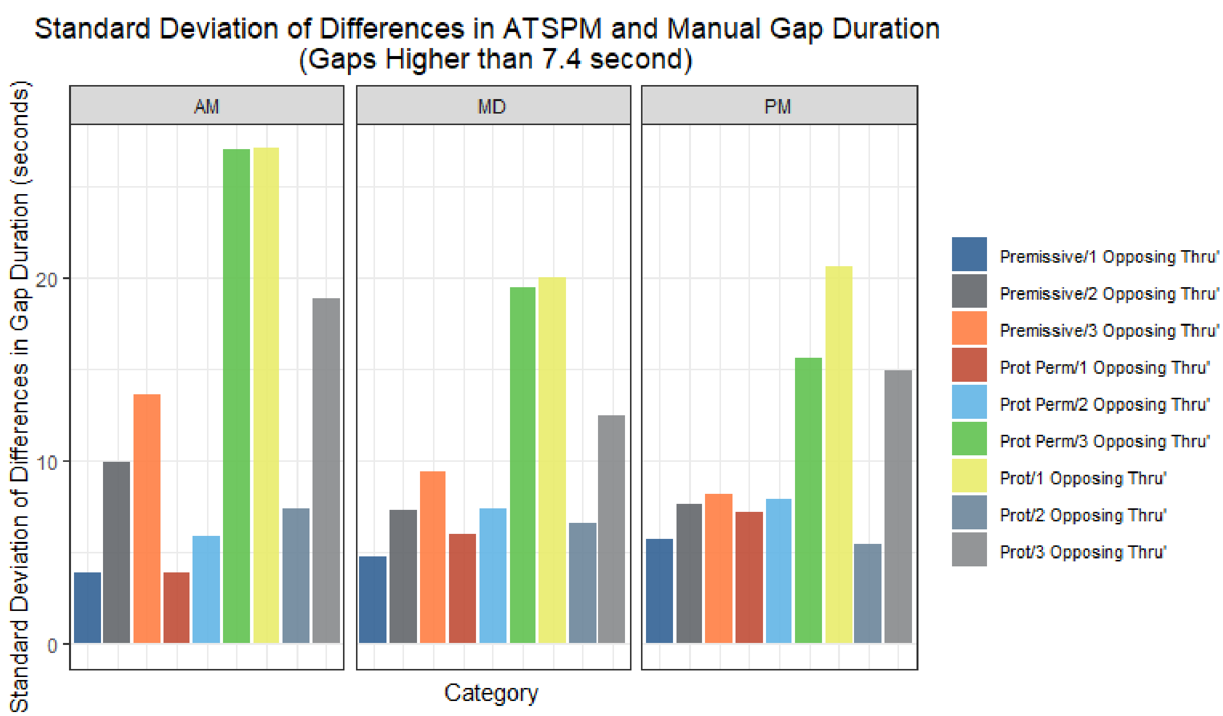

Standard Deviation of Differences in ATSPM and Manual Gap Counts
(Gaps Higher than 1.0 second)
AM
MD
PM
Standard Deviation of Differences in Gap Counts
0
10
20
Category
Premissive/1 Opposing Thru'
Premissive/2 Opposing Thru'
Premissive/3 Opposing Thru'
Prot Perm/1 Opposing Thru'
Prot Perm/2 Opposing Thru'
Prot Perm/3 Opposing Thru'
Prot/1 Opposing Thru'
Prot/2 Opposing Thru'
Prot/3 Opposing Thru'


Standard Deviation of Differences in ATSPM and Manual Gap Counts
(Gaps Higher than 3.7 second)
AM
MD
PM
Standard Deviation of Differences in Gap Counts
0
5
10
15
Category
Premissive/1 Opposing Thru'
Premissive/2 Opposing Thru'
Premissive/3 Opposing Thru'
Prot Perm/1 Opposing Thru'
Prot Perm/2 Opposing Thru'
Prot Perm/3 Opposing Thru'
Prot/1 Opposing Thru'
Prot/2 Opposing Thru'
Prot/3 Opposing Thru'


Standard Deviation of Differences in ATSPM and Manual Gap Counts
(Gaps Higher than 7.4 second)
AM
MD
PM
Standard Deviation of Differences in Gap Counts
1.2
0.8
0.4
0.0
Category
Premissive/1 Opposing Thru'
Premissive/2 Opposing Thru'
Premissive/3 Opposing Thru'
Prot Perm/1 Opposing Thru'
Prot Perm/2 Opposing Thru'
Prot Perm/3 Opposing Thru'
Prot/1 Opposing Thru'
Prot/2 Opposing Thru'
Prot/3 Opposing Thru'


Standard Deviation of Differences in ATSPM and Manual Gap Duration
(Gaps Higher than 1.0 second)
AM
MD
PM
Standard Deviation of Differences in Gap Duration (seconds)
20
15
10
5
0
Category
Premissive/1 Opposing Thru'
Premissive/2 Opposing Thru'
Premissive/3 Opposing Thru'
Prot Perm/1 Opposing Thru'
Prot Perm/2 Opposing Thru'
Prot Perm/3 Opposing Thru'
Prot/1 Opposing Thru'
Prot/2 Opposing Thru'
Prot/3 Opposing Thru'


Standard Deviation of Differences in ATSPM and Manual Gap Duration
(Gaps Higher than 3.7 second)
AM
MD
PM
Standard Deviation of Differences in Gap Duration (seconds)
0
10
20
30
Category
Premissive/1 Opposing Thru'
Premissive/2 Opposing Thru'
Premissive/3 Opposing Thru'
Prot Perm/1 Opposing Thru'
Prot Perm/2 Opposing Thru'
Prot Perm/3 Opposing Thru'
Prot/1 Opposing Thru'
Prot/2 Opposing Thru'
Prot/3 Opposing Thru'


Standard Deviation of Differences in ATSPM and Manual Gap Duration
(Gaps Higher than 7.4 second)
AM
MD
PM
Standard Deviation of Differences in Gap Duration (seconds)
0
10
20
Category
Premissive/1 Opposing Thru'
Premissive/2 Opposing Thru'
Premissive/3 Opposing Thru'
Prot Perm/1 Opposing Thru'
Prot Perm/2 Opposing Thru'
Prot Perm/3 Opposing Thru'
Prot/1 Opposing Thru'
Prot/2 Opposing Thru'
Prot/3 Opposing Thru'

APPENDIX E: LEFT TURN FLAGGING FLOWCHART

This flowchart is the concept for the GUI flagging tool. Initially it was presented as a draft for UDOT which they reviewed and commented on. The flowchart shows the finalized concept after addressing UDOT's comments.