

CHAPTER 1. FINAL REPORT

Data-Driven Evaluation for ADOT Ramp Metering: Developing Ramp Metering Evaluation Tool

Prepared for

Arizona Department of Transportation

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16. ABSTRACT Arizona Department of Transportation (ADOT) has been using ramp metering strategies to improve traffic along SB State Route 51, a 15-mile long corridor in the Phoenix Metropolitan area. The purpose of this project is to develop a responsive evaluation tool to help ADOT improve existing strategies. First, new databases are designed and optimized to collect traffic controller data and third party (INRIX) traffic data in real-time. A software tool is developed to facilitate the data collection process. Second, several performance measures are chosen to facilitate engineering decision making. Finally, a ramp metering evaluation tool is developed to visualize performance measures. The platform has shown significant benefits of helping ADOT fine tune ramp metering strategies and reduce travelers' delay.					
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EXECUTIVE SUMMARY

Ramp metering has been deployed as an effective tool to address reoccurring congestion and safety issues in many states in the U.S. Arizona Department of Transportation (ADOT) has been using ramp metering strategies to actively manage the traffic on the freeway network of the Phoenix Metropolitan area.

The purpose of this project was to develop a ramp metering evaluation tool to assess three possible strategies for ramp metering: 1- fixed time ramp metering, 2- responsive ramp metering, and 3- adaptive ramp metering. A 15-mile corridor along southbound State Route 51 (SB SR-51), in the State of Arizona, was used as a case study site. Due to close collaboration between the University of Arizona (UA) project team and ADOT engineers, many innovative ideas were developed and implemented in this tool to help ADOT better manage their freeways.

Different performance measures are utilized to quantify the impacts of each strategy on the freeway traffic operations,.

The following topics are explored in this project:

- Designing and optimizing existing databases to collect real-time traffic data;
- Identifying the performance measurements for ramp metering evaluation;
- Identifying the statistical methods for ramp metering evaluation;
- Developing a ramp metering evaluation tool to visualize the results of three different ramp metering control strategies in terms of different performance measures and statistical methods.

First, new databases are designed and optimized to collect traffic controller data and third party (INRIX) traffic data in real-time. A software tool is developed to facilitate the data collection process. In this project, MaxView loop-based data, MaxView cabinet event-based data, and INRIX data are collected from ADOT and INRIX's cloud API. The data collection tool is packaged into one standalone piece of software written in C#. The collection tool reformats all the raw data into an easy to use format and stores them into three different databases: a MaxView loop-based database, a MaxView cabinet event-based database, and an INRIX Database. The first two databases are located at the "TSMO ITS" database on ADOT's "tocsqlddev" server. The INRIX Database is located at UA based on storage capacity.

Second, several performance measures are chosen to facilitate engineering decision making. Each corridor is evaluated based on a variety of criteria including speed analysis, flow analysis, speed-flow analysis, delay analysis, cost-benefit analysis, and real-time monitoring. Those key performance measures are identified through published literature while also considering data availability and simplicity. The identified performance measures are demonstrated using data obtained from the adaptive ramp meter study corridor.

Finally, a ramp metering evaluation tool is developed to visualize the performance measures. The purpose of the ramp metering evaluation tool is to provide ADOT with a tool that they can use to evaluate the performance of their ramp meters and to quantify improvement in a before and after scenario. The ramp metering evaluation tool is written in the open-source programming language “R”. It is hosted by the UA on their web-servers. The platform developed in this project has shown significant benefits of helping ADOT tune up their ramp metering strategies to reduce travelers’ delay.

To further assist ADOT in tuning up the ramp metering control strategies, the UA project team made the following conclusions and recommendations:

- The tool utilizes the traffic data coming from loop-based data and INRIX data. Both data sources provide complimentary analytical results to give a comprehensive view of roadway conditions;
- Compared with fixed ramp meters, responsive ramp meters result in lower speeds and longer travel times for both mainlines and ramps during peak hours;
- Changing ramp metering control strategies from responsive mode to adaptive mode can increase mainline speed and reduce mainline congestion;
- Additional performance measures and analytical modules could be added into the evaluation tool using the data collected in this project, such as a network wide ramp monitoring module using cabinet event-based data, or a capacity analysis module;
- To maximize the versatility of the tool, the proposed tool could be used to analyze traffic speed differentials on the entire freeway network throughout the state of Arizona.
- The tool needs to be routinely updated as do all computer software packages. A maintenance plan should be developed, and the related costs should be budgeted.

It was found that the ramp metering evaluation tool can be regarded as an effective way of helping ADOT traffic engineers to continuously and consistently evaluate ramp metering strategies in a cost-effective manner, and ADOT can dynamically implement ramp metering strategies based on the analysis results.

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CHAPTER 1. INTRODUCTION

Ramp metering is known to be an effective freeway control strategy to increase the overall efficiency and safety of a highway system by regulating the inflow traffic of on-ramps. Therefore, it is crucial for agencies to assess the performance of their ramp meters.

Arizona Department of Transportation (ADOT) has been using ramp metering strategies to actively control the traffic on the freeway network of the Phoenix Metropolitan area since 1972. This project aimed at developing an evaluation tool to assess three possible strategies for ramp metering: 1) fixed time ramp metering, 2) responsive ramp metering, and 3) adaptive ramp metering. Performance measures are utilized to quantify the impacts of each strategy on the freeway traffic operations,. Through close collaboration between the University of Arizona (UA) project team and ADOT engineers, many innovative ideas were developed and implemented in this tool to help ADOT better manage their freeways.

The major benefits of this project are: 1) ADOT traffic engineers can continuously and consistently evaluate ramp metering strategies in a cost-effective manner, 2) ADOT can dynamically implement traffic management (ramp metering) strategies based on the analysis results, and 3) road users would experience less delay and be more satisfied with ADOT's services due to the continuous improvement in traffic conditions.

1.1 Project Objectives

The following topics are explored in this project:

- Designing and optimizing new databases to collect real-time traffic data;
- Identifying the performance measurements for ramp metering evaluation;
- Identifying the statistical methods for ramp metering evaluation;
- Developing a ramp metering evaluation tool to visualize the evaluation results of three different ramp metering control strategies in terms of different performance measures and statistical methods;

1.2 Study Corridor

The corridor selected for the initial study is southbound State Route 51 SR-51, a 15-mile corridor in Phoenix, as highlighted in Figure 1. SR-51, also known as the Piestewa Freeway, is a numbered state highway in Phoenix, Arizona. It connects from Interstate 10 just outside Downtown Phoenix to Loop 101 on the north side of Phoenix, making it one of the area's major freeways. It is a largely north-south route and is known for traversing the Piestewa Peak Recreation Area.

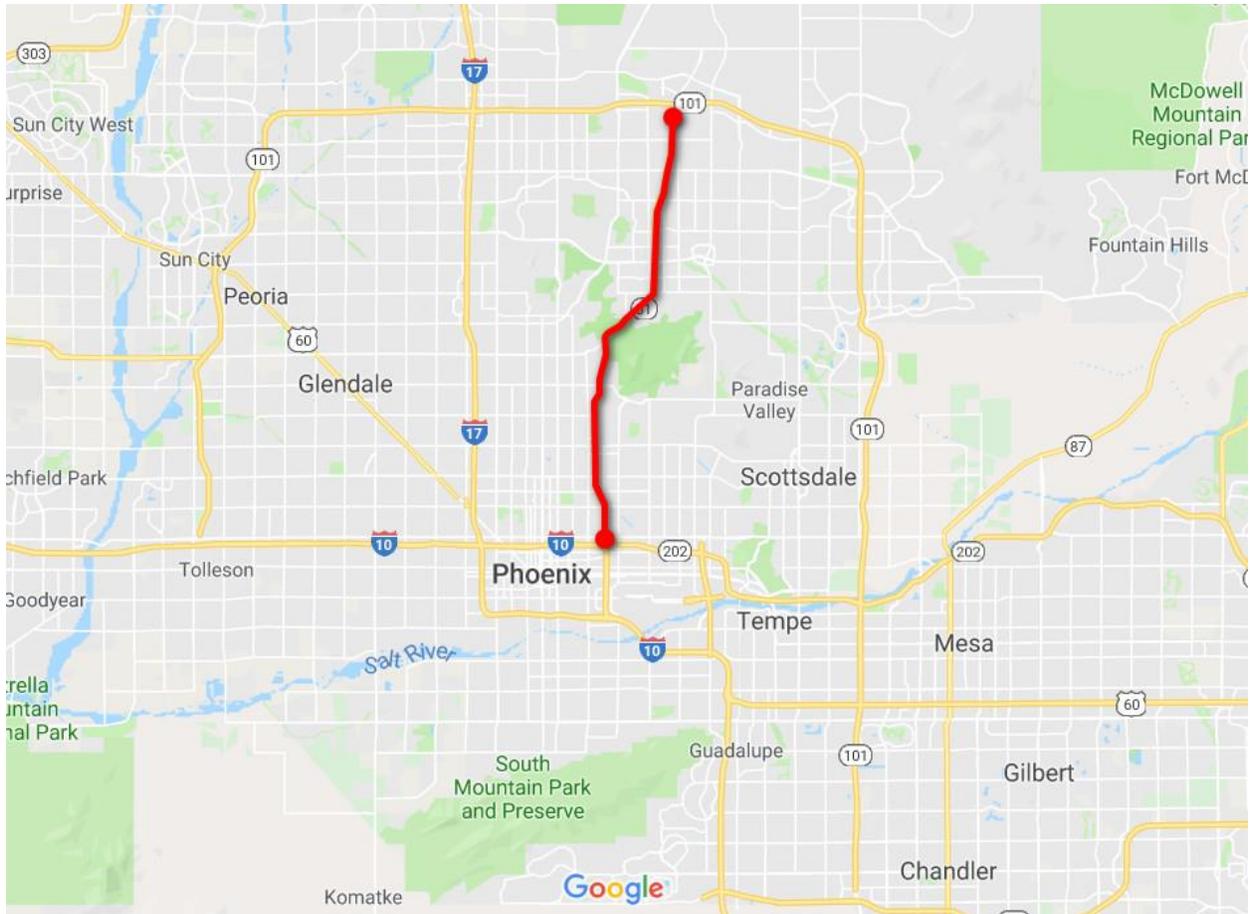


Figure 1 SR 51 Study Corridor in Phoenix (Map Source: Google Maps)

1.3 Project Framework

The project framework is presented in Figure 2. The overall approach involves the collection of data and visualization of data. Both the MaxView loop-based data and the MaxView cabinet event-based data are sourced from the MaxView SQL database at ADOT. INRIX data is sourced from the INRIX cloud.

A data collection tool is developed to automatically collect data from the MaxView SQL database and through using the INRIX API. The data collection tool can facilitate the collection and transfer of MaxView loop-based data and MaxView Controller Event-Based data. The MaxView loop-based data in its original format is very difficult to use in practice, so the tool reformats it into an easy to use format. Similarly, the data collection tool can collect INRIX data from the INRIX cloud API, and process it into a format compatible with SQL.

The data from the data collection tool is saved to three different databases: a MaxView loop-based database, a MaxView cabinet event-based database, and an INRIX Database. The purpose of the ramp metering evaluation tool is to provide ADOT with a tool that they can use to evaluate the performance of their ramp meters, and to quantify the improvement in a before and after scenario using the above mentioned three databases. The performance measures will be calculated and visualized to evaluate different ramp metering strategies. These measures can be utilized to analyze each segment as well as the entire corridor.

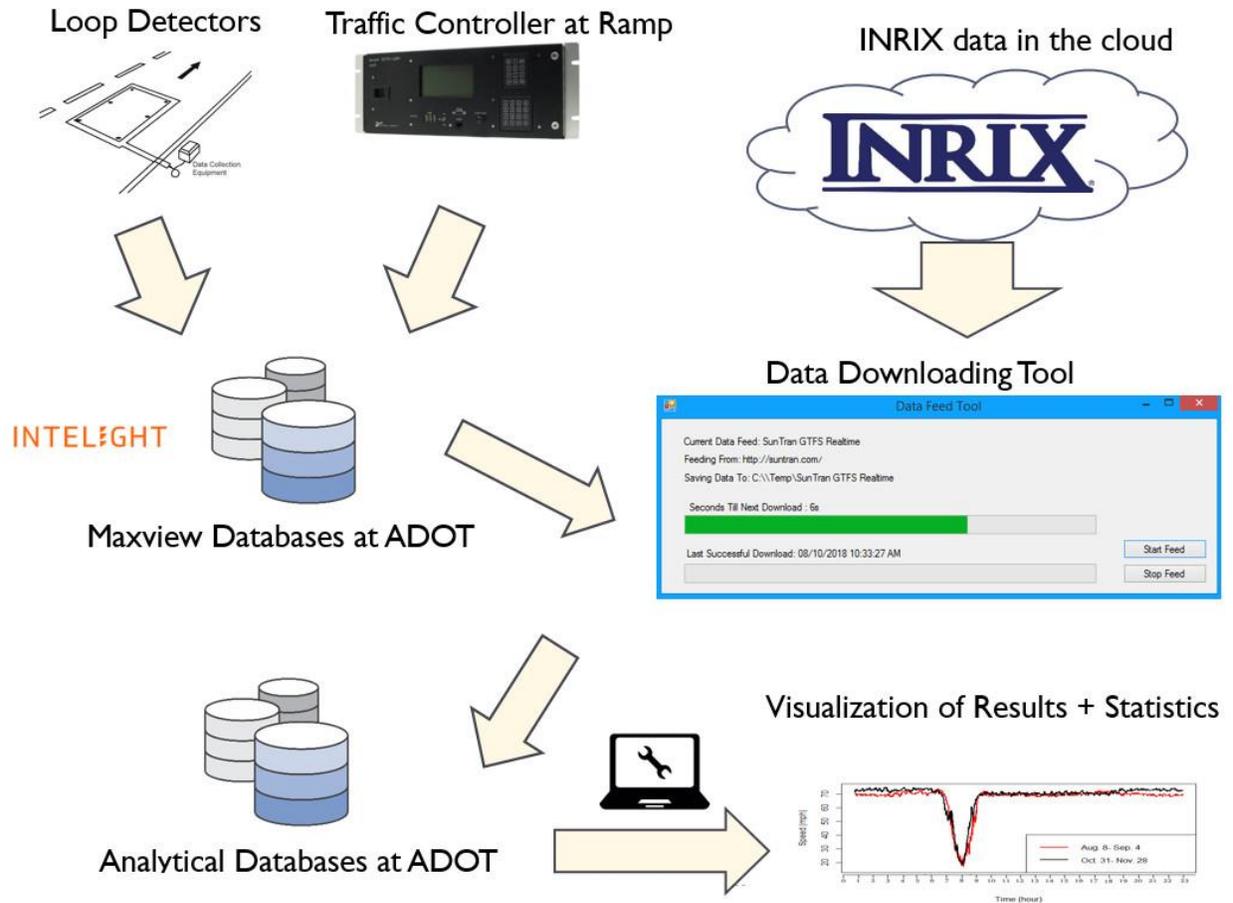


Figure 2 Project Framework

CHAPTER 2. LITERATURE REVIEW

This chapter establishes the state of practice by addressing the following questions:

- What relevant performance measurements are used for ramp metering evaluation?
- What relevant statistical methods are used for ramp metering evaluation?
- What practices implemented by other states can provide guidance?

These questions are addressed to better understand the research problem.

2.1 Performance Measurements for Ramp Metering Evaluation

The literature review completed in the preliminary study focused on best practices. This task is to continuously review literature related technical reports and academic papers, focusing on 1) performance measurement methods, and 2) statistical methods for ramp metering evaluation.

Table 1 presents the study sites and corresponding performance measures used for ramp metering evaluation. Speed, travel time, traffic flow, delay, and economic benefits are some of the most frequently used performance measures. Considering data availability and simplicity, this project chose speed, flow, speed-flow, delay, and cost-benefit as the criteria for ramp metering evaluation.

Table 1 Performance Measurements for Ramp Metering Evaluation

Reference	Study site	Performance measures
(Diakaki, Papageorgiou and McLean, 2000)	M8 corridor in Glasgow, Scotland	Users' acceptance assessment, travel times throughput
(Levinson and Zhang, 2006)	Twin Cities, Minnesota State	Mobility, equity, productivity, consumers' surplus, accessibility, productivity, accessibility, travel time variation, and travel demand responses
(Ahn <i>et al.</i> , 2007)	OR-217 corridor in Portland, Oregon State	Travel time, delay, vehicle miles traveled, vehicle hours traveled
(Papamichail <i>et al.</i> , 2010)	Monash Freeway, Australia	Speed, traffic flow, productivity, mean speed deviation, reliability
(Bhourri and Kauppila, 2011)	The motorway section A6W in Paris, French	Travel time variability, the monetary value of time-savings benefits
(Li <i>et al.</i> , 2012)	East 4 th ring Rd. of Beijing, China	Reduplicated waiting time
(Haj-Salem, Farhi and Lebacque, 2012)	The motorway section A6W in Paris, French	Total traveled time, total travel distance, mean speed, congestion mapping, safety index, fuel consumption
(Xie, Hoefft and Grayson, 2012)	US 95 in Las Vegas, Nevada	Average speed, speed standard deviation, interquartile speed range, travel time index, buffer index, delay volume, average vehicle delay
(Faulkner <i>et al.</i> , 2014)	M1 and M3 Freeways in Queensland, Australia	Congestion, speed, volume, travel speed reliability, ramp delays, economic benefits
(Haj-Salem, Farhi and Lebacque, 2014)	Ile de France motorway network	Total traveled time, total travel distance, mean speed, congestion mapping, fuel consumption, pollutant emission
(Cohen <i>et al.</i> , 2017)	The motorway section A25 of the French	Travel time, travel time variability, capacity, level of service

2.2 Statistical Methods for Ramp Metering Evaluation

A z-test is a statistical test used to determine whether two population means are different when the sample size is large. The z-test performs better when used with more than 30 samples. Table 2 shows that in previous studies, those reviewed employ t-test as their statistical method to conduct comparison. In this project, considering the relatively large sample size, it is reasonable to use z-test instead of t-test to conduct statistical analysis, based on the definition of the z-test. A t-test is used when there are up to 30 samples, but because of the volume of the data used in this study, a z-test was chosen because there would always be greater than 30 samples.

All the segments with ramp meters in the study corridor will be analyzed based on the defined statistical methods and one or more of the performance measures identified in *Chapter 2.1: Performance Measurements for Ramp Metering Evaluation*. The analysis for the study corridor and individual ramps is aimed at providing ADOT with an understanding of the effectiveness of different ramp metering algorithms as well as the system performance.

Table 2 Statistical Methods for Ramp Metering Evaluation

Author, year,[Ref]	Statistical Methods	Conclusions
(Zheng and McDonald, 2007)	t-test	After ramp meter turned on, the distribution of the number of eye movements in each merging operation is significantly different from that of metering off. Merging drivers tend to take more looks back when ramp metering is in operation.
(Zhang and Levinson, 2010)	t-test	Ramp metering increases the capacity at freeway bottlenecks
(Sun, Edara and Zhu, 2013)	t-test, F-test	The changes in mean speed and standard deviation of speed for both mainline and ramp are statistically significant, with and without ramp metering.
(Osman <i>et al.</i> , 2015)	t-test	The changes in mean speed are statistically significant, with and without ramp metering.

CHAPTER 3. DATA DESCRIPTION

The purpose of this chapter is to describe the three data sources briefly. This includes the introduction of data sources and the raw data format.

3.1 MaxView loop-based data

The MaxView loop-based data is sourced from the MaxView SQL database at ADOT. Currently, the data source location is on the “tocsq102” Microsoft SQL server, and the table in the MaxView database is “[dbo].[VolumeOccupancyEvents]”. A sample of the raw data format is given in Table 3.

Table 3 MaxView loop-based data Sample

ID	Data	VoIOccDataTypeID	GroupableElementID	TimeStamp	SequenceNumber
500173843	1=0;2=0;3=0;4=0;	2	40	01/03/2019 01:10:40	219
500173844	1=0;2=0;3=0;4=0;	1	133	01/03/2019 01:10:40	108
500173845	1=0;2=0;3=0;4=0;	2	133	01/03/2019 01:10:40	108

3.2 MaxView cabinet event-based data

The MaxView cabinet event-based data is sourced from the MaxView SQL database at ADOT. Currently, the data source location is on the “tocsq102” Microsoft SQL server, and the table in the MaxView database is “[dbo].[ASC_RampMeter_Events_<date>]”, where <date> is the most recent available week date given in MaxView. Currently, only ramp-metering events are collected. A sample of the raw data format is given in Table 4. Currently the cabinet event-based data is being archived for use in future projects for low level analysis and for network monitoring, but was not used during this study.

Table 4 MaxView cabinet event-based data Sample

TimeStamp	DeviceId	EventId	Parameter
01/07/2019 11:49:13	160	1372	116
01/07/2019 11:49:13	160	1373	89
01/07/2019 11:49:33	160	1371	1368
01/07/2019 11:49:33	160	1372	91

3.3 INRIX Data

The INRIX data is collected directly from INRIX’s cloud API. Details about the API can be found at <http://docs.INRIX.com/>. The data consists of speed and travel time data for the whole of Arizona and is collected every minute. The raw data is returned in XML format, as shown in Figure 3.

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```
<SegmentSpeedResultSet coverage="255">
  <SegmentSpeedResults timestamp="2019-01-07T20:38:21Z">
    <Segment code="1226245398" type="XDS" speed="52" average="52" reference="52" travelTimeMinutes="1.09" speedBucket="3" />
    <Segment code="1226245382" type="XDS" speed="60" average="60" reference="60" travelTimeMinutes="0.638" speedBucket="3" />
    <Segment code="384894385" type="XDS" speed="52" average="52" reference="52" travelTimeMinutes="0.369" speedBucket="3" />
    <Segment code="1226207075" type="XDS" speed="35" average="35" reference="36" travelTimeMinutes="1.412" speedBucket="3" />
    <Segment code="1226220322" type="XDS" speed="34" average="35" reference="36" travelTimeMinutes="1.041" speedBucket="3" />
    <Segment code="122118196" type="XDS" speed="36" average="35" reference="36" travelTimeMinutes="0.585" speedBucket="3" />
    <Segment code="1226220360" type="XDS" speed="30" average="35" reference="36" travelTimeMinutes="1.168" speedBucket="2" />
    <Segment code="1226247765" type="XDS" speed="31" average="37" reference="37" travelTimeMinutes="1.145" speedBucket="2" />
    <Segment code="1226263096" type="XDS" speed="48" average="45" reference="45" travelTimeMinutes="0.503" speedBucket="3" />
    <Segment code="1226263039" type="XDS" speed="47" average="41" reference="40" travelTimeMinutes="0.51" speedBucket="3" />
    <Segment code="1226242921" type="XDS" speed="31" average="35" reference="33" travelTimeMinutes="0.498" speedBucket="3" />
  </SegmentSpeedResults>
</SegmentSpeedResultSet>
```

Figure 3 A Screenshot of INRIX Raw Data XML Format

CHAPTER 4. REAL-TIME DATA COLLECTION TOOL

This chapter introduces the architecture and implementation of the real-time data collection tool.

4.1 Architecture

The data collection tool is packaged into one standalone piece of software written in C#. It has four tabs: INRIX Data, MaxView Data, FTP Receiver, and Settings. Each tab is explained and detailed below.

4.1.1 INRIX Data Tab

The primary purpose of the INRIX Data tab is to collect INRIX data from the INRIX cloud API, process it into a format compatible with SQL, and then save the raw data, save the data as a CSV, and insert the data into a SQL table depending on the user's selection. It also provides the ability to create the necessary SQL tables for the tool, and can automatically update an INRIX segment table with information on each segment. Furthermore, if at any step in the process an error occurs the tool will automatically send a warning email to staff. Figure 4 gives a view of the INRIX tab during run time.

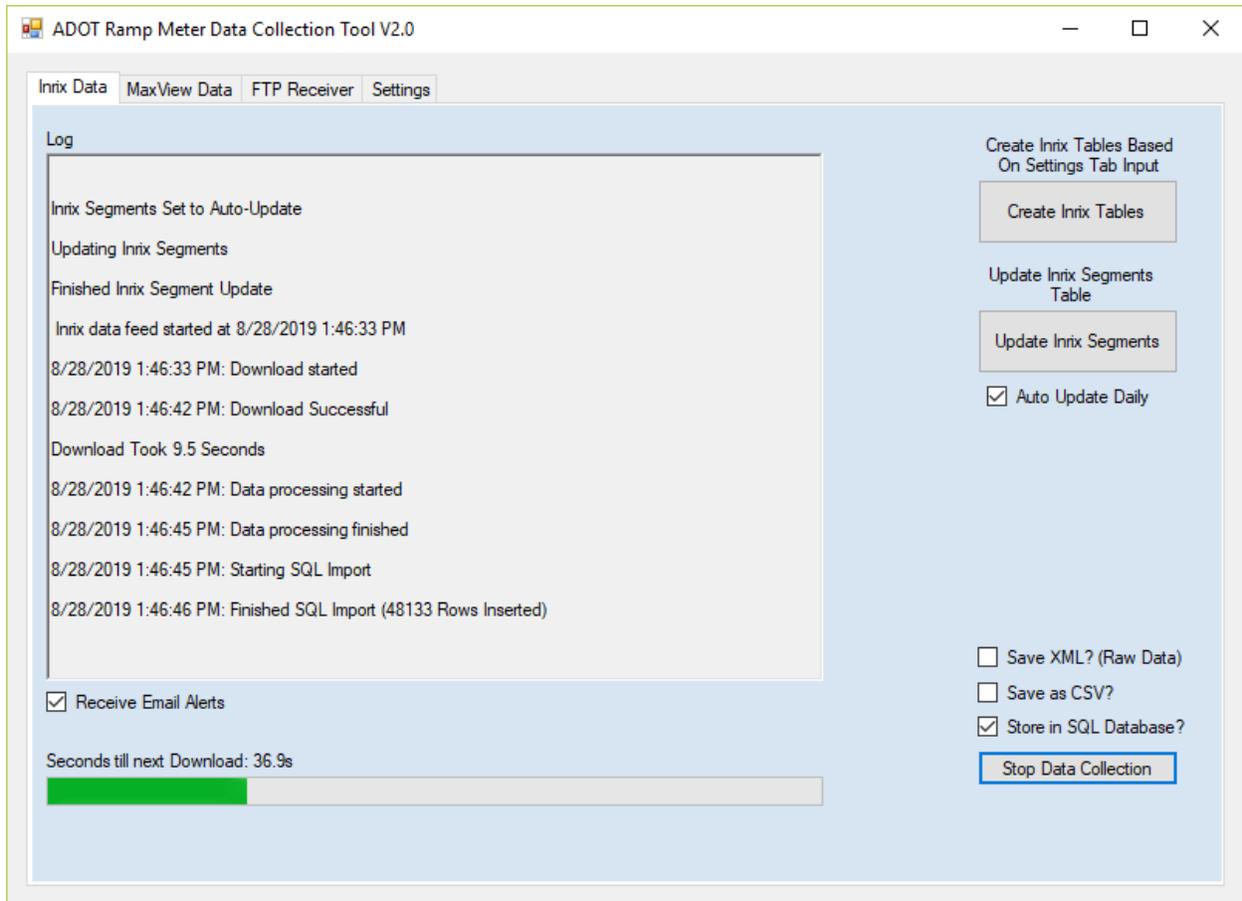


Figure 4 A Screenshot of INRIX Data Tab Running

Every minute the tool queries the INRIX API for the newest data for the whole state and receives the data in a response formatted as XML. If the user selected “Save XML” then this raw data is directly saved to the hard drive and ordered according to the query timestamp. The XML data is then parsed and sent to a multi-threaded data processor. The data processor splits the XML data into several “data-chunks” and each thread converts the XML formatted data-chunk into a row and column-based format that is compatible with SQL. The data processor then collects all the re-formatted data-chunks and reorders them back together into a final dataset formatted for SQL. If the “Save as CSV” option is selected, this data is directly written to the hard drive and ordered according to the query timestamp. Next, if the “Store in SQL Database” option is selected, the data is read into a C# DataTable and is inserted into SQL using a “BulkInsert”. Once the whole process is completed, the time used during processing is calculated, and the remaining time in the query interval (1 minute) is set as a countdown delay. Once the countdown delay has finished, the process begins all over again. All of the parameters and locations required for the process are defined in the Settings tab, and will be discussed in the Settings tab section. A summary of the entire INRIX Data Collection process is shown in Figure 5.

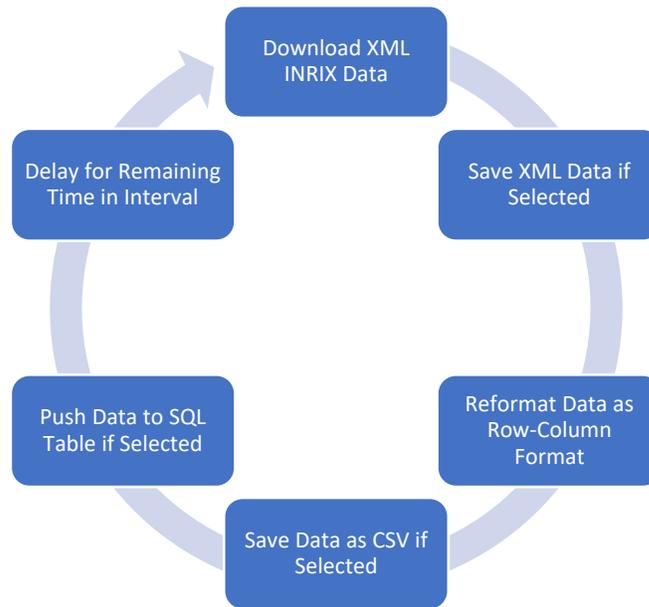


Figure 5 The INRIX Query Process

4.1.2 MaxView Data Tab

The purpose of the MaxView Data tab is to facilitate the collection and transfer of MaxView loop-based data and MaxView Controller Event-Based data. The MaxView loop-based data in its original format is very difficult to use in practice. For this reason, the tool reformats it into an easy to use format. The tool automatically scans for the newest database version with every cycle (1 minute by default), because the MaxView database changes with each MaxView update. The tool can also create the tables required for saving the data to SQL, or send the data to an FTP site as a CSV file. If at any step in the process an error occurs the tool will automatically send a warning email to staff. A screenshot of the MaxView Data tab is shown in Figure 6.

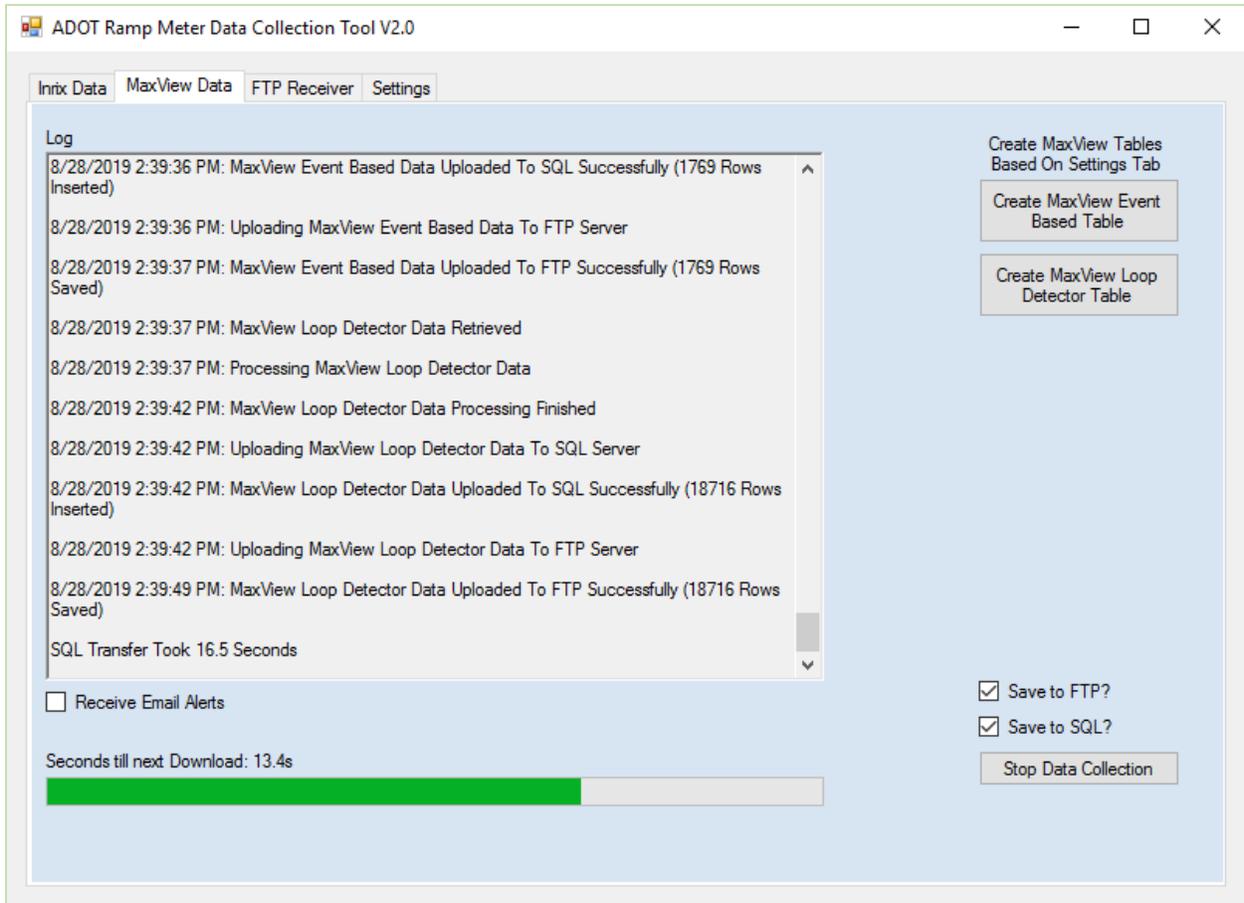


Figure 6 A Screenshot of MaxView Data Tab Running

The MaxView Data tab collects data every minute by default, but the query interval is configurable in the Settings tab. First, the tool queries the source SQL server for Databases, and determines the newest MaxView database version. Next, the tool scans the MaxView database for Tables, and finds the newest cabinet event-based data tables and chooses the newest data table as the source (MaxView creates separate data tables for every week). It then collects the cabinet event-based data from the last minute and either pushes it to SQL or saves it as a CSV to an FTP site, or both depending on the user’s selection. The loop data from the last minute is queried and passed to a data processor. The original data format is shown in Table 3, and it is not very usable because all the data is put into one data column. For this reason, the data processor reformats the data so that each row represents one data point, rather than having multiple data points in one row like the original data format. A sample of the new data format is shown in Table 5.

Table 5 Sample MaxView loop-based data New Format

ID	TimeStamp	DetectorstationID	SlotNumber	Volume	Speed	Occupancy	SequenceNumber
702389924	04/09/2019 12:12:20	310	33	4	81	4	NULL
702389924	04/09/2019 12:12:20	310	34	4	81	4	NULL
702389924	04/09/2019 12:12:20	310	35	2	73	2	NULL

Once the data processor is finished reformatting the data to the new format, it pushes it to SQL, saves it as a CSV to an FTP site, or both depending on the user’s selection. Next, the remaining time in the query interval is calculated, and a countdown delay is started for the remaining time. Once the countdown timer finishes, the entire process starts all over again. A summary of the entire MaxView Data Collection process is shown in Figure 7.

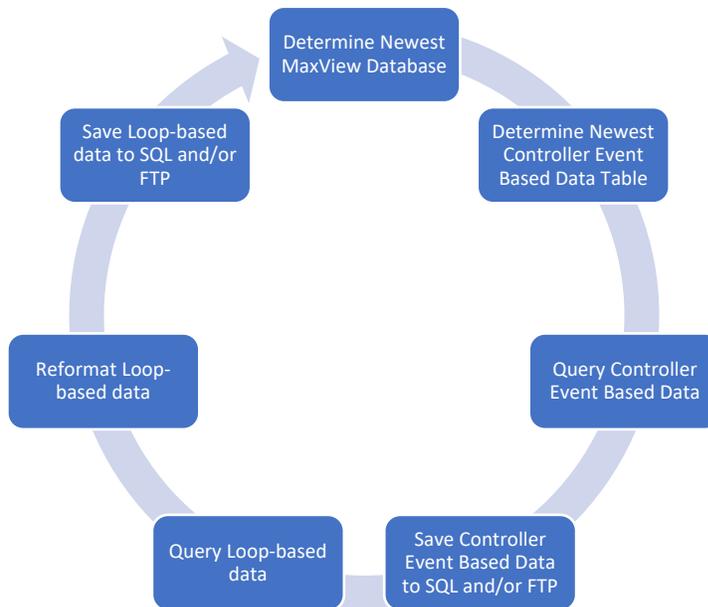


Figure 7 The MaxView Data Query Process

4.1.3 FTP Receiver Tab

The FTP Receiver tab simply scans the designated folder on the FTP site for new MaxView loop-based data or MaxView Controller Event-Based data every minute, and uploads any data found to the SQL server. The MaxView Data tab (Section 4.1.2) is the source of the FTP data, and is used to send real time data from one network to another. Note that this means two copies of the Data Collection Tool have to be running, one for sending data and the other to receive it. A screenshot of the FTP Receiver tab is shown in Figure 8.

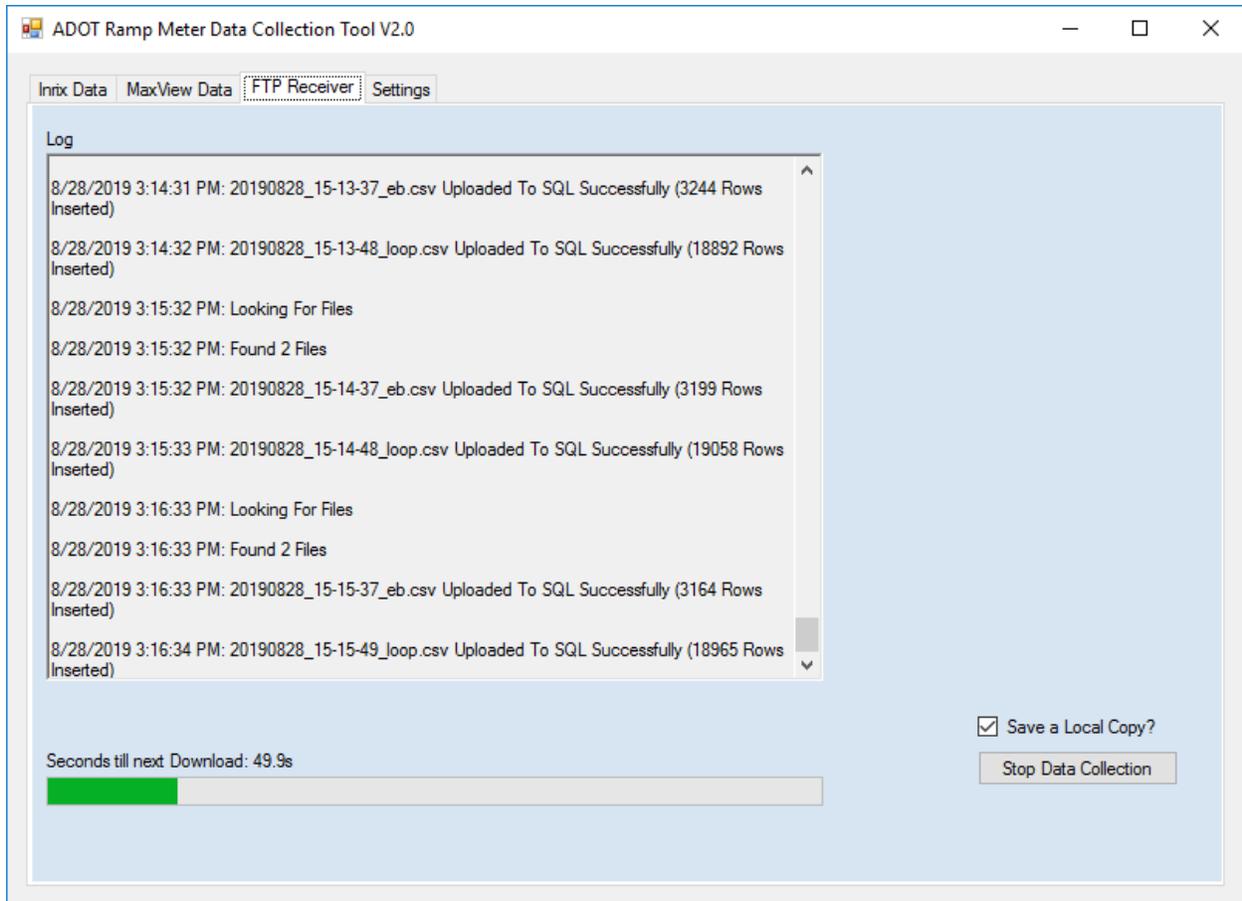


Figure 8 A Screenshot of FTP Receiver Tab Running

Every minute the FTP Receiver tab gets a list of the files in the designated FTP site folder, and if it finds files it determines if they are valid, and if they are loop-based data or controller event-based data. If no files are found, it just waits for another minute and then tries again. If files are found, it then parses each file and reads each one into its own C# DataTable, and then uses a SQL BulkCopy to insert them into their corresponding SQL table. If the “Save a Local Copy” box is checked, the CSV files will be organized into a designated location, otherwise they are deleted. Once it completes the SQL insertion process for every file found, a countdown delay is started for one minute. Once the countdown delay is finished, the entire process begins again. A simple overview of this process is given in Figure 9.

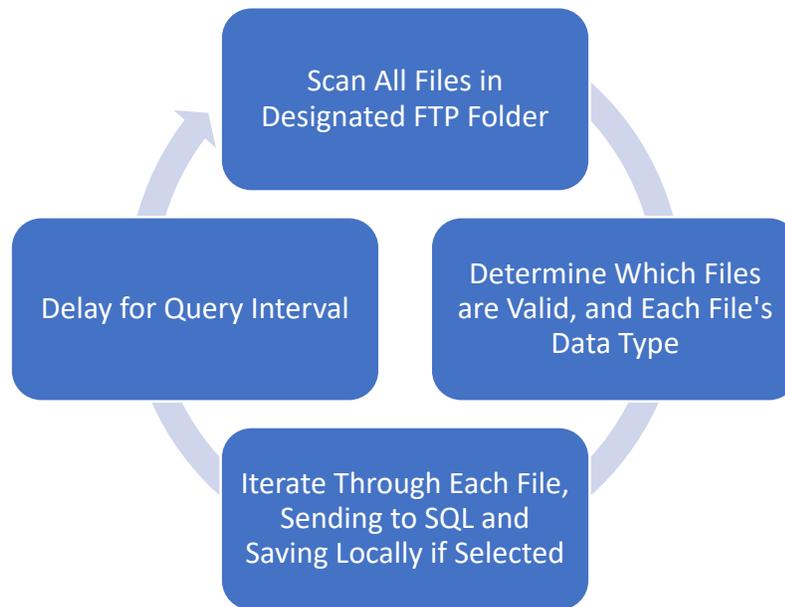


Figure 9 The FTP Receiver Process

4.1.4 Settings Tab

The Settings tab is where all of the specifics are set for each variable used in each data retrieval process. The Settings tab has two sub-tabs: the “Data and SQL” tab and the “FTP” tab. The necessary settings can be set in these two sub-tabs and then saved. When the settings are saved, they are applied to the tool immediately, and are also saved to the configuration so that they will be the same the next time the tool is launched. The usage of the Settings tab will be described in the Usage section.

4.2 Data Destinations

The data from the data collection tool is saved to three different databases: a MaxView loop-based database, a MaxView cabinet event-based database, and an INRIX Database.

4.2.1 MaxView loop-based database

The MaxView loop-based data table is in the “tocsqlddev” Microsoft SQL server and is in the “TSMO ITS” database. Because the ID, TimeStamp, DetectorstationID, and SlotNumber columns all have repeating values, it is not possible to set a primary key. The data size is over 18.6 million rows per day, using approximately 0.791 GB of storage space per day. A sample of the data is given in Table 6 below.

Table 6 Sample MaxView loop-based data

ID	TimeStamp	DetectorstationID	SlotNumber	Volume	Speed	Occupancy	SequenceNumber
702389924	04/09/2019 12:12:20	310	33	4	81	4	NULL
702389924	04/09/2019 12:12:20	310	34	4	81	4	NULL
702389924	04/09/2019 12:12:20	310	35	2	73	2	NULL

4.2.2 MaxView cabinet event-based database

The MaxView cabinet event-based data table is in the “tocsqlddev” Microsoft SQL server and is in the “TSMO ITS” database. The original data format is kept, so it is merely a historical data table for keeping data for more than a month. Because both the TimeStamp and DeviceID columns are repeating, it is not possible to set a primary key. The data size is over 2.6 million rows per day, using approximately 70.5MB of storage space per day. A sample of the cabinet event-based data is given in Table 7.

Table 7 MaxView cabinet event-based data

TimeStamp	DeviceId	EventId	Parameter
01/07/2019 11:49:13	160	1372	116
01/07/2019 11:49:13	160	1373	89
01/07/2019 11:49:33	160	1371	1368
01/07/2019 11:49:33	160	1372	91

4.2.3 INRIX Database

The INRIX Database is located at UA for storage reasons. Because it is an archive of the whole state’s data, the data size is over 69.3 million rows per day, occupying approximately 3.5GB of storage space each day. The timestamp and SegmentID columns are used as the primary keys for the table to increase query speed. A sample of the INRIX data is given in Table 8.

Table 8 INRIX Data

timestamp	SegmentID	type	speed	average	reference	score	confidenceValue	travelTimeMinutes	speedBucket	segment_closed
08/22/2019 20:52:26	121535794	XDS	21	28	34	30	100	0.23	1	0
08/22/2019 20:51:26	121535794	XDS	21	28	34	30	100	0.23	1	0
08/22/2019 20:50:26	121535794	XDS	21	28	34	30	100	0.23	1	0

4.3 Implementation

The proper usage of the data collection tool will be outlined below for each of the following four tabs: INRIX Data, MaxView Data, FTP Receiver, and Settings.

4.3.1 INRIX Data Tab

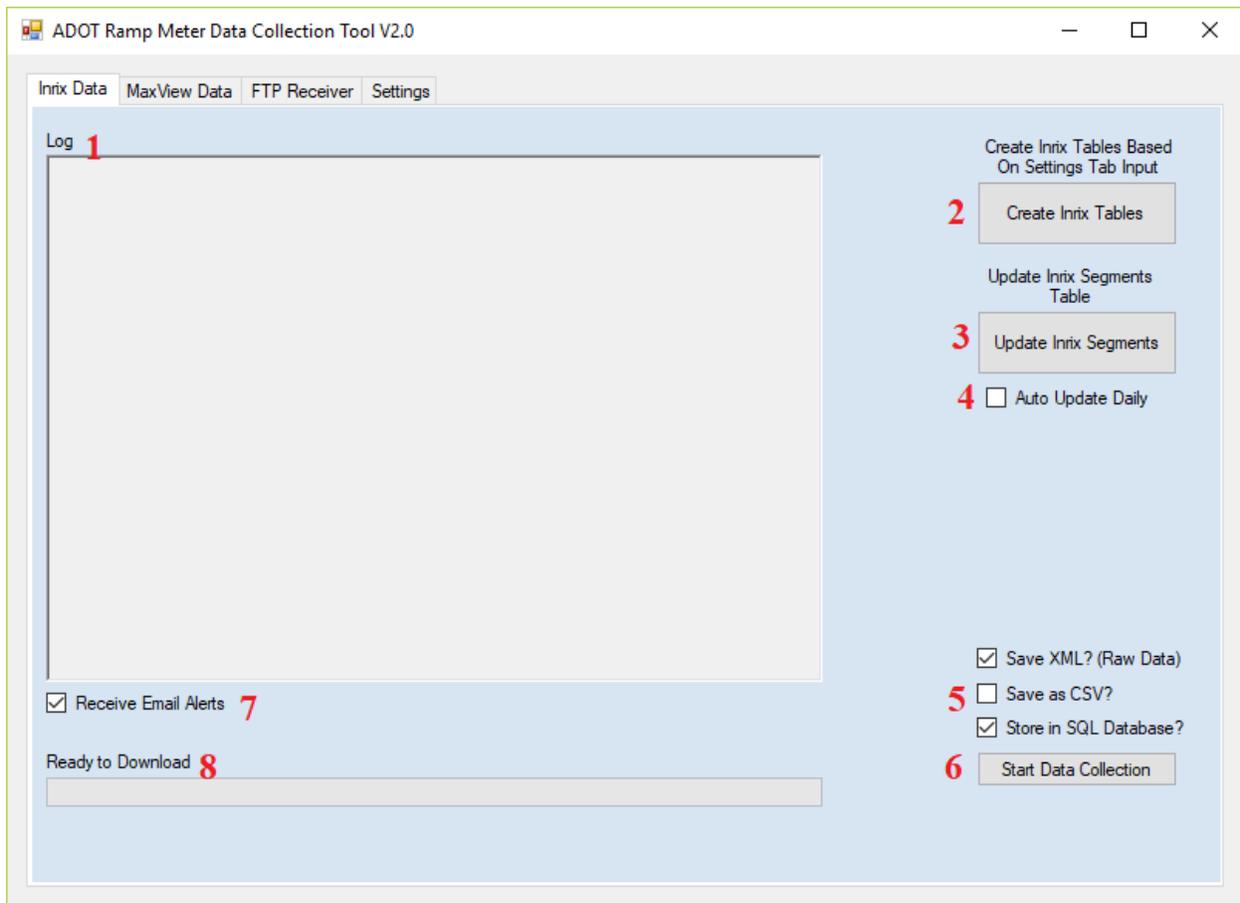


Figure 10 Outline of INRIX Data Tab Functions

The INRIX Data Tab Functions as seen in Figure 10 are outlined below:

1. **Log:** The log provides an update on each step of the process the INRIX tab is using. The log is also locally saved as a txt file in the same directory as the data collection tool.
2. **Create INRIX Tables:** The Create INRIX Tables button creates the INRIX data analytical table and the INRIX Segments table in the location set in the Settings tab. Note that if the tables already exist you will receive an error in the log.
3. **Update INRIX Segments:** The Update INRIX Segments button queries the newest list of all available segments in Arizona and saves them to the Segments table in the destination database as set in the Settings tab.
4. **Auto Update Daily:** The Auto Update Daily button sets the tool to automatically update the INRIX segments every day using the same method as the Update INRIX Segments button.
5. **Data Storage Options:** The three data storage options available are either XML (raw data), CSV, or SQL. If the local save options (XML or CSV) are chosen, they are saved in the local folder set in the settings tab in the structure of

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<localfolder>/Year/Month/Day/Datatype_timestamp.format so that the data is structured and to improve folder load times.

6. Start/Stop Data Collection: The Start/Stop Data Collection button starts the INRIX data collection cycle.
7. Receive Email Alerts: The Receive Email Alerts checkbox lets the user choose whether or not they would like to be notified of errors by email.
8. Progress Bar: The Progress Bar gives the user visual feedback as to the status of the countdown timer.

The basic process taken to use the INRIX tab is to first set up the settings (See the Settings Tab section for more details). Next, if it is the first time the tool is being run, the “Create INRIX Tables” button can be clicked to create the required destination tables. If the INRIX segment information is required, either the “Update INRIX Segments” button can be clicked, or the “Auto Update Daily” checkbox can be selected if it is necessary to maintain an updated INRIX Segment table. Next, the data storage options can be selected to save as either an XML file, a CSV file, a SQL table insert, or any combination of the three depending on the user’s needs. If the user would like to be notified of any error occurrences, the “Receive Email Alerts” checkbox should be checked. Finally, the user can click the “Start Data Collection” button to begin the data collection process, and the progress can be monitored via the Log and Progress Bar. The tool will collect INRIX data until the “Stop Data Collection” button is clicked or if the application is closed.

4.3.2 MaxView Data Tab

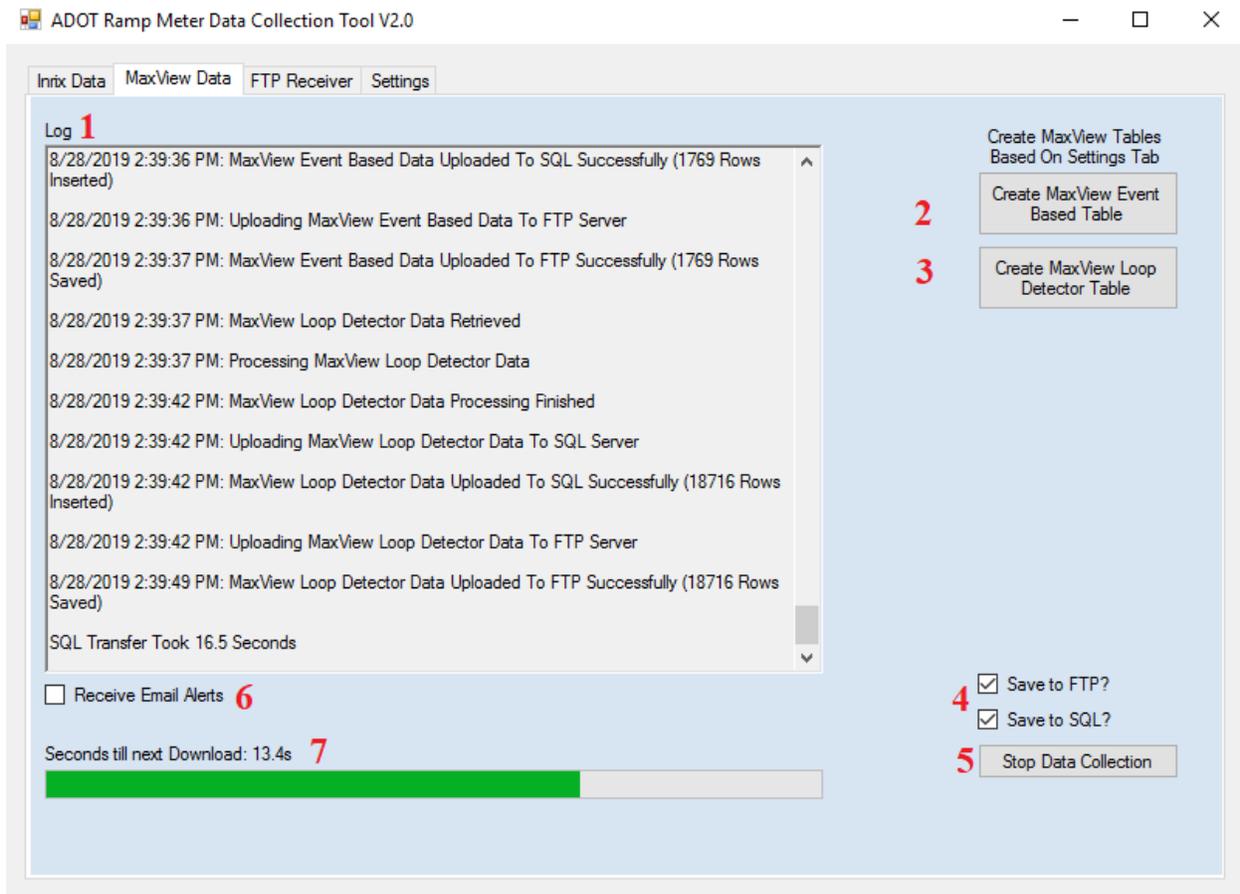


Figure 11 Outline of MaxView Data Tab Functions

The MaxView Data Tab Functions as seen in Figure 11 are outlined below:

1. **Log:** The log provides an update on each step of the process the MaxView Data tab is using. The log is also locally saved as a txt file in the same directory as the data collection tool.
2. **Create MaxView Event-Based Table:** The Create MaxView Event-Based Table button creates the MaxView Event-Based data analytical table in the location set in the Settings tab. Note that if the tables already exist you will receive an error in the log.
3. **Create MaxView Loop Detector Table:** The Create MaxView Loop Detector Table button creates the MaxView loop-based data analytical table in the location set in the Settings tab. Note that if the tables already exist you will receive an error in the log.
4. **Data Storage Options:** The two data storage options available are either Save to FTP or Save to SQL. If Save to FTP is selected, the data will be saved in CSV format to the FTP folder set in the Settings tab.
5. **Start/Stop Data Collection:** The Start/Stop Data Collection button starts the MaxView data collection cycle.

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6. **Receive Email Alerts:** The Receive Email Alerts checkbox lets the user choose whether or not they would like to be notified of errors by email.
7. **Progress Bar:** The Progress Bar gives the user visual feedback as to the status of the countdown timer.

To collect MaxView data using the MaxView Data tab, first, all the necessary settings should be set up in the Settings tab (See the Settings Tab section for more details). If it is the first time collecting MaxView data, both the Create MaxView Event-Based Table button and the Create MaxView Loop Detector Table button should be pressed to create the necessary SQL tables to insert data to (Note: Only necessary if SQL is being used, not necessary for FTP). Next, the user can choose to save the data to FTP, insert it to SQL, or both depending on the user's needs. If the user would like to be notified of any error occurrences, the "Receive Email Alerts" checkbox should be checked. Finally, the user can click the "Start Data Collection" button to begin the data collection process, and the progress can be monitored via the Log and Progress Bar. The tool will collect MaxView data until the "Stop Data Collection" button is clicked or if the application is closed.

4.3.3 FTP Receiver Tab

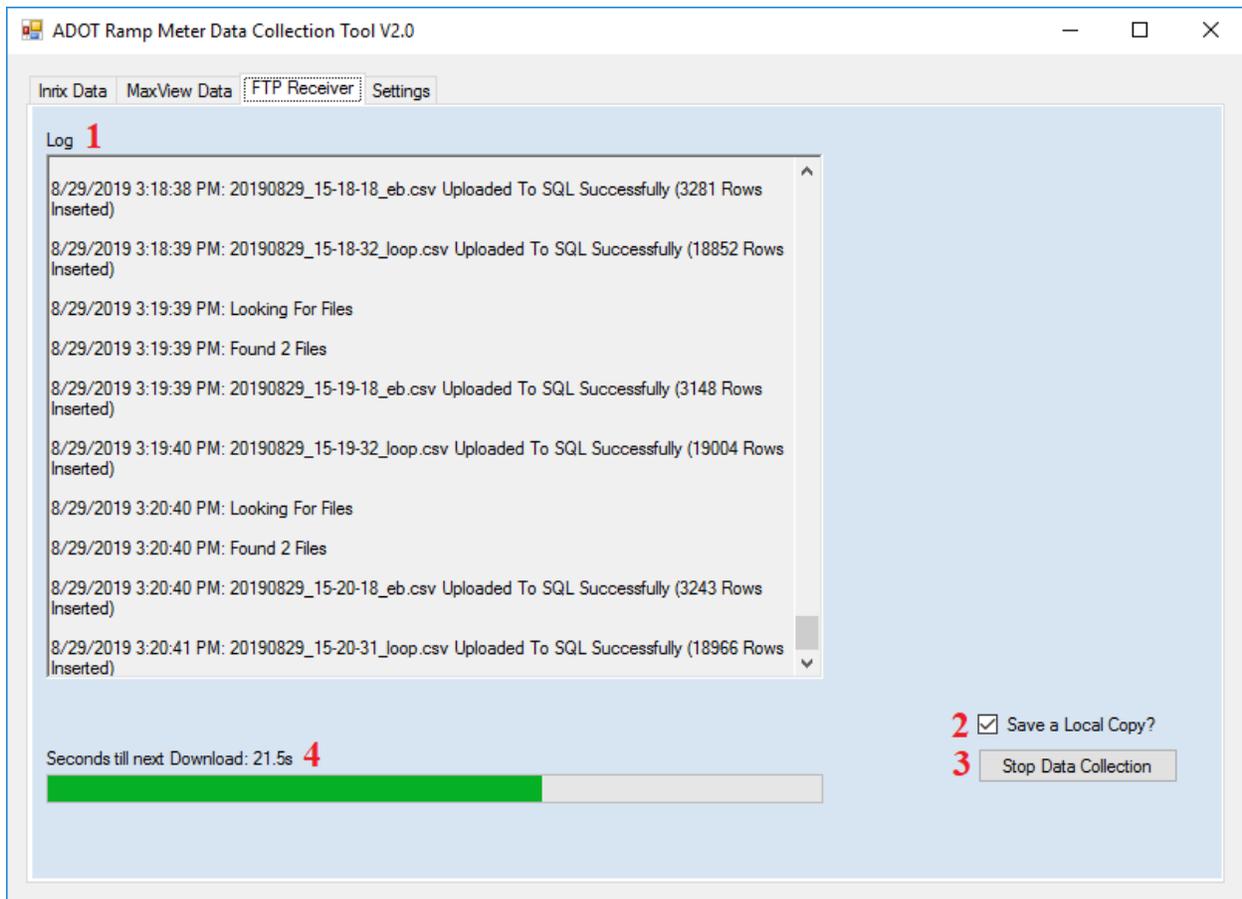


Figure 12 Outline of FTP Receiver Tab Functions

The FTP Receiver Tab Functions as seen in Figure 12 are outlined below:

1. **Log:** The log provides an update on each step of the process FTP Receiver Tab is using. The log is also locally saved as a txt file in the same directory as the data collection tool.
2. **Save a Local Copy:** If the Save a Local Copy checkbox is checked, the data will be saved to the local folder set in the Settings Tab in CSV format in the structure of <localfolder>/Year/Month/Day/Datatype_timestamp.csv so that the data is structured and to improve folder load times.
3. **Start/Stop Data Collection:** The Start/Stop Data Collection button starts the FTP receiver process.
4. **Progress Bar:** The Progress Bar gives the user visual feedback as to the status of the countdown timer.

To collect data using the FTP Receiver tab, first, all the necessary settings should be set up in the Settings tab (See the Settings Tab section for more details). Next, the user can decide whether or not they want to save a local copy of the data and select the Save a Local Copy checkbox accordingly. Finally, the user can just press the Start Data Collection button to begin

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the collection cycle. The cycle will repeat every query interval until either the Stop Data Collection button is pressed, or the application is closed.

4.3.4 Settings Tab

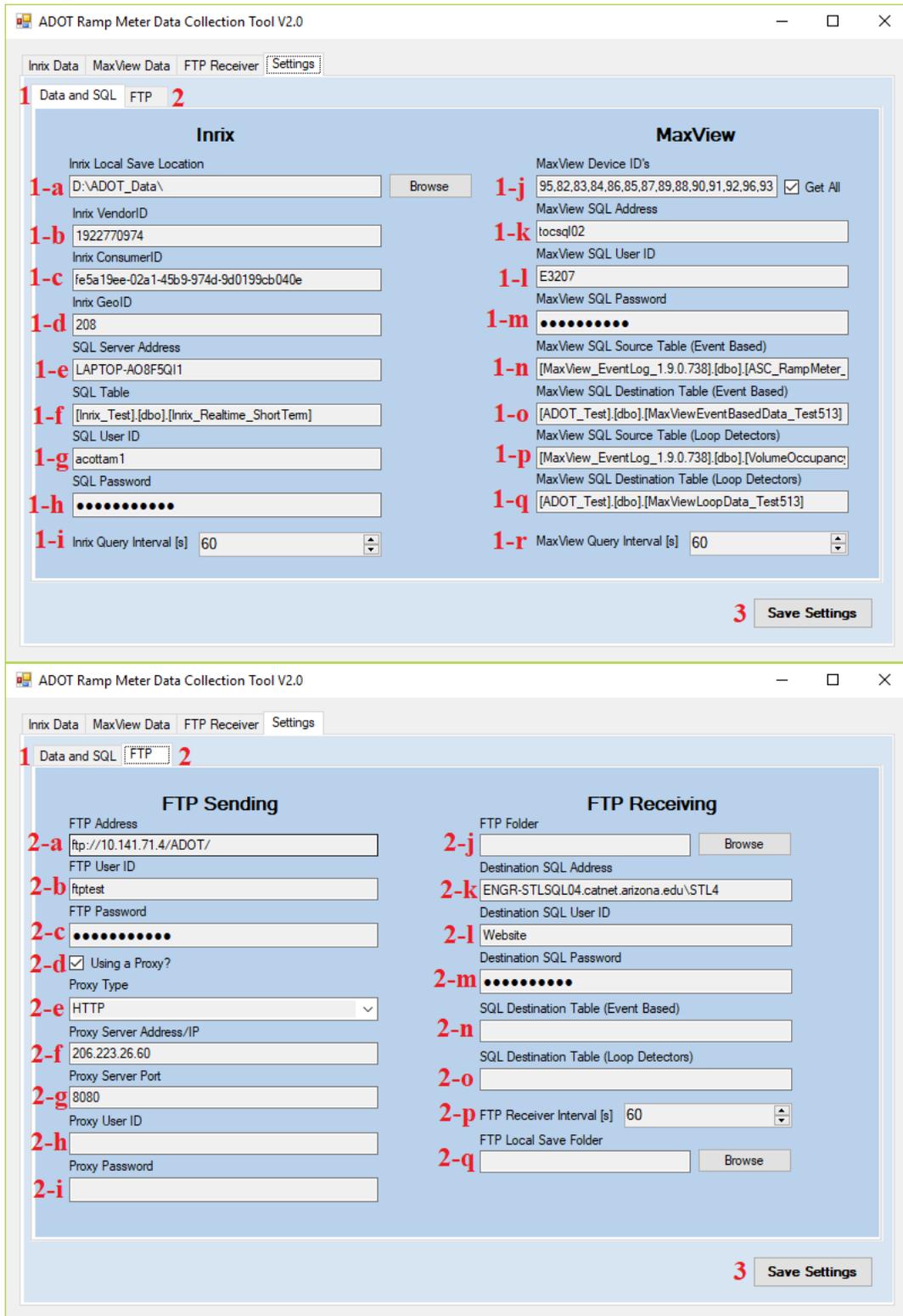


Figure 13 Outline of Settings Tab Functions

The Settings Tab Functions as seen in Figure 13 are outlined below:

1. Data and SQL Tab: This tab contains the SQL parameters and the parameters for the INRIX Data and MaxView Data tabs.
 - a. INRIX Local Save Location: This is a dialog to select the folder the INRIX data will be saved to.
 - b. INRIX VendorID: This box is where the INRIX VendorID is placed for the INRIX API call.
 - c. INRIX ConsumerID: This box is where the INRIX ConsumerID is placed for the INRIX API call.
 - d. INRIX GeoID: This is where the user provides an INRIX GeoID that determines the area that is returned from a query. For example, GeoID 208 is the state of Arizona.
 - e. SQL Server Address: This is where the user can set the destination Microsoft SQL Server address
 - f. SQL Table: This is where the user can provide the destination SQL table. Note that it includes the database name, so for example it could be [`<database>`].[`dbo`].[`<datatable>`]
 - g. SQL User ID: This is the User ID that will be used to establish a SQL connection for the INRIX data insertion
 - h. SQL Password: This is the password that will be used to authenticate the SQL user for the INRIX data insertion
 - i. INRIX Query Interval: This is where the INRIX query interval in seconds is set, and INRIX data will be collected every interval.
 - j. MaxView Device ID's: This box allows the user to select the MaxView devices the Controller Event-Based data will be collected from, or if the Get All checkbox is selected the tool will collect the Controller Event-Based data of all available devices
 - k. MaxView SQL Address: This is where the address of the Microsoft SQL Server containing the MaxView *Source* data will be saved to. The *Destination* Microsoft SQL Server will be the same server as set in the INRIX destination server.
 - l. MaxView SQL User ID: This is where the SQL UserID for the MaxView *Source* server is set.
 - m. MaxView SQL Password: This is where the SQL Password for the MaxView *Source* server is set.
 - n. MaxView Source Table (Event-Based): This is where the MaxView Controller Event-Based data source table is set. Note that the tool will automatically update this value to the newest available data table, and also will reflect the newest available version of MaxView database. The format includes the database name, so for example it could be [`<database>`].[`dbo`].[`<datatable>`]
 - o. MaxView SQL Destination Table (Event-Based): This is where the destination SQL table for the MaxView Controller Event-Based data will be provided. This table will be located on the destination server (i.e. on the same server as set up in

- the INRIX destination section). If a non-existent table is provided, the Create MaxView Event-Based Table button on the MaxView Data tab can be used to create the table with the name provided.
- p. MaxView Source Table (Loop Detectors): This is where the MaxView loop-based data source table is set. Note that the tool will automatically update this box to reflect the newest available version of the MaxView database. The format includes the database name, so for example it could be
[<database>].[dbo].[<datatable>]
 - q. MaxView SQL Destination Table (Loop Detectors): This is where the destination SQL table for the MaxView loop-based data will be provided. This table will be located on the destination server (i.e. on the same server as set up in the INRIX destination section). If a non-existent table is provided, the Create MaxView Loop Detector Table button on the MaxView Data tab can be used to create the table with the name provided.
 - r. MaxView Query Interval: This is where the MaxView query interval in seconds is set, and MaxView data will be collected every interval.
2. FTP Tab: This tab contains all the FTP parameters, including the FTP sending parameters for the MaxView Data tab and the FTP Receiver tab.
- a. FTP Address: This is where the address of the *Destination* FTP server is specified. The ftp address should be specified in the format of
ftp://<ftpserveraddress>/<ftpfolder>
 - b. FTP User ID: This is where the FTP User ID is specified to authenticate with the FTP Server
 - c. FTP Password: This is where the FTP Password is specified to authenticate with the FTP Server
 - d. Using a Proxy: This allows the user to send the source FTP files through a Proxy to the Destination FTP Server. This should only be chosen if the tool is running in a proxied environment.
 - e. Proxy Type: This allows the user to select the proxy type if a proxy is necessary
 - f. Proxy Server Address/IP: This is where the address of the proxy server is specified if a proxy is necessary.
 - g. Proxy Server Port: This is where the proxy server port is specified.
 - h. Proxy User ID: If the proxy is authenticated, this is where the proxy User ID can be specified. If no authentication is required, it can be left blank.
 - i. Proxy Password: If the proxy is authenticated, this is where the proxy password can be specified. If no authentication is required, it can be left blank.
 - j. FTP Folder: This is where the FTP Receiver tab's *Source* FTP folder is specified. The FTP Receiver tab will search this folder for files to upload to SQL.
 - k. Destination SQL Address: This is the Microsoft SQL Address of the server where the FTP Receiver tab will send the received data to.
 - l. Destination SQL User ID: This is the User ID used to authenticate with the SQL server where the FTP Receiver tab will send the received data to.

- m. Destination SQL Password: This is the password used to authenticate with the SQL server where the FTP Receiver tab will send the received data to.
 - n. SQL Destination Table (Event-Based): This is where the destination SQL table for MaxView Controller Event-Based data is set. The FTP Receiver tab will save the parsed MaxView Controller Event-Based data to this location.
 - o. SQL Destination Table (Loop Detectors): This is where the destination SQL table for MaxView loop-based data is set. The FTP Receiver tab will save the parsed MaxView loop-based data to this location.
 - p. FTP Receiver Interval: This is where the interval in seconds for the FTP Receiver tab is set. The FTP Receiver tab will check for new files every time this amount of time has passed.
 - q. FTP Local Save Folder: This is where the FTP Receiver tab will save the received data locally, if the user has selected to do so. The user can select a folder using the folder browser dialog by pressing the Browse button.
3. Save Settings: The Save Settings button saves the settings to the current environment, and saves them to the user's configuration so they will be available next time the program loads.

To use the settings tab, the user will set the settings to whatever meets their requirements. Once all the settings have been successfully set, the user can click Save Settings to apply them to the current environment. The settings will be saved in the user's configuration for the next time that the application is loaded.

CHAPTER 5. RAMP METERING EVALUATION TOOL

The purpose of the Ramp Metering Evaluation Tool is to provide ADOT with a tool that they can use to evaluate the performance of their ramp meters, and to quantify the improvement in a before and after scenario. The Ramp Metering Evaluation Tool is written in the open-source programming language “R”. It is hosted by the University of Arizona on their web-servers. The tool can be accessed at <https://adot.ua-star.org>. The log-in credentials have been provided to managers in the ADOT TSMO division.

5.1 Data Sources

The data used by the Ramp Metering Evaluation Tool is located at three different databases: a MaxView loop-based database, a MaxView cabinet event-based database, and an INRIX Database. Note that these are the same databases mentioned in Section 4.2.

5.1.1 MaxView loop-based database

The MaxView loop-based data table used by the Ramp Metering Evaluation Tool is located in the Smart Transportation Lab SQL Server at the University of Arizona. The data size is over 18.6 million rows per day, using approximately 0.791 GB of storage space per day. A sample of the data is given in Table 9 below.

Table 9 Sample MaxView loop-based data

ID	TimeStamp	DetectorstationID	SlotNumber	Volume	Speed	Occupancy	SequenceNumber
702389924	04/09/2019 12:12:20	310	33	4	81	4	NULL
702389924	04/09/2019 12:12:20	310	34	4	81	4	NULL
702389924	04/09/2019 12:12:20	310	35	2	73	2	NULL

5.1.2 MaxView cabinet event-based database

The MaxView cabinet event-based data table used by the Ramp Metering Evaluation Tool is located in the Smart Transportation Lab SQL Server at the University of Arizona. The data size is over 2.6 million rows per day, using approximately 70.5MB of storage space per day. A sample of the cabinet event-based data is given in Table 10.

Table 10 MaxView cabinet event-based data

TimeStamp	DeviceId	EventId	Parameter
01/07/2019 11:49:13	160	1372	116
01/07/2019 11:49:13	160	1373	89
01/07/2019 11:49:33	160	1371	1368
01/07/2019 11:49:33	160	1372	91

5.1.3 INRIX Database

The INRIX Database used by the Ramp Metering Evaluation Tool is located in the Smart Transportation Lab SQL Server at the University of Arizona. The data size is over 69.3 million rows per day, occupying approximately 3.5GB of storage space each day. A sample of the INRIX data is given in Table 11.

Table 11 INRIX Data

timestamp	SegmentID	type	speed	average	reference	score	confidenceValue	travelTimeMinutes	speedBucket	segment_closed
08/22/2019 20:52:26	121535794	XDS	21	28	34	30	100	0.23	1	0
08/22/2019 20:51:26	121535794	XDS	21	28	34	30	100	0.23	1	0
08/22/2019 20:50:26	121535794	XDS	21	28	34	30	100	0.23	1	0

5.2 System Architecture

The Ramp Metering Evaluation Tool structure can be split into two categories: Back-End Server Architecture, and Front-End Website Design.

5.2.1 Back-End Server Architecture

The Server Architecture for the Ramp Metering Evaluation Tool is made up of a SQL Server to supply data, a Linux Server to host the website with, and a Microsoft IIS Proxy Website so the website can be secured with SSL (allowing https). The University of Arizona Smart Transportation Lab Server, hereafter referred to as the “master server,” is a very powerful server capable of handling the entire Back-End Server Architecture. The master server hosts a SQL Server. This SQL Server has a constant feed of all three data sources coming into it from the Data Collection Tool. The Ramp Metering Evaluation Tool is based on R with the Shiny package, and so an R and Shiny based web-server is used to host the Ramp Metering Evaluation Tool. Because the R and Shiny based web-server requires a Linux OS, it is run on a Linux Virtual Machine on the master server. A Microsoft IIS proxy website is run on the master server, and it routes traffic in and out of the R and Shiny Web Host through SSL to encrypt the web traffic. The Microsoft IIS Proxy Website is allowed to pass through the University of Arizona firewall, so that it can be accessed via the internet. A diagram of this architecture is shown in Figure 14.

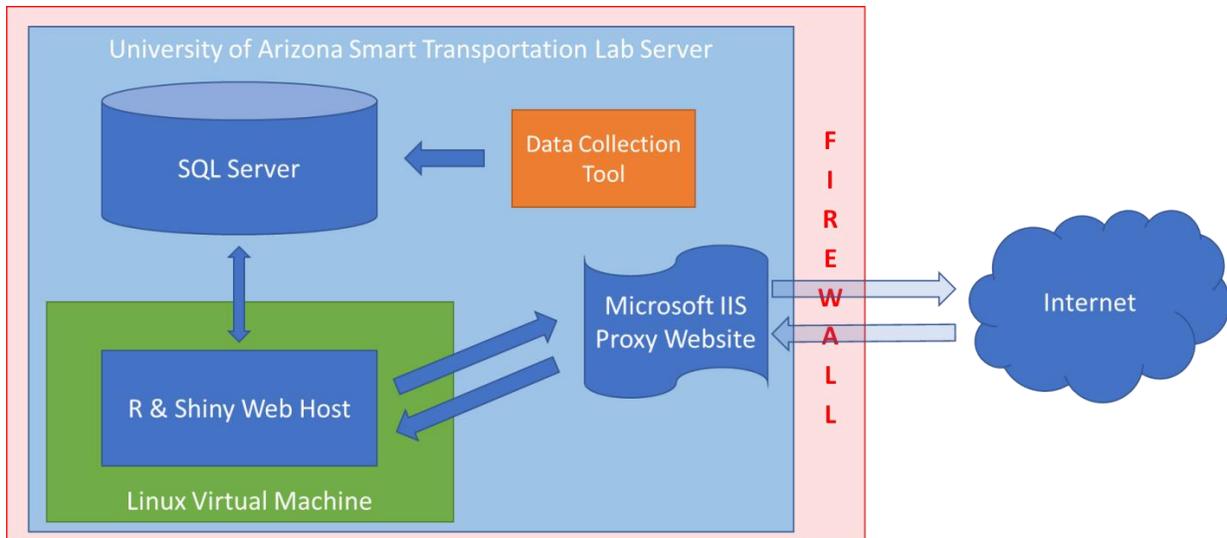


Figure 14 A Diagram of the Back-End Server Architecture

5.2.2 Front-End Website Design

The Front-End Website Design is done using R, an open-source programming language, along with several open-source packages. A list of the primary packages used is given below:

1. Shiny (Base website hosting framework for R)
2. RODBC (Provides ODBC connections to SQL)
3. Leaflet (Provides Maps)
4. ggplot2 (Provides Charts)
5. shinyjs (Allows shiny to interface with JavaScript)
6. shinydashboard (Provides an enhanced UI for shiny)
7. leaflet.extras (Provides extra leaflet map functions)
8. shinyauthr (Provides authentication page for shiny)

5.3 Performance Measurements

These foundational packages helped with the development of the Ramp Metering Evaluation Tool. The Ramp Metering Evaluation Tool in its current version has six modules: Speed Analysis, Flow Analysis, Speed-Flow Analysis, Delay Analysis, Cost-Benefit Analysis, and Real-Time Monitoring. The details behind each module are given below, including a brief summary of the algorithms used and the assumptions made.

5.3.1 Speed Analysis

The Speed Analysis algorithm is kept as simple as possible. The user can select any number of segments during any time or date range. First, the INRIX data in the selected date and time range for the selected segments is collected from the server. Next, the median speeds are calculated for each segment, and for every five minutes during the selected time of day. Next, the median of the five-minute speeds is taken between all the selected segments, if more than one is selected. This is the final result, and is plotted to the output for both the before and after data. If

the Aggregate speeds checkbox is not checked, the five-minute median speeds of every segment for every day are plotted. When the Aggregate speeds checkbox is checked, the medians of all the speeds for each time of day are aggregated into 5-minute intervals. When it is unchecked, a separate line for each day is shown on the graph, showing the five-minute median speeds of every segment for every day. The aggregation simply aggregates the whole time period into one line, whereas the non-aggregated shows each day and segment separately. The Statistical Analysis results are from a z-test between the before and after data at the user selected confidence level during the time of day provided.

5.3.2 Flow Analysis

The Flow Analysis algorithm is similar to the Speed Analysis algorithm. First, the MaxView loop-based data in the selected date and time range for the selected loop detector stations are collected from the server. Next, the volumes are summed for each loop detector station for every minute for the three outermost lanes (the loop data is in 20-second intervals). Next, the average 15-minute volume during the selected time of day is calculated, and is converted to flow in vehicles per hour per lane with an average value correction for any missing data. This is then plotted for the before and after case. The Statistical Analysis results are from a z-test between the before and after data at the user selected confidence level during the time of day provided.

5.3.3 Speed-Flow Analysis

The Speed-Flow analysis algorithm uses the speed and volume obtained from the MaxView loop-based data. First, the MaxView loop-based data in the selected date and time range for the selected loop detector station is collected from the server. Next, the volumes are summed for every minute for the three outermost lanes (the loop data is in 20-second intervals). Next, the average 15-minute volume is calculated, and is converted to flow in vehicles per hour per lane with a correction for any missing data. The median 15-minute speed is also calculated, and the speed vs flow relationship is then plotted.

5.3.4 Delay Analysis

The first step in the Delay Analysis is to determine the statewide free-flow travel times. This is assumed to be the 5th percentile travel time (i.e. 95% of travelers would take longer than this time to traverse the segment). This assumption is deemed reasonable, because at times in the middle of the night (e.g. 12:00 am – 3:00 am), the difference between the measured travel time and the calculated free-flow travel time is very small, indicating that at free-flow speed the travelers took approximately that much time to traverse the segment. Based on this assumption, the free flow travel times are calculated for the entire state, and are saved in the Smart Transportation Lab SQL Server. The Delay Analysis algorithm is based on the simple calculation of freeway delay. The delay at a given time is measured as the free-flow travel time minus the travel time at the given time. In the rare event that the calculated delay is less than 0, it is set to be 0 as having a negative delay is not possible by definition. Using this method, the delay is calculated by calculating the delay using INRIX data for the selected segments and time of day,

for the selected before and after periods. The delay is aggregated into five-minute intervals during the selected time of day. If more than one segment is selected, the average five-minute delay for each selected segment is summed together for every five-minute interval during the selected time of day. The reason the delay is summed is that the drivers driving through the selected segments will experience a delay in each segment, so taking the average would be incorrect. The resulting output is the travel time delay in seconds per vehicle for the total selected segments over the selected time of day, and is plotted for the selected before and after cases.

5.3.5 Cost-Benefit Analysis

The Cost-Benefit Analysis algorithm uses the same method as the Delay Analysis algorithm to calculate the delay per vehicle in seconds for every five minutes for the selected segments and time of day. Next, this delay is multiplied by the vehicular volume from the Loop-Based data during every five minutes, and is calculated by summing up the actual volume for the outermost three lanes for every five minutes for each loop detector station. The total delay in vehicle-hours is then calculated by multiplying the delay per vehicle with the volume of vehicles for every five minutes, and converting from seconds to hours. The total delay before and after in vehicle-hours is calculated by summing up all the delay experienced in the before and after cases. This is then converted to a dollar amount representing the total delay cost during the selected time period by multiplying the total delay by the average hourly wage in the area. The hourly wage used for this calculation is user configurable for when it changes.

5.3.6 Real-Time Monitoring

The Real-Time Monitoring module merely reports the real-time values of flow and speed and Level of Service (LOS). The flow is calculated by summing the real-time MaxView Loop Based volume across the three outermost lanes for the selected loop detector station, and then converting it to flow. Both the MaxView Loop Based speed and the INRIX speed are reported for the selected loop detector station. The LOS is calculated by first using the calculated MaxView Loop Based speed and flow to calculate density. The density values are then converted to LOS using the methods prescribed for freeways in the Highway Capacity Manual Sixth Edition.

5.4 System Implementation

The primary goal for this project is to help ADOT improve their ramp metering system by using an online website evaluation tool to evaluate the corridors. To help users get familiar with the evaluation tool, the following content introduces how to use it.

After typing the website in the browser, the login page is shown below. After logging in, Figure 15 shows the interface of the evaluation tool. The evaluation tool displays different kinds of data under a series of seven tabs appearing along the left side of the window. The contents of the various tabs are as follows: Speed Analysis, Flow Analysis, Speed-Flow Analysis, Delay Analysis, Cost-Benefit Analysis, Real-Time Monitoring, and In-progress. These tabs represent different evaluation modules, and users can simply click a tab to switch to different evaluation modules.

This report takes the speed analysis module as an example to illustrate how to use the website. As shown in Figure 16 the whole interface can be divided into 5 parts:

1. Evaluation modules selection: Select different analytic modules based on the user's needs.
2. Maps of Segment: Select any number of segments based on the user's needs. Users can also choose any type of road and direction, helping to accurately filter the segments for comparison.
3. Inputs: Choose before/after cases based on dates, time of day, and day of week. One feature to note is that Detailed view allows users to choose different counties.
4. Statistical Analysis: Select different confidential levels for comparison, then statistical analysis results are provided for users.
5. Plot of Results: Results of before and after cases are plotted for the selected segment.

The Functions as seen in Figure 17 are outlined below:

1. Zoom in: This makes the segments to be bigger and closer.
2. Zoom out: This makes the segments to be smaller and farther away.
3. Draw a polygon: Draw a polygon to select segments that users are interested in.
4. Draw a rectangle: Draw a rectangle to select segments that users are interested in.
5. Draw a circle: Draw a circle to select segments that users are interested in.
6. Delete layers: Delete all selected segments.
7. Zoom to extents: Showing the largest possible view of all segments.
8. Choose a Road Type: Select specific road type to accurately filter the segments for comparison. The Dropbox contains the following options: All types, Freeways, Highways, Major Arterials, Minor Arterials, and Minor Streets.
9. Choose a Direction: Select a specific direction to accurately filter the segments for comparison. The Dropbox contains the following options: Any Direction, North, South, East, and West.
10. Apply Selection: Results are calculated considering the selected criteria.

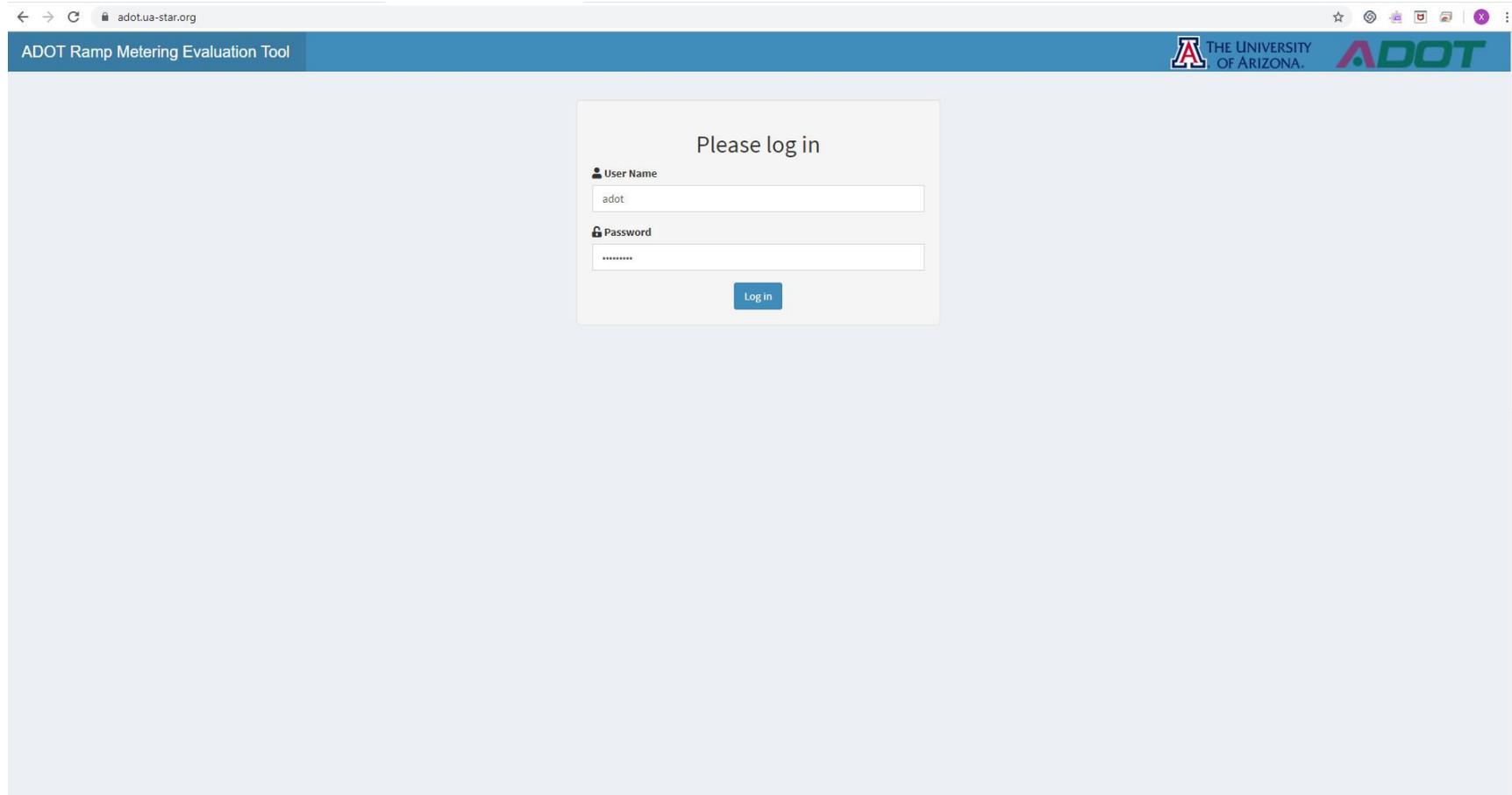


Figure 15 ADOT Ramp metering evaluation tool login page

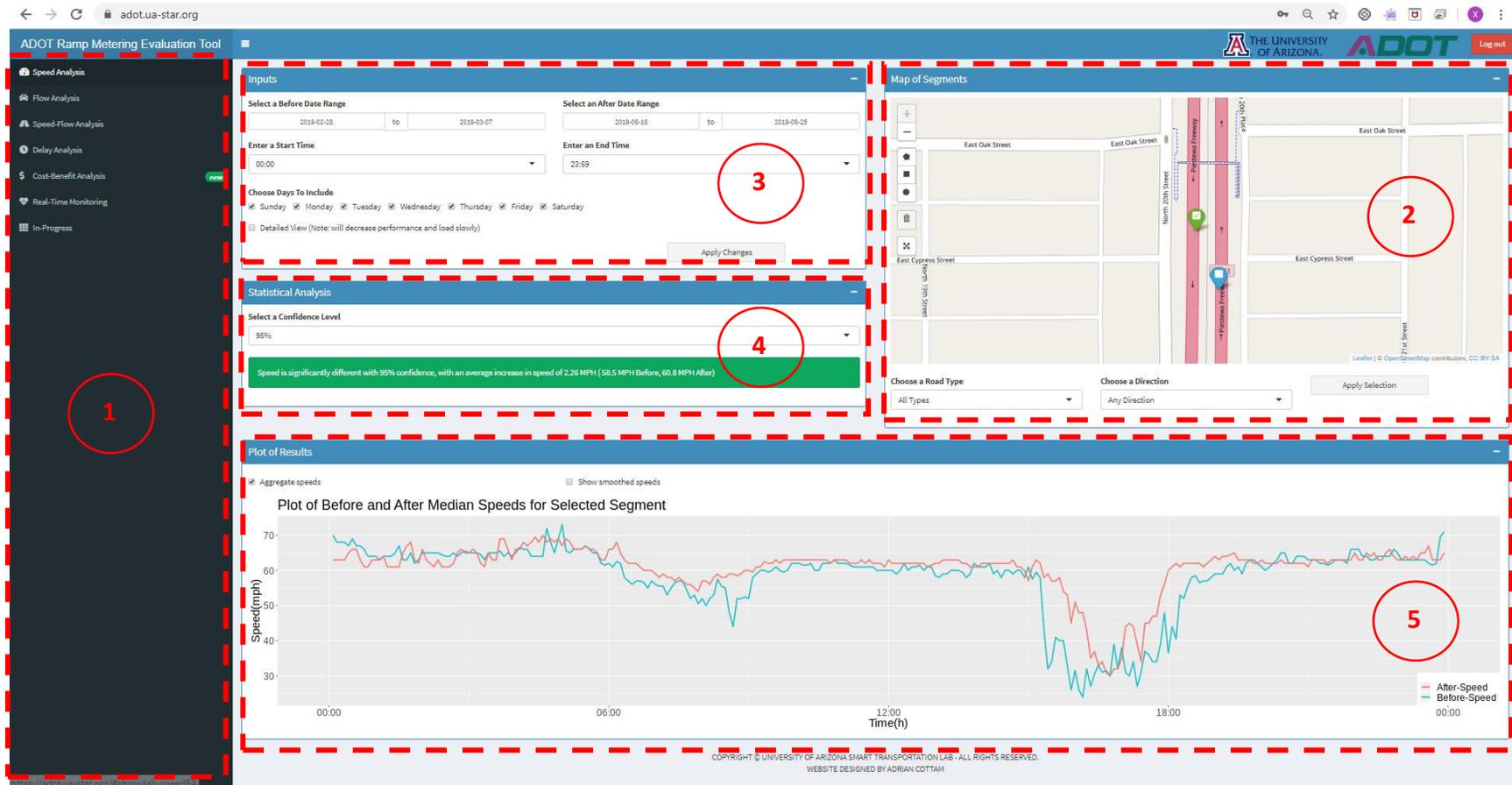


Figure 16 ADOT Ramp metering evaluation tool interface

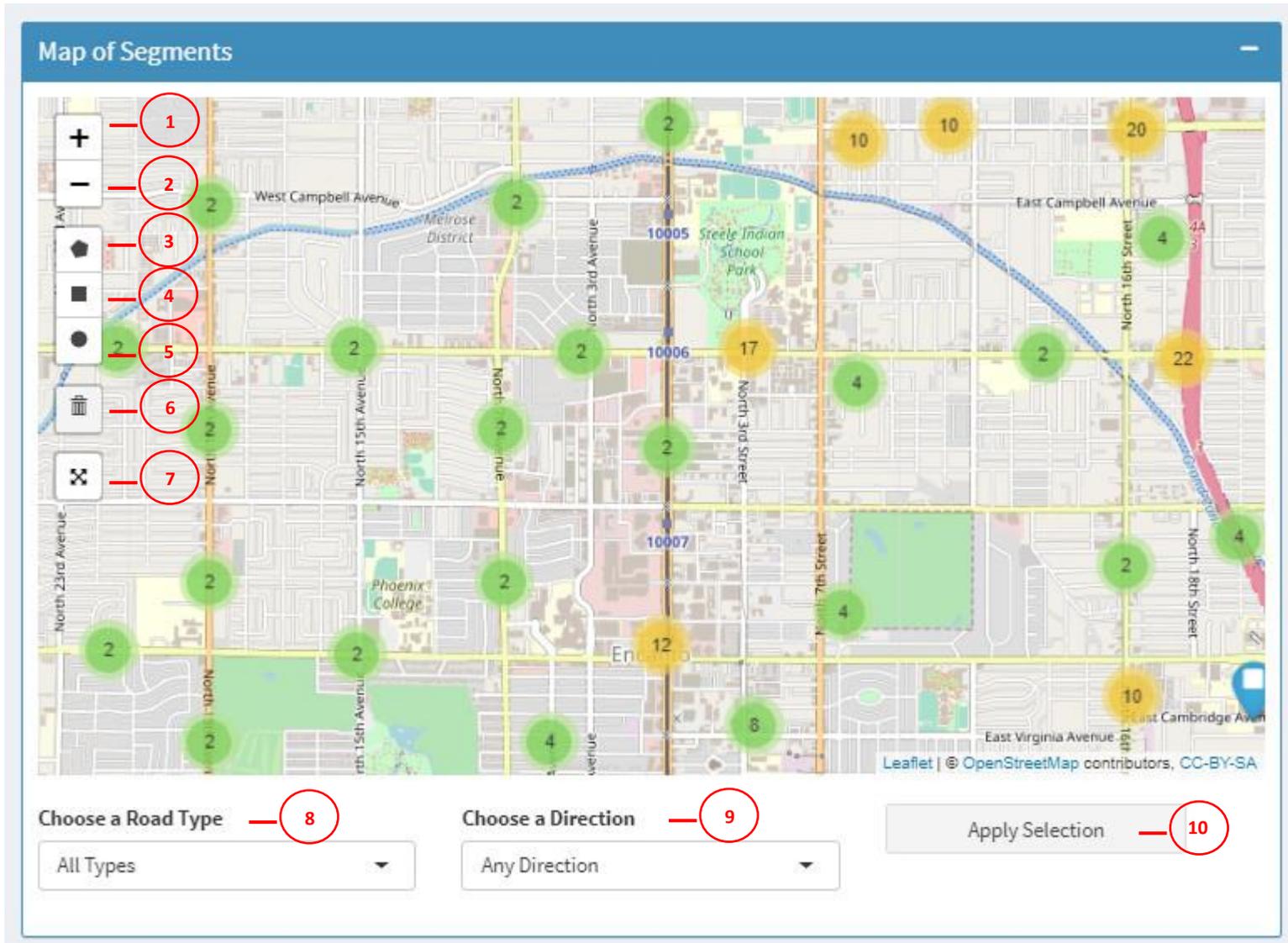


Figure 17 Outline of Maps of Segments Part Functions

The screenshot shows a web form titled "Inputs" with a blue header. The form contains several sections:

- Select a Before Date Range** (1): A date range selector showing "2019-02-28" to "2019-03-07".
- Select an After Date Range** (2): A date range selector showing "2019-08-23" to "2019-08-30".
- Enter a Start Time** (3): A time selector dropdown showing "00:00".
- Enter an End Time** (4): A time selector dropdown showing "23:59".
- Choose Days To Include** (5): A row of checkboxes for "Sunday", "Monday", "Tuesday", "Wednesday", "Thursday", "Friday", and "Saturday", all of which are checked. Below this is a checkbox for "Detailed View (Note: will decrease performance and load slowly)", which is also checked.
- Choose a County** (6): A dropdown menu showing "Santa Cruz".
- Apply Changes** (7): A button located at the bottom right of the form.

Figure 18 Outline of Inputs Part Functions

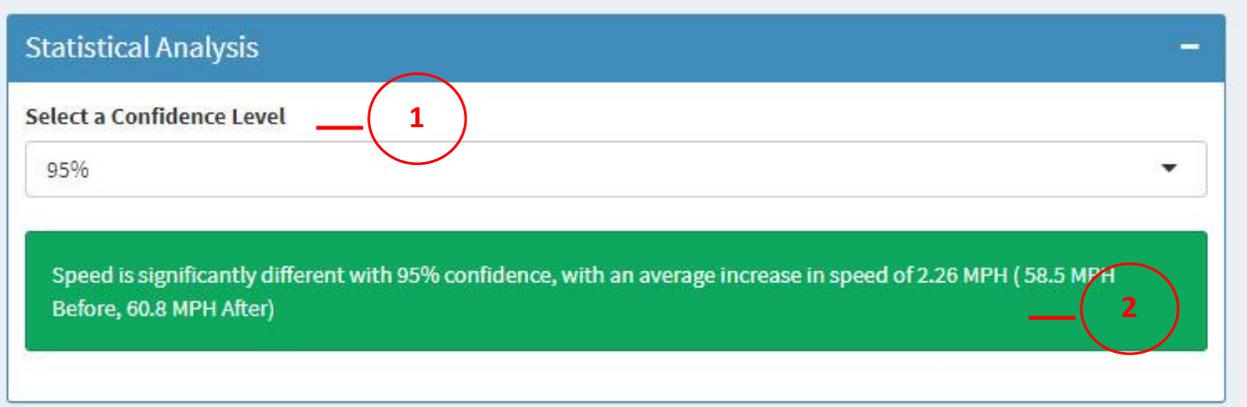


Figure 19 Outline of Statistical Analysis Part Functions



Figure 20 Comparison of Plots of Before and After Median Speeds for Selected Segment

The Functions seen in Figure 18 are outlined below:

1. Select a Before Date Range: This is where the before date range is specified.
2. Select an After Date Range: This is where the after date range is specified.
3. Enter a Start Time: This is where the start time is specified.
4. Enter an End Time: This is where the end time is specified.
5. Choose Days To Include: This allows users to select specific days.
6. Detailed View: This allows users to choose different counties.
7. Apply Changes: Results are calculated considering the selected criteria.

The Functions as seen in Figure 19 are outlined below:

1. Select a Confidence level: This allows users to select a specific confidence level to conduct z-test. The Dropbox contains the following options: 90%, 95%, 99%, and 99.9%.
2. Statistical Analysis Results: This is where the statistical analysis results are provided for users. The statistical analysis results use a z-test to determine whether or not the results are significantly different from each-other. The percent difference is just the average difference between the two data-sets. In other words, the z-test tells you whether or not you can trust that there is a significant difference and is not random noise, and then the difference in means gives you an average amount of difference.

Figure 20 shows the plots of before and after median speeds for the selected segment. Checking the Aggregate speeds option can reduce the fluctuation of median speeds, and by checking Show smoothed speeds option, two smooth trendlines are added.

The basic process for using the speed analysis module is to first click Speed Analysis tab, and, then by clicking, using the functions of “Draw a polygon”, “Draw a rectangle”, or “Draw a circle” buttons in “Maps of Segments” part, select segments. Users can use the Dropbox of “Choose a Road Type” and “Choose a Direction” to accurately filter the segments for comparison. Click the “Apply Selection” button to finish segment selection. Next, in the “Inputs” part, choose before/after cases based on dates, time of day, and day of week. Click the “Apply Changes” or “Apply Selection” button to run the selected criteria. Finally, users can select a confidence level in the Dropbox of “Select a Confidence level” to begin the process of calculation and visualization of results.

Compared with the speed analysis module, other modules have many differences in terms of data selection or results visualization. In the following, this report lists those differences.

1. In the “Plot of Results” part of “Speed-Flow Analysis” tab. This evaluation tool provides two types of plot, one is “Before and After Speed-Flow Scatter Plot”, the other is “Before and After Speed-Flow Density Plot”.
2. In the “Cost-Benefit Analysis” tab, the results of “Total Delay Cost Before” and “Total Delay Cost After” replace the “Statistical Analysis” part in “Speed Analysis” tab.

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Besides, the “Plot of Results” also provides two types of plot, one is “Before and After Median Delay Costs for Selected Segment”, the other is “Before and After Median Total Delays for Selected Segment”.

3. Very different from “Speed Analysis” tab, in the tab of “Real-Time Monitoring”, this tool allows users to click available sites, then current speed, current volume, current Los, real-time speed plot, and real-time flow plot are provided for users.

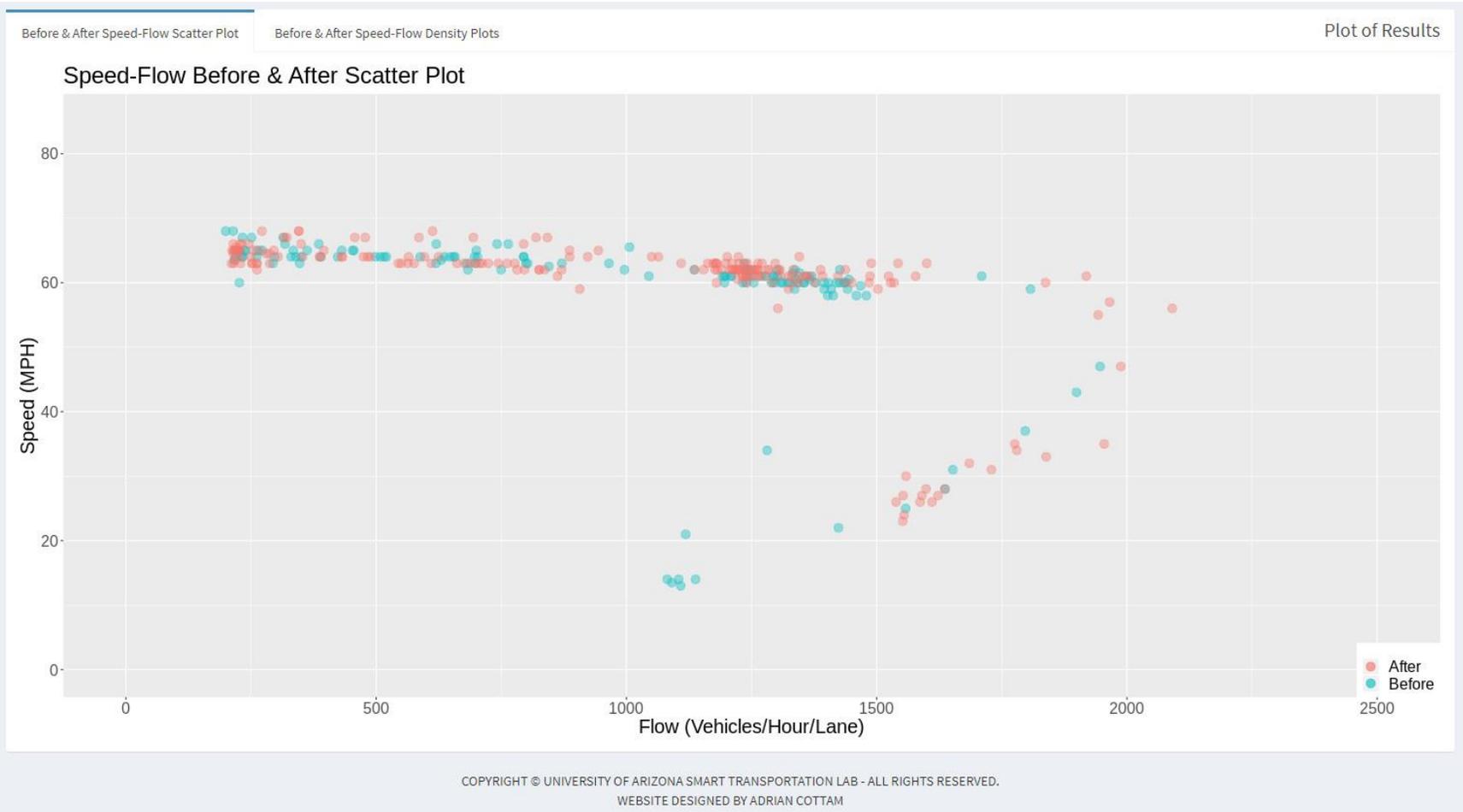


Figure 21 Before and After Speed-Flow Scatter Plot

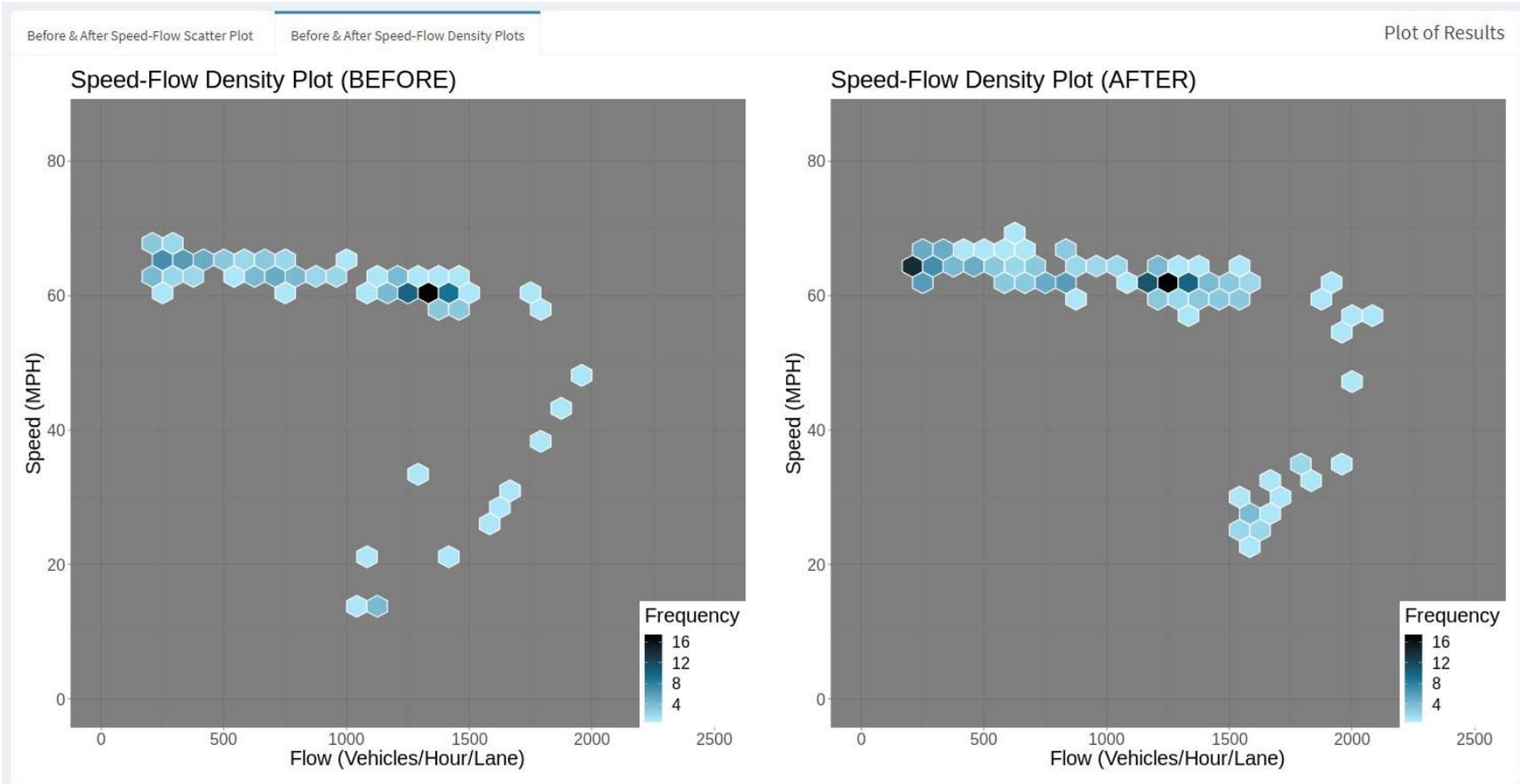


Figure 22 Before and After Speed-Flow Density Plot

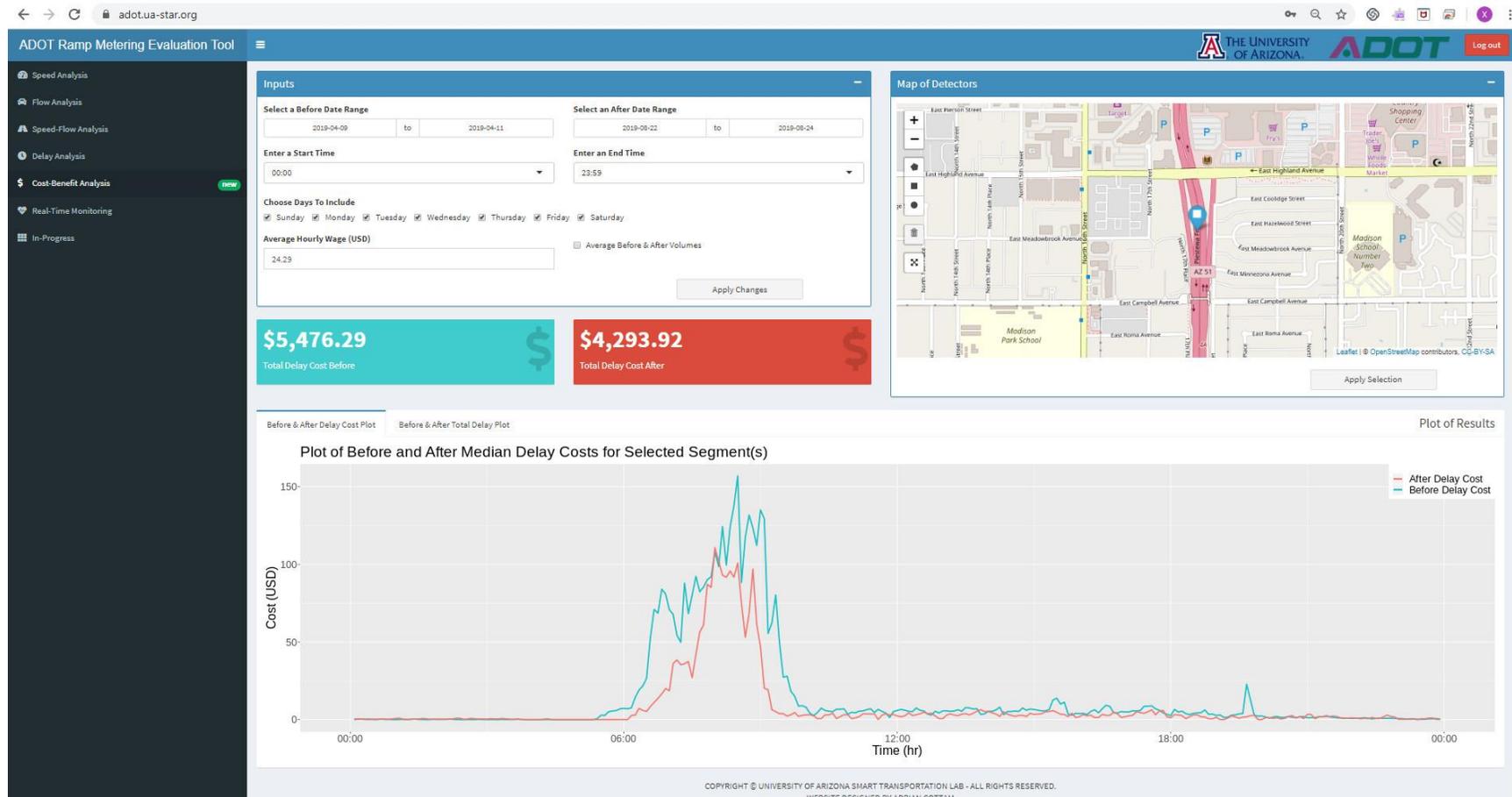


Figure 23 ADOT Ramp Metering Evaluation Tool Cost-Benefit Analysis Interface

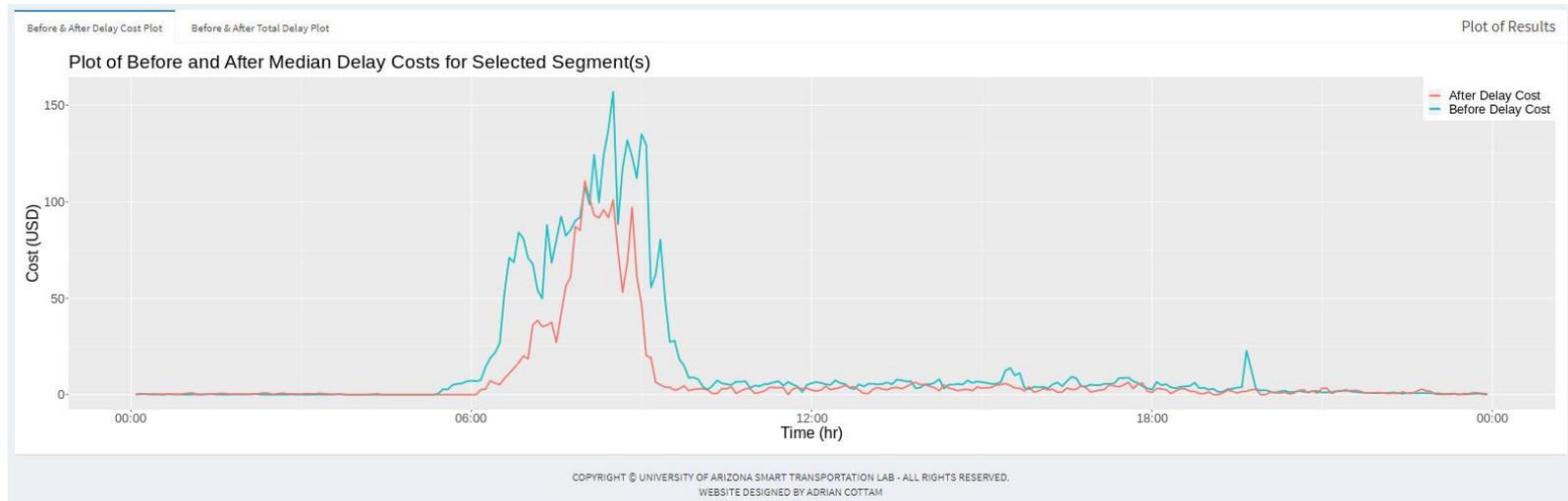


Figure 24 Plot of Before and After Median Delay Costs for Selected Segment

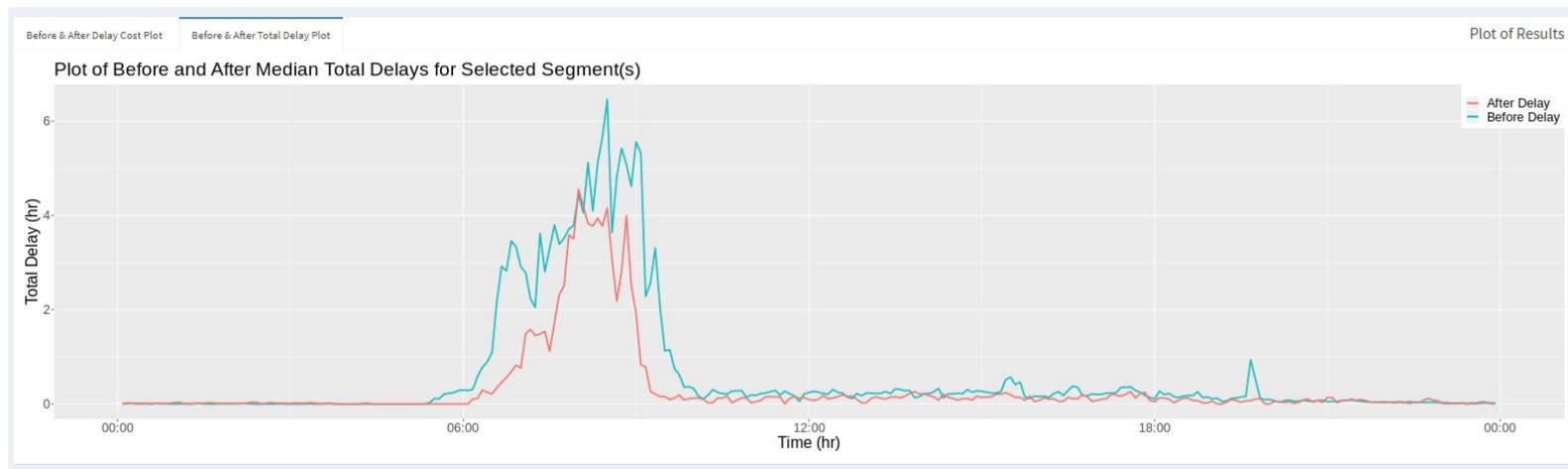


Figure 25 Plot of Before and After Median Total Delays for Selected Segment

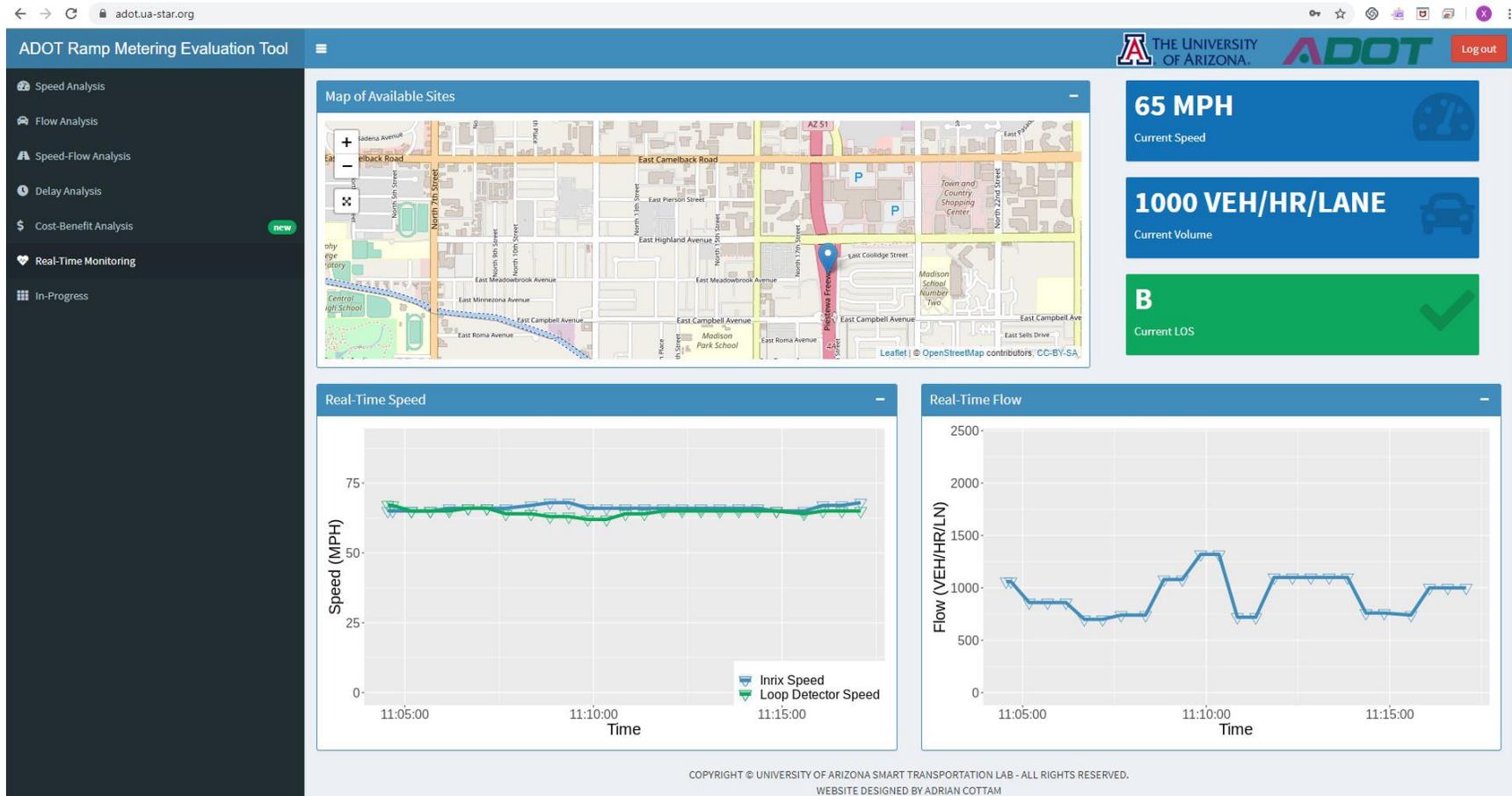


Figure 26 ADOT Ramp Metering Evaluation Tool Real-Time Monitoring Interface

5.4 Enhancement and Testing of the Proposed Tool

During the course of the project, the UA project team worked with the ADOT ITS engineers to optimize the performance of the proposed tool and system to achieve their best performance. However, due to accumulation of the new datasets, the UA team project team recommends ADOT to continue enhancement and testing of the proposed system/tool. These tasks could include but not limited to:

1. Assist ADOT in tuning up the “MaxFlow” smart ramp metering algorithm
2. Compare INRIX ramp travel time data with the data collected through video or other methods
3. Continuous improvement of the prototype ramp metering evaluation tool. The potential improvement includes but not limited to:
 - a. Adding more statistical analysis modules
 - b. Improve data extraction performance
 - c. More visualization options
 - d. Additional reporting functions, e.g. exporting results to EXCEL files.
 - e. Ramp meter operating hours/uptime
4. Continue maintaining the data collection process and optimizing databases

CHAPTER 6. CASE STUDIES**6.1 INRIX Data Verification**

In order to verify the data quality of INRIX data, SR-51 & E Highland Ave is selected as a study site to compare the mainline speed difference between MaxView loop-based data and INRIX data. The selected date is Mar. 14, 2019. The selected time range is 3:15pm~4:15 pm. Figure 27 shows the location of SR-51 & Highland Ave. Figure 28 presents the MaxView loop-based data and INRIX data mainline speed plot. Apparently, Figure 28 shows that there is a 5 minutes time lag between mainline speed curve of MaxView loop-based data and mainline speed curve of INRIX data. Figure 29 presents the result after moving INRIX data speed curve to the left with 5 minutes. After revising, those two speed curves are very similar.

**Figure 27 SR-51 & Highland Ave**

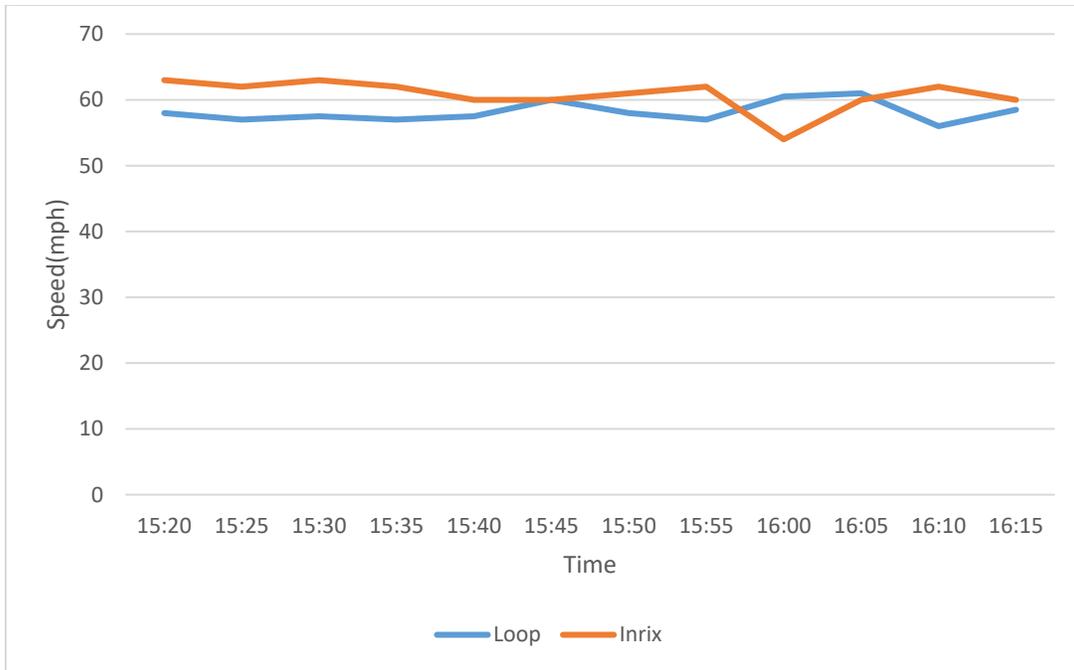


Figure 28 MaxView loop-based data and INRIX data mainline speed comparison

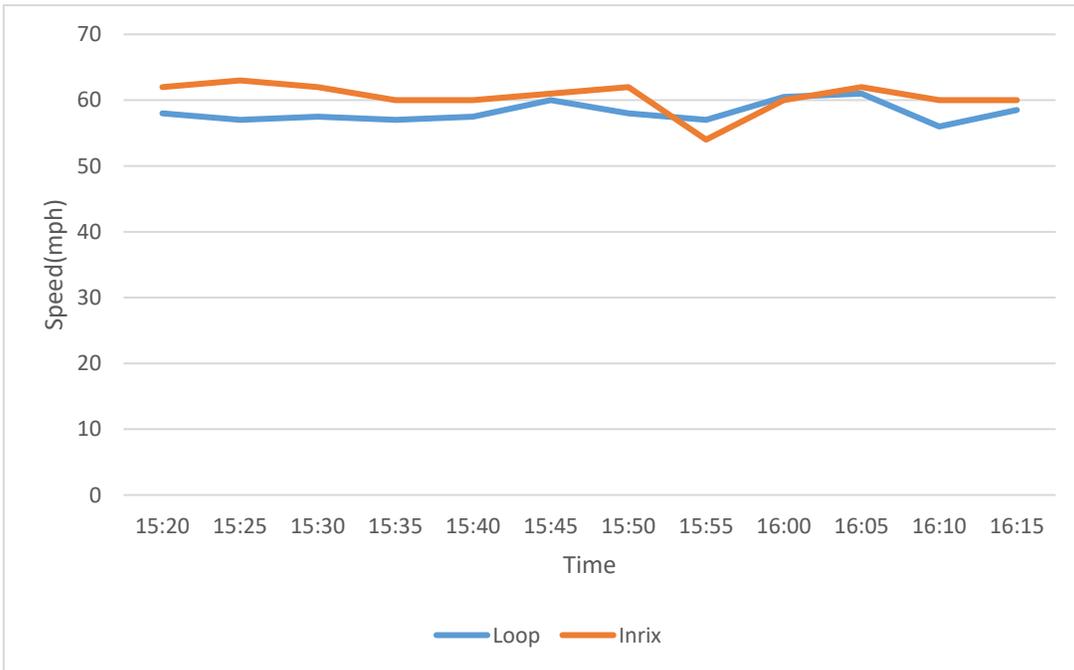


Figure 29 MaxView loop-based data and INRIX data mainline speed comparison after revision

6.2 Case Study 1

Ramp metering control strategy changed from fixed rate meter to responsive ramp meter on Aug. 7, 2017. To evaluate the effectiveness of responsive ramp metering control strategy, this project evaluates the performance of the entire corridor by choosing one month before (July 1, 2017- July 31, 2017) and one month after (September 1, 2017- September 30, 2017) to conduct comparison using INRIX data. One thing to be noted is that we only consider weekdays (Tuesday, Wednesday, and Thursday) in the evaluation process.

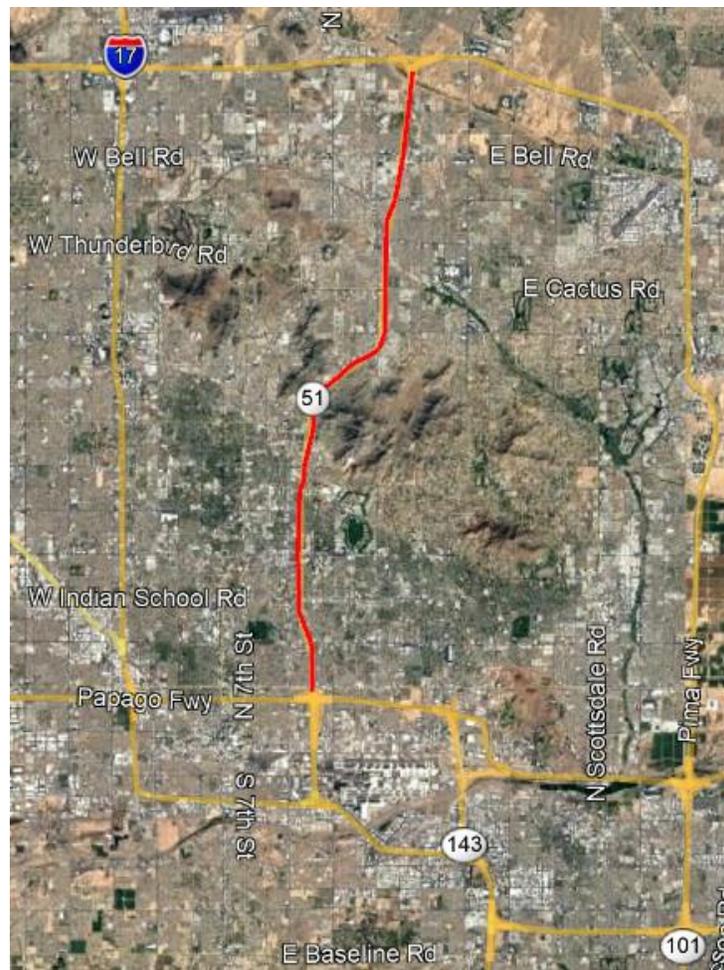


Figure 30 SR-51 Southbound

Figures 31 through 34 show the performance of fixed ramp meter and responsive ramp meter in term of median speed and travel time based on different freeway segments. Responsive ramp meter results in lower speed and longer travel time for both mainlines and ramps during peak hours. Another finding is that responsive ramp meter produces different influences on mainlines and ramps. During peak hours, responsive ramp metering has a greater negative impact on mainline traffic than it does on ramps.

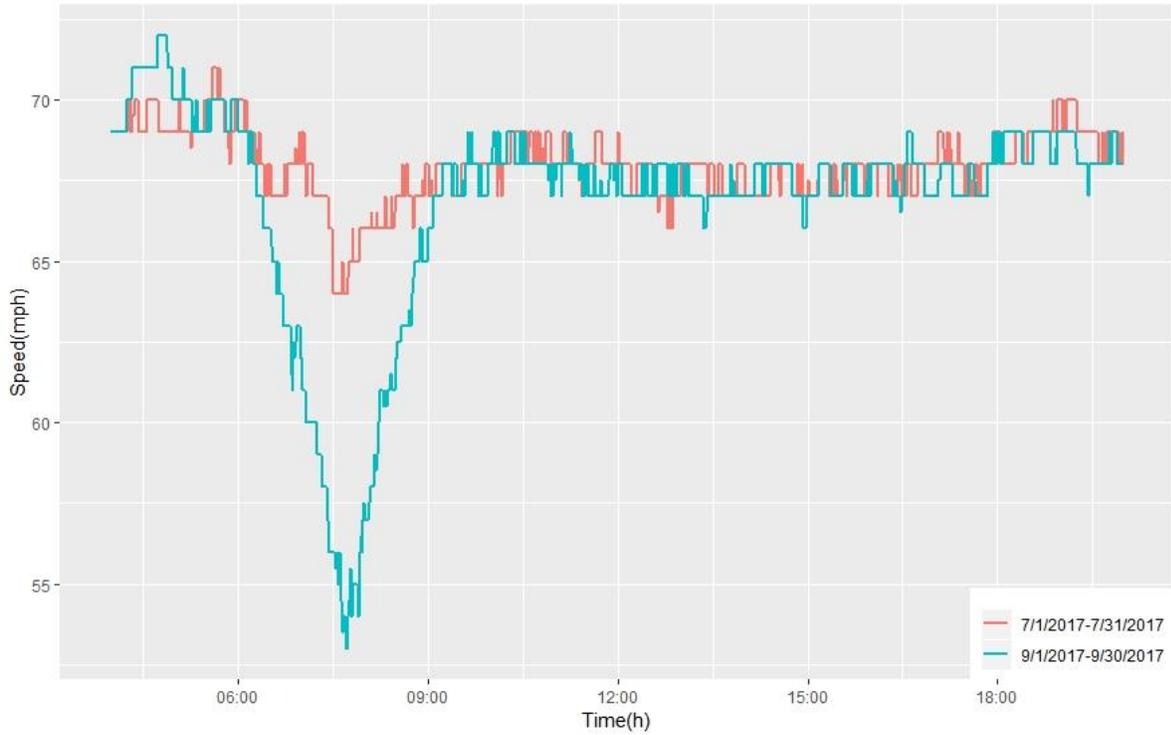


Figure 31 Median speed analysis from 4 am to 8 pm (Mainline Segment)

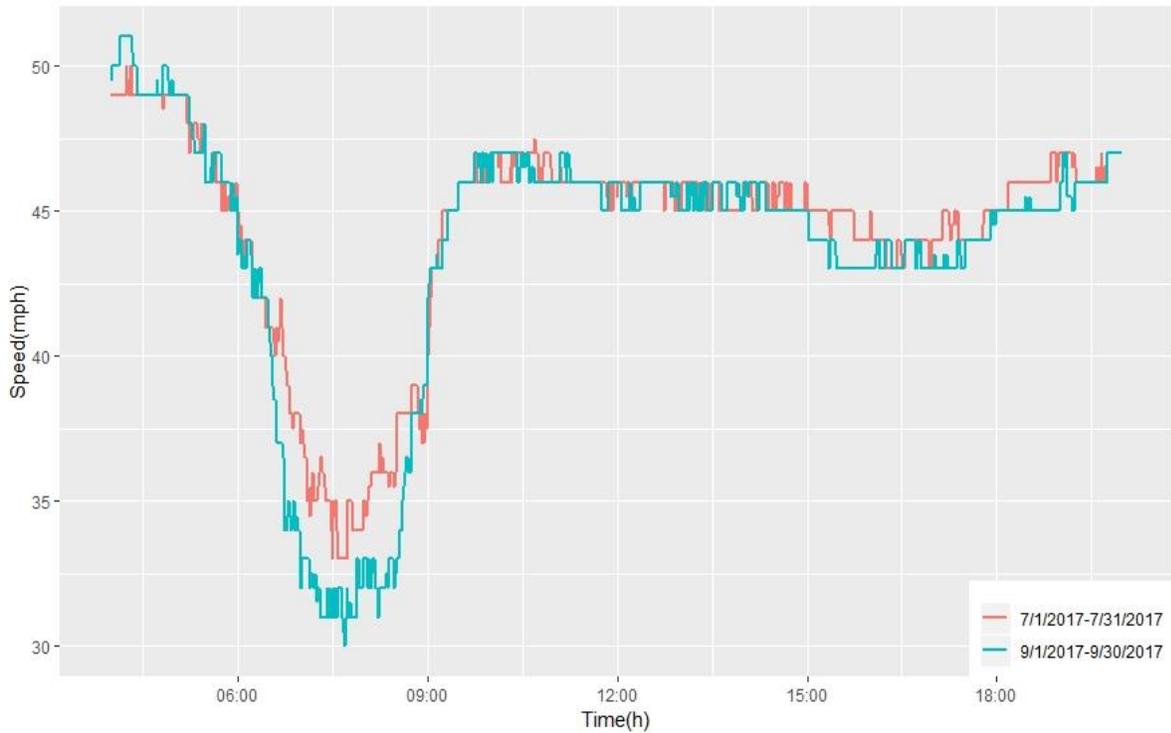


Figure 32 Median speed analysis from 4 am to 8 pm (Ramp Segment)

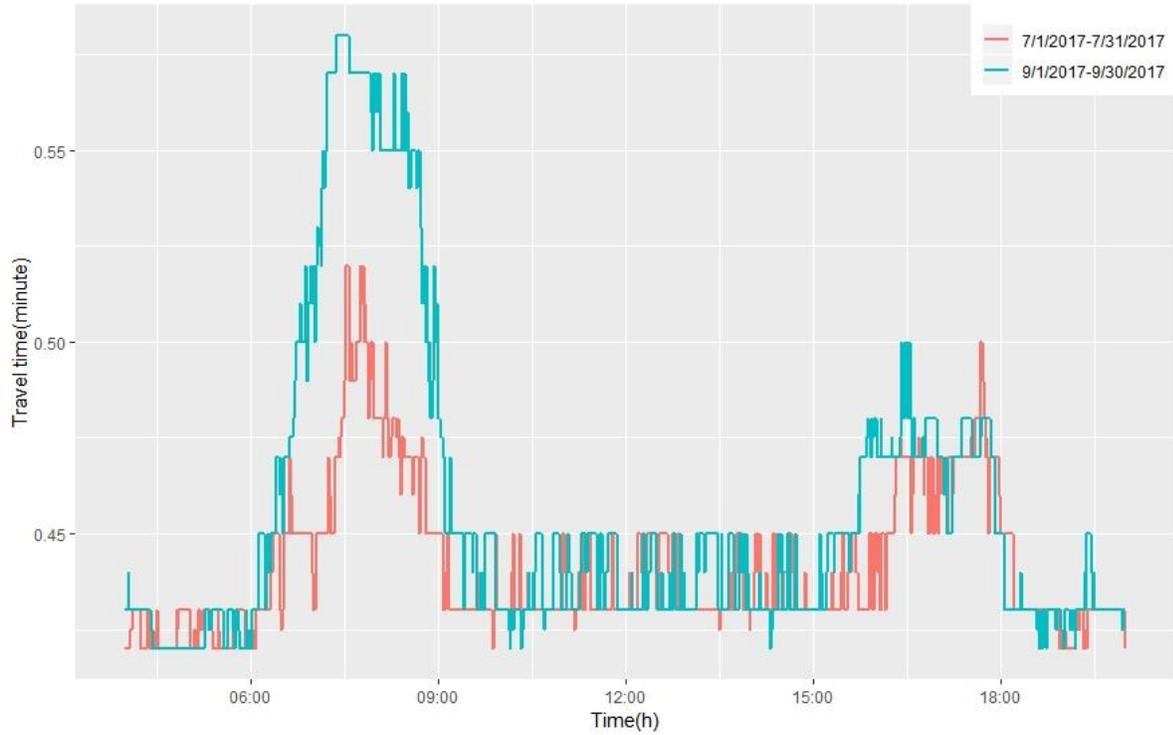


Figure 33 Travel time analysis from 4 am to 8 pm (Mainline Segment)

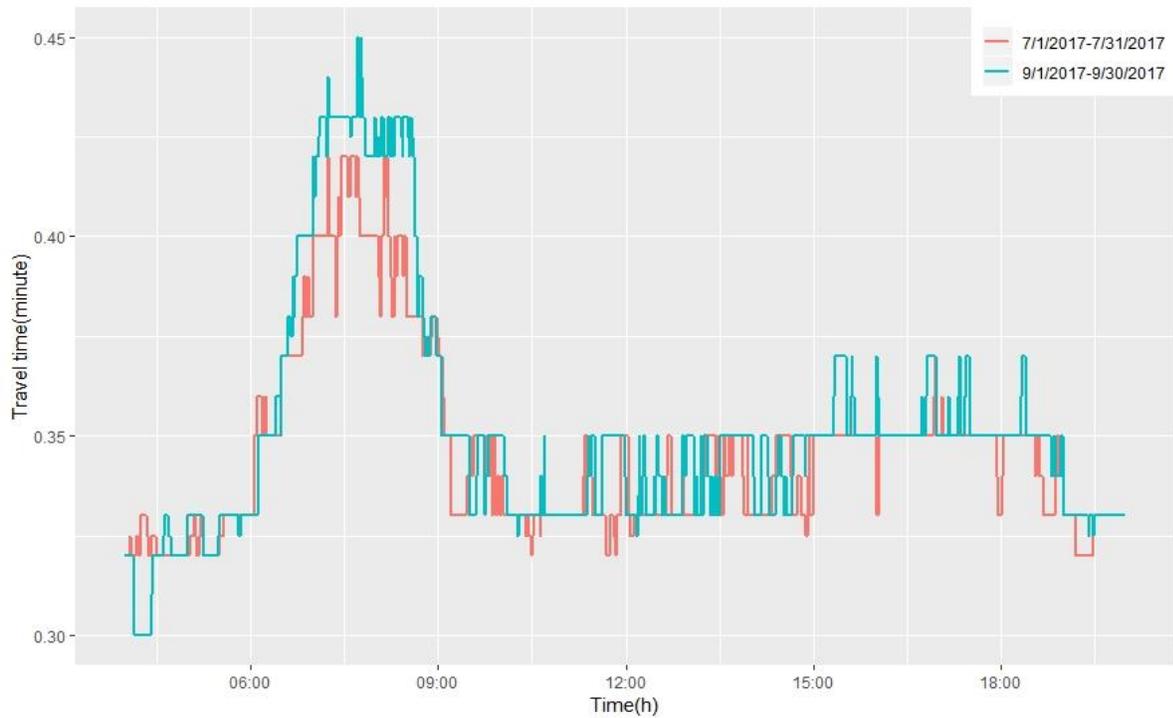


Figure 34 Travel time analysis from 4 am to 8 pm (Ramp Segment)

6.3 Case Study 2

As a pilot study to assess the effectiveness of fixed ramp meter control strategy, ADOT turned on the fixed mode at the ramp near 202 WB & S McQueen Rd on Feb. 20, 2019. This case study was outside of the original project scope. Due to the flexibility of the proposed tool, this case study was conducted outside SR-51 as a pro bono task for ADOT for their information. Figure 35 presents the layout of 202 WB & S McQueen Rd, the blue line marks the ramp and the red line marks the mainline.

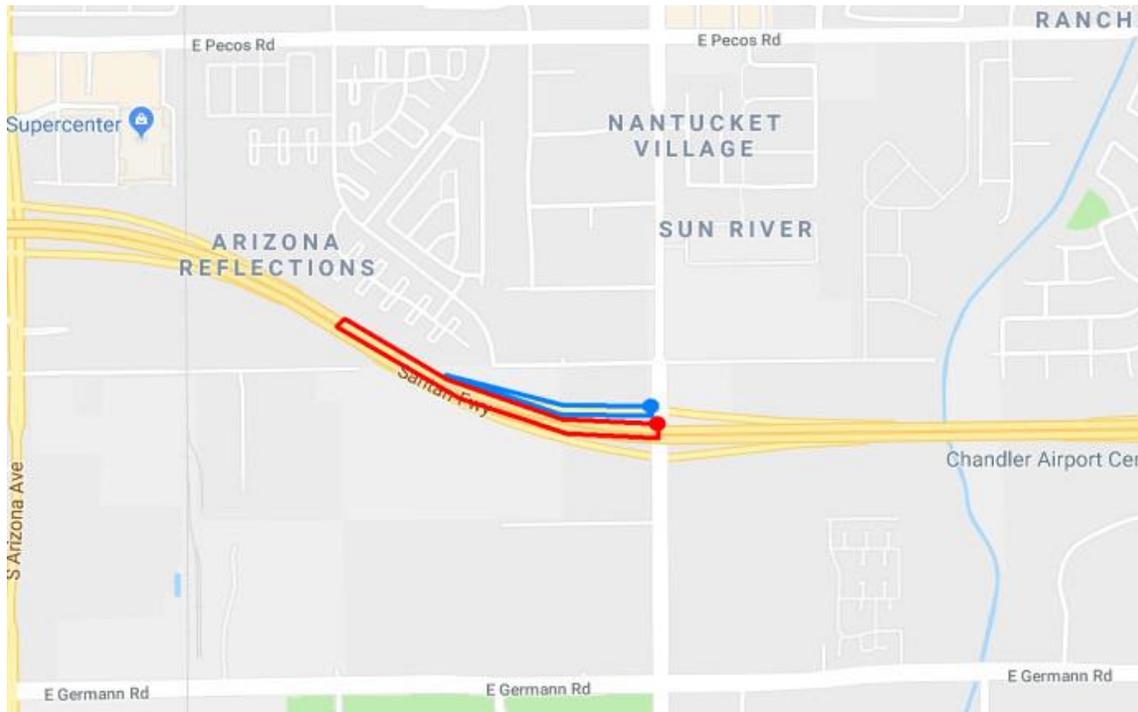


Figure 35 202 WB & S McQueen Rd

Similar with Case Study 1, Case Study 2 also chooses one month before (2019-01-22~2019-02-19) and one month after (2019-02-21~2019-03-20), only Tuesday, Wednesday, and Thursday are included, to assess the effectiveness of adaptive ramp meter. This case study analyzes the performance of fixed ramp meter in terms of mainline median speed and mainline occupancy using MaxView loop detector data. Figure 36 offers the detector slot numbering scheme for the study site. Figure 37-40 show the performance of no ramp meter and fixed ramp meter in term of median speed based on different lanes, which was calculated by hand because the tool does not have a lane-by-lane option. Figure 41-44 show the performance of no ramp meter and fixed ramp meter in terms of occupancy based on different lanes. Compared with no ramp meter, the fixed ramp meter promotes the speed and occupancy for all three lanes during 6am~7am. But when it comes to 7am~9am, the performance of no ramp meter and fixed ramp meter are very similar from the perspective of median speed and occupancy. Another finding is that the improvements in median speed and occupancy are different for different lanes. The closer the lanes to the ramp, the more improvements the lanes have in terms of speed and occupancy.

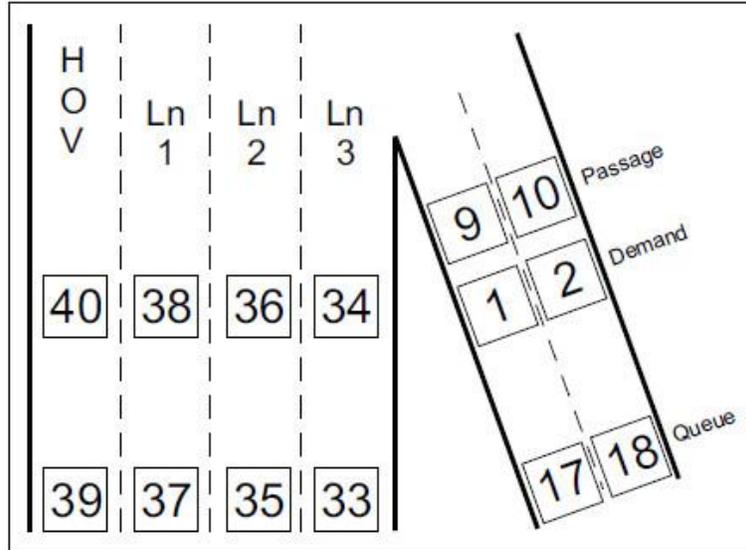


Figure 36 202 WB & S McQueen Rd detector slot numbering scheme (Source: ADOT)

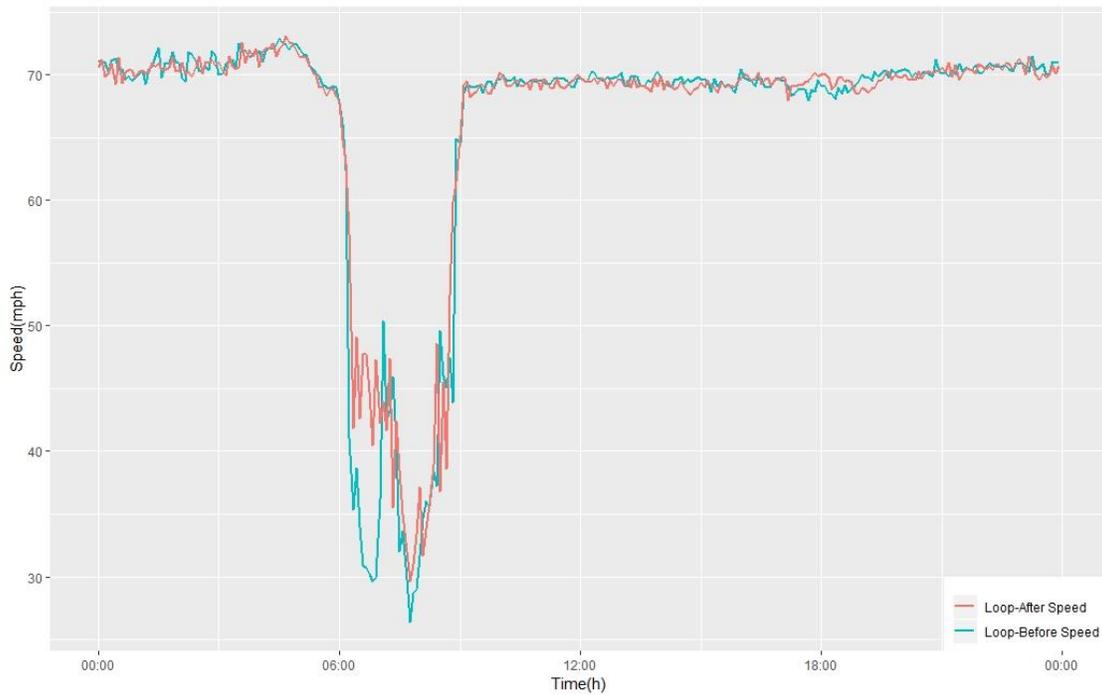


Figure 37 202 WB & S McQueen Rd mainline median speed comparison

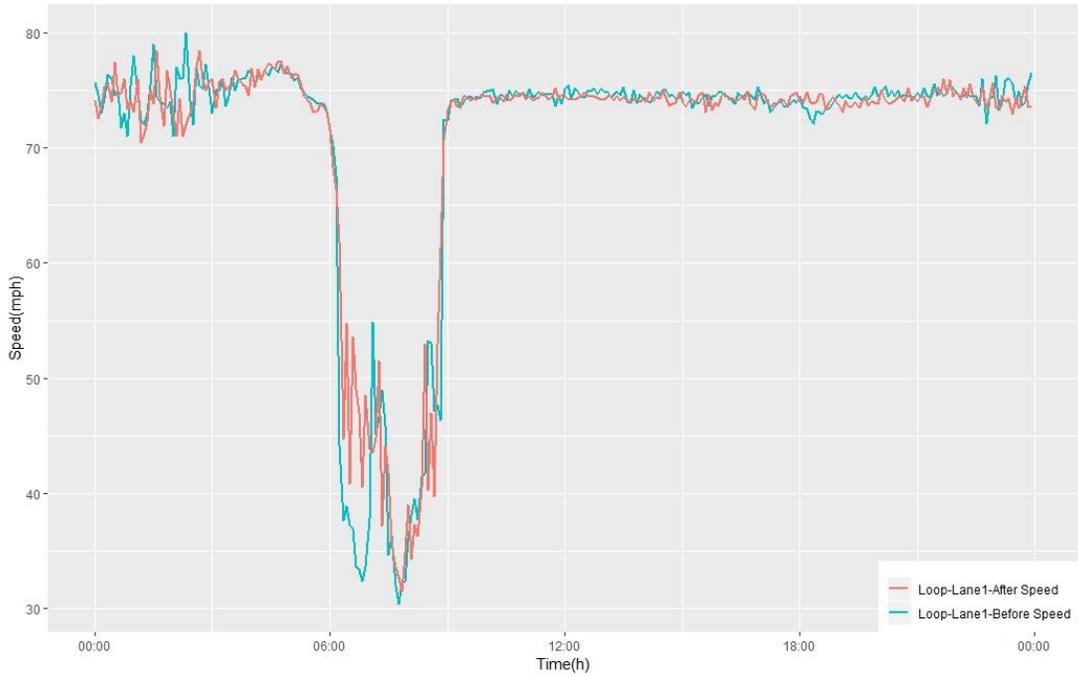


Figure 38 202 WB & S McQueen Rd lane 1 median speed comparison

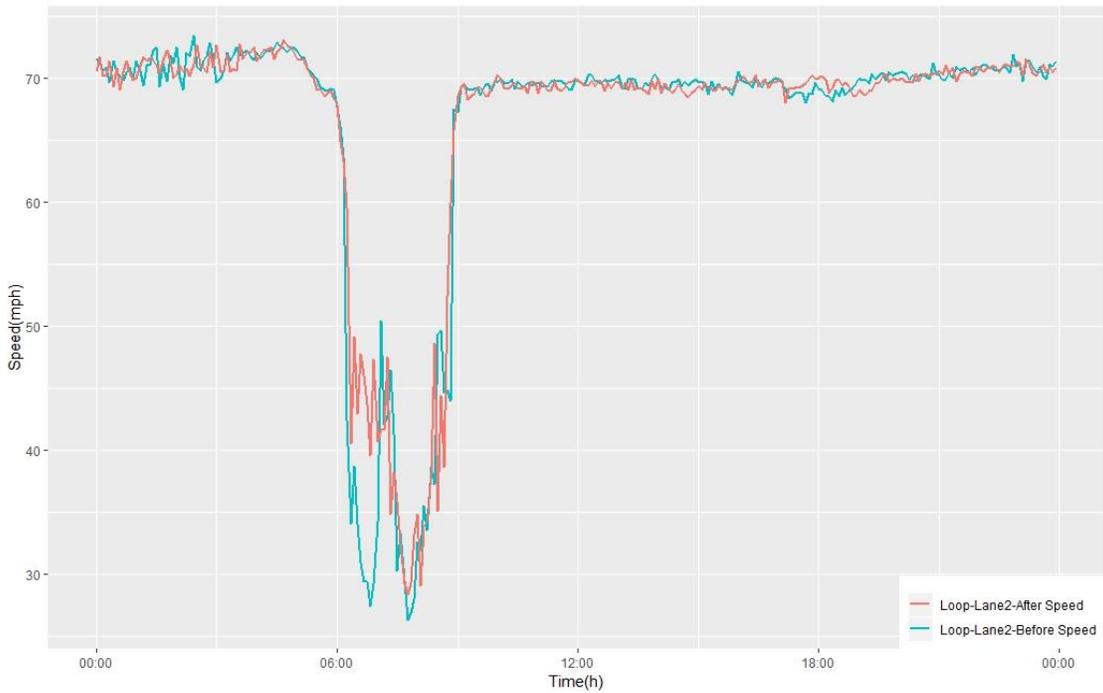


Figure 39 202 WB & S McQueen Rd lane 2 median speed comparison

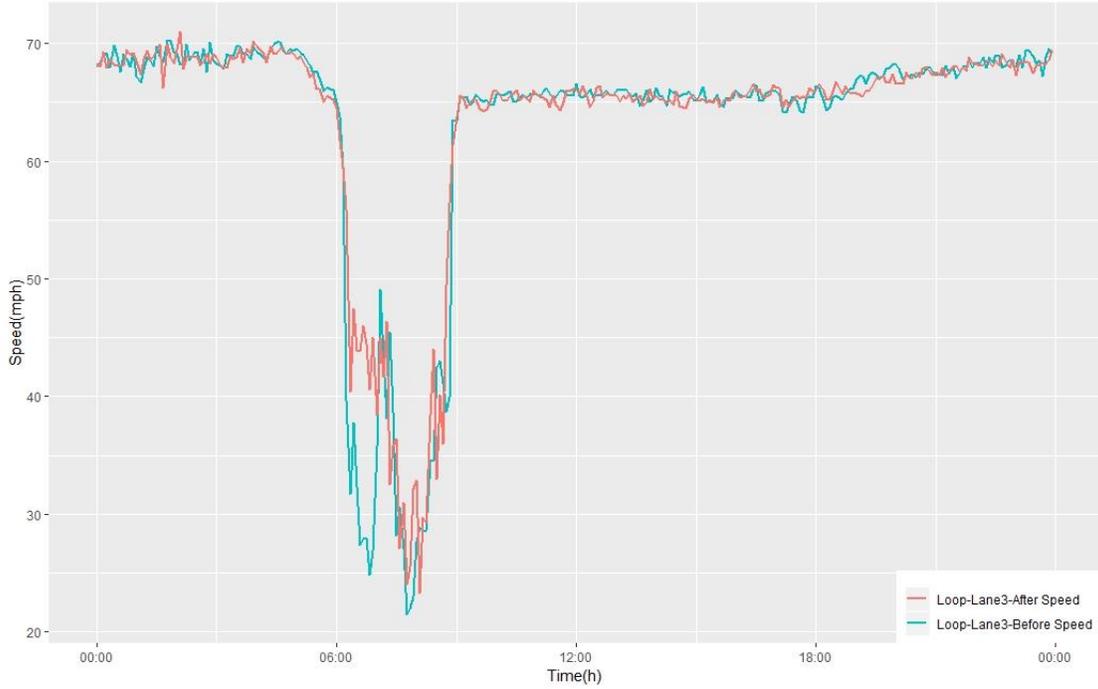


Figure 40 202 WB & S McQueen Rd lane 3 median speed comparison

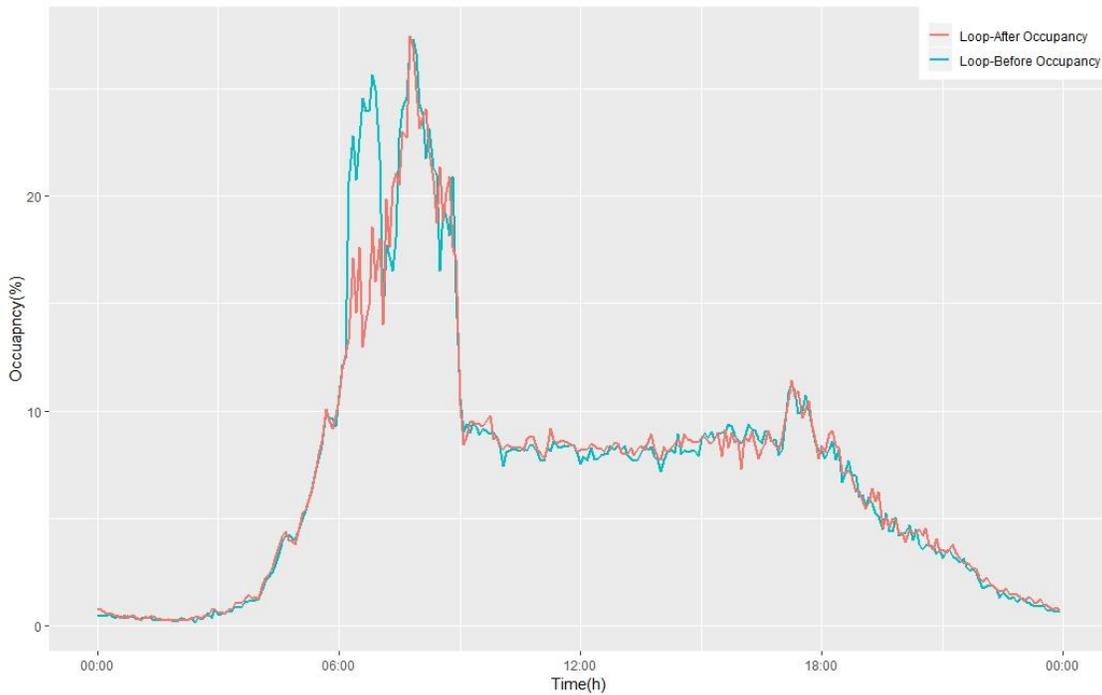


Figure 41 202 WB & S McQueen Rd mainline occupancy comparison

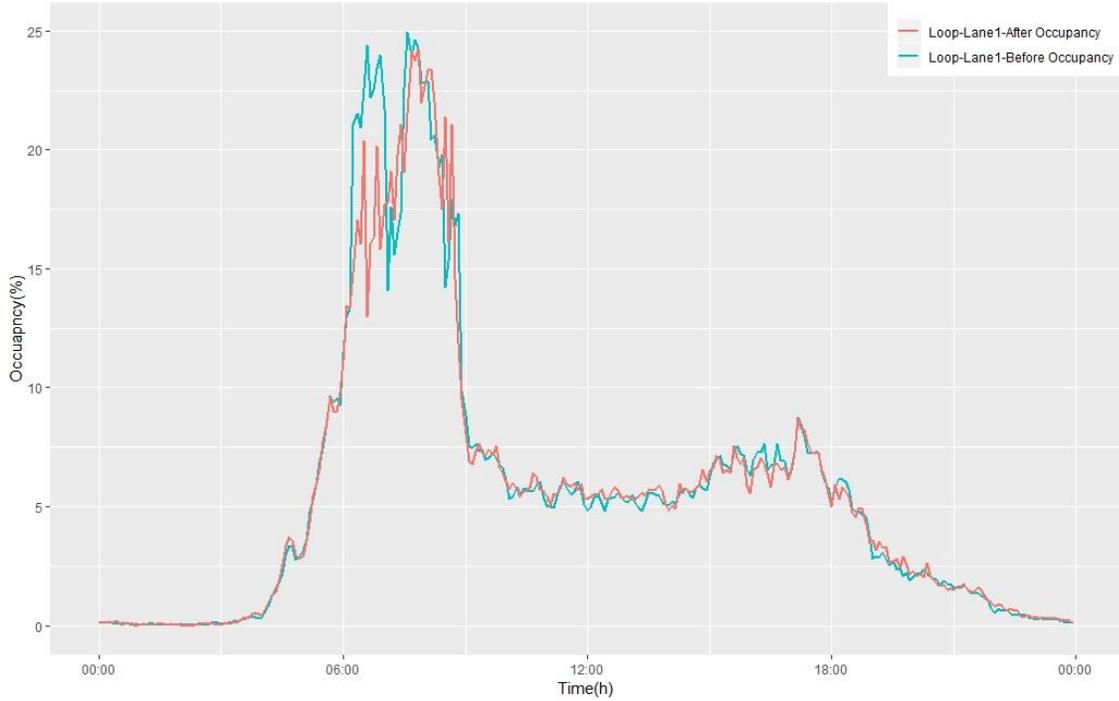


Figure 42 202 WB & S McQueen Rd Lane 1 Occupancy Comparison

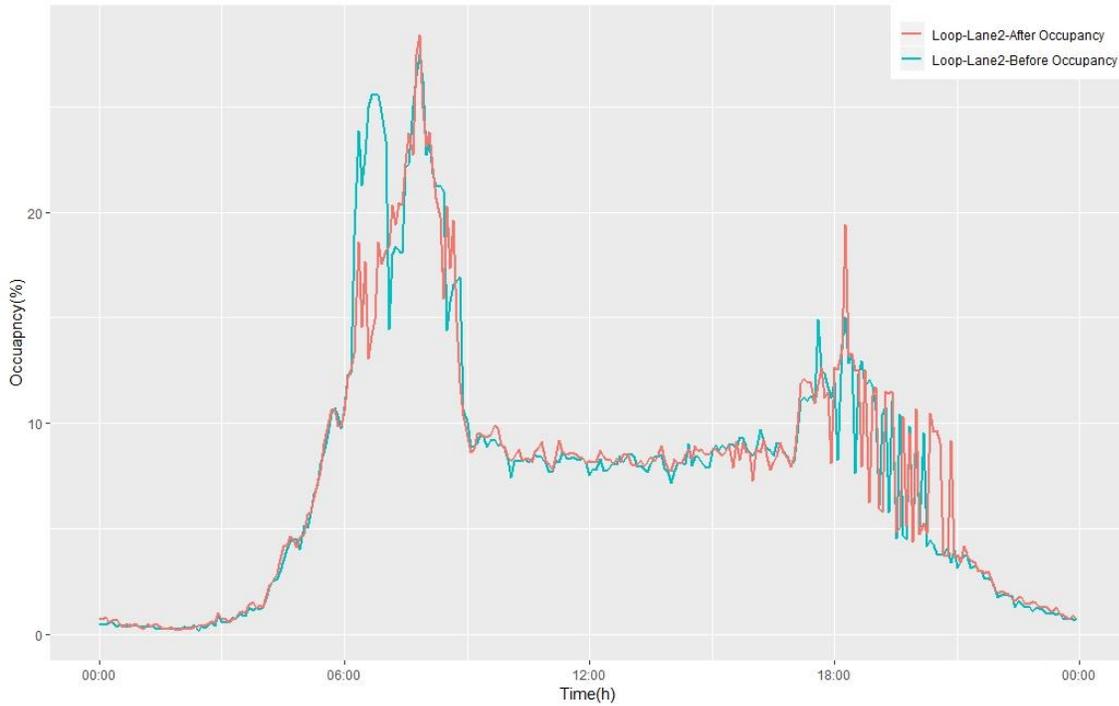


Figure 43 202 WB & S McQueen Rd Lane 2 Occupancy Comparison

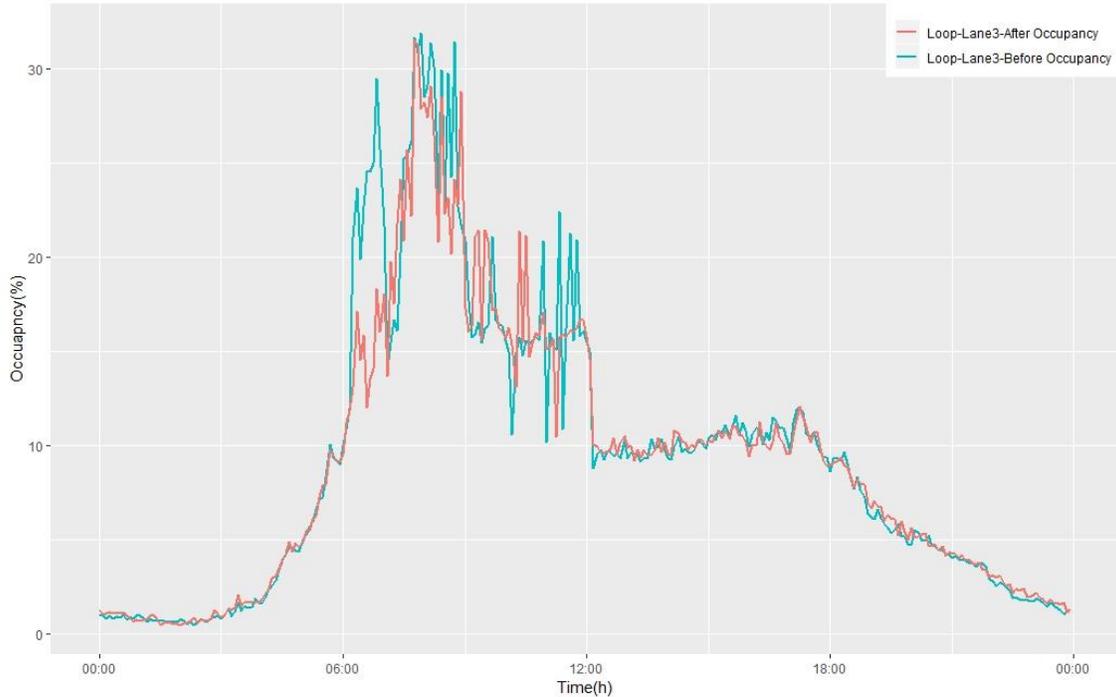


Figure 44 202 WB & S McQueen Rd Lane 3 Occupancy Comparison

6.4 Case Study 3

ADOT changed ramp metering control strategies from responsive mode to adaptive mode on May 13, 2019, in the following locations along SB SR-51: Highland Ave, Bethany Home Rd, Glendale Ave, and Northern Ave. to evaluate the effectiveness of ramp metering control strategies in terms of speed and cost-benefit. This study chooses one month before (2019-04-14 ~ 2019-05-12) and one month after (2019-05-14 ~ 2019-06-10) to conduct comparison. In this study, we only consider morning peak hours (6am – 9am), Tuesdays, Wednesdays, and Thursdays.



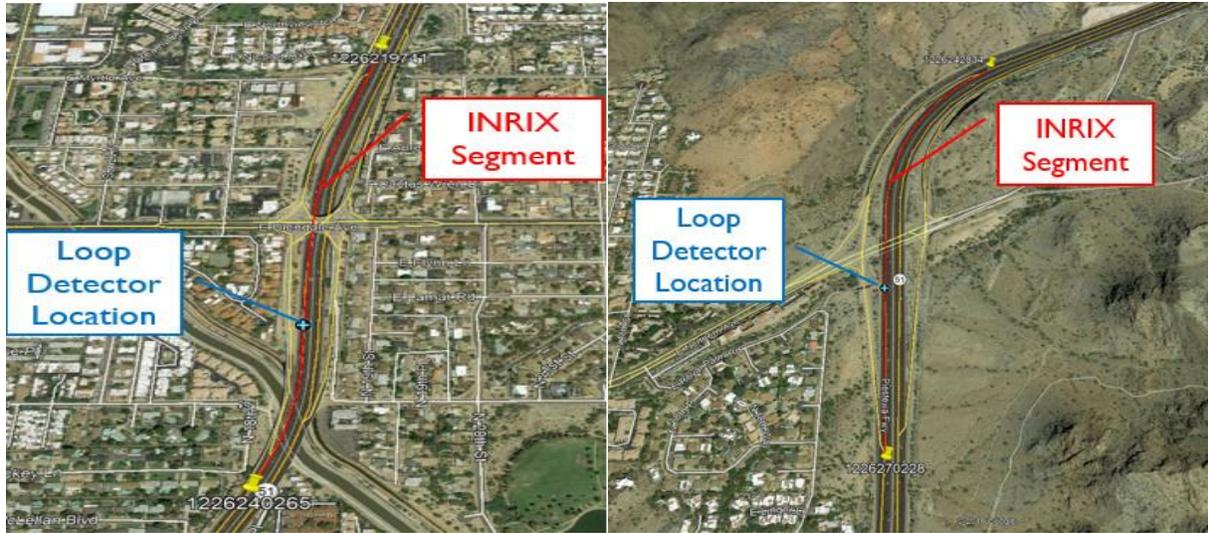


Figure 45 Layouts of four study sites

Table 12 INRIX Data Mainline Median Speed Comparison

Locations	INRIX Data Speed Comparison		
	Before speed (mph)	After speed (mph)	Speed change (mph)
Highland Ave	35.80	44.06	+8.26
Bethany Home Rd	38.49	50.35	+11.85
Glendale Ave	36.90	49.41	+12.51
Northern Ave	49.69	61.90	+12.21
Overall	40.19	51.40	+11.21

Table 13 INRIX Data Ramp Median Speed Comparison

Locations	INRIX Data Speed Comparison		
	Before speed(mph)	After speed (mph)	Speed change (mph)
Highland Ave	25.70	22.66	-3.04
Bethany Home Rd	23.19	19.66	-3.53
Glendale Ave	25.71	27.71	+2.00
Northern Ave	34.11	29.87	-4.24
Overall	27.19	24.99	-2.20

Table 14 INRIX Data Mainline Cost-benefit Comparison

Locations	INRIX Data Cost-benefit Comparison		
	Travel Time Change (Second/veh)	Volume (veh)	Benefit (\$)
Highland Ave	-8.46	189325	10677
Bethany Home Rd	-11.75	190497	14922
Glendale Ave	-10.68	182404	12987
Northern Ave	-10.99	208632	15285
Money saved			\$53,873*

*: Note that the cost was calculated only based on morning peak hours (6am – 9am) on Tuesdays, Wednesdays, and Thursdays over the study period (one month for the before study and one month for the after study).

Table 15 INRIX Data Ramp Cost-benefit Comparison

Locations	INRIX Data Cost-benefit Comparison		
	Travel Time Change (Second/veh)	Volume (veh)	Cost (\$)
Highland Ave	+3.01	42998	863
Bethany Home Rd	+ 5.86	73692	2879
Glendale Ave	-3.14	35487	-743
Northern Ave	+ 4.01	72478	1938
Money cost			\$4,936*

*: Note that the cost was calculated only based on morning peak hours (6am – 9am) on Tuesdays, Wednesdays, and Thursdays over the study period (one month for the before study and one month for the after study).

In summary, after changing ramp metering control strategies from responsive mode to adaptive mode, the mainline speeds are promoted in those four locations and the ramp speeds decrease except for SR-51 & Glendale Ave. As for the cost-benefit comparison, the money saved in the mainline is \$53,873 and the money cost in the ramp is \$4,936. Because the ramp metering evaluation tool cannot currently account for total ramp delay costs, these costs were obtained through a manual analysis of the data. These two costs are calculated only based on morning peak hours (6am – 9am) on Tuesdays, Wednesdays and Thursdays over the study period (one month for the before study and one month for the after study). The money saved in the mainline is much more than the money cost on the ramp. That is, changing ramp metering control strategies from responsive mode to adaptive mode demonstrated its effectiveness in increasing mainline speed and reduce road users’ delay costs.

CHAPTER 7. CONCLUSIONS

This project successfully developed an evaluation tool to evaluate ramp metering control strategies. The tasks that were accomplished in this project are summarized below:

- A comprehensive literature review was conducted to summarize the performance measures used for ramp metering evaluation. The literature review also assisted in identifying an efficient statistical method for understanding of the effectiveness of different ramp metering algorithms.
- New databases were designed and optimized to collect MaxView loop-based data, MaxView cabinet event-based data, and INRIX data. A real-time data collection tool written in C# was developed to facilitate the data collection process.
- Using the data collected in the new databases, a variety of performance measures covering speed analysis, flow analysis, speed-flow analysis, delay analysis, cost-benefit analysis, and real-time monitoring were employed to demonstrate the effectiveness of ramp metering control strategies. Furthermore, a z-test was also used to determine the difference between the before and after scenarios.
- The ramp metering evaluation tool was written in the open-source programming language “R”. It was hosted by the University of Arizona on their web-servers. The interface of this tool allows users to choose before/after cases based on time of day, dates, segments and performance measures for comparisons.

To further assist ADOT in tuning up the ramp metering control strategies, the UA project team made the following conclusions and recommendations:

- The tool utilizes the traffic data comes from loop-based data and INRIX data. Both data sources provide complimentary analytical results to give a comprehensive view of roadway conditions;
- Compared with fixed ramp meters, responsive ramp meters result in lower speeds and longer travel times for both mainlines and ramps during peak hours;
- Changing ramp metering control strategies from responsive mode to adaptive mode can increase mainline speed and reduce mainline congestion effectively;
- Additional performance measures and analytical modules could be added into the evaluation tool using the data collected in this project;
- To maximize the usability of the tool, the results could be shown on the entire freeway network in the state of Arizona;

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- The tool needs to be routinely updated as do all computer software packages. A maintenance plan should be developed, and the related costs should be budgeted.

It was found that the ramp metering evaluation tool can be regarded as an effective way of helping ADOT traffic engineers to continuously and consistently evaluate ramp metering strategies in a cost-effective manner, and ADOT can dynamically implement ramp metering strategies based on the analysis results.

This project had the unique benefit of allowing ADOT to collaborate with the University of Arizona (UA) to develop a highly effective tool to continuously improve the transportation network. ADOT developed the “MaxFlow” adaptive ramp metering algorithm in-house using existing infrastructure. Therefore, the only costs associated with its development were the labor hours of the ADOT engineers. Furthermore, ADOT was able to support a local institution by working with the UA to develop the ramp metering evaluation tool. This tool provided definite feedback that ADOT engineers could act upon for further design changes. Several of ADOT’s pressing questions were answered along the way through case studies conducted by the UA, with some even being conducted outside the scope. In summary, the collaborative work between ADOT and the UA throughout this project sparked innovation and provided tangible benefits for the community, for relatively low cost to ADOT.

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