REPORT CDOT-2020-17

May 2020

I-25 South Gap Queue Warning System Evaluation

APPLIED RESEARCH & INNOVATION BRANCH

Ben Waldman, PE
Jason Freitas, PE, MSc
Alvin Stamp, PE, MSc, MPA
Negar Karimi, EIT, MSc

COLORADO
Department of Transportation

Technical Report Documentation Page

1. Report No. CDOT-2020-17	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle I-25 GAP QUEUE WARNING SYSTEM EVALUATION		5. Report Date May 2020
		6. Performing Organization Code
7. Author(s) Ben Waldman, PE. Jason Freitas, PE, MSc, Alvin Stamp, PE, MSc, MPA. Negar Karimi, EIT, MSc.		8. Performing Organization Report No.
9. Performing Organization Name and Address Apex Design, PC 1675 Larimer Street, Suite 400 Denver, CO 80202		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 320.05
12. Sponsoring Agency Name and Address Colorado Department of Transportation - Research 2829 W. Howard Pl. Denver CO, 80204		13. Type of Report and Period Covered Final (Aug 2019 – May 2020)
		14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the US Department of Transportation, Federal Highway Administration
Alvin Stamp, PE (CDOT Champion), Negar Karimi (CDOT Co-Champion)

16. Abstract
During a construction project, traffic traveling through the construction zone experiences frequent instances where construction vehicles, incidents, and recurring congestion interrupt traffic flow that result in long queues and delays as well as increased crash rates. In an effort to help mitigate these instances, CDOT has deployed numerous smart work zone systems throughout the I-25 Gap construction zone including Queue Warning Systems (QWS)This report discusses the deployment of a QWS in the I-25 Gap work zone. Lessons learned regarding the QWS set up are discussed and field speed data has been analyzed to verify the system was operating as intended and to quantify the effectiveness of it.

The results are intended to give CDOT confidence QWS are effective in mitigating sudden stops due to unanticipated queueing. Two measures of effectiveness (MOEs) were observed and evaluated for a one month period with I-25 Gap QWS activated (December 2019) and a one month period with the system deactivated (September 2019). The two MOEs include:
1. The average speed of vehicles during queue warning activation consisting of spot measurements of average speeds at each sensor location during QWS activation time periods.
2. The comparison of abrupt speed drop frequencies within 1 minute periods during QWS activation periods. Taken together, the results of the Average Speed and Abrupt Speed Reduction measures of effectiveness demonstrate the positive impacts of the QWS on traffic flow.

17. Keywords CDOT, smart work zone, safety, mobility, construction	18. Distribution Statement This document is available on CDOT's website https://www.codot.gov/programs/research/pdfs

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 33	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

EXECUTIVE SUMMARY

Travel through the I-25 Gap construction work zone presents significant challenges to both travelers and work crews, especially when the construction work is adjacent to a highway that is open to traffic carrying high traffic volumes and/or high speed traffic. I-25 between mile markers 161 and 181 is currently two lanes in each direction and has experienced an increase in congestion (higher volume) over the years as well as a steady increase in crashes. A separate safety evaluation by CDOT has found steady increases in the total number of crashes over the last five years. The corridor also carries high speed traffic, especially during off peak time periods, which makes this site a more complicated location to mitigate the impact of construction and lane closures. **Figure 1** illustrates the I-25 Gap construction work zone limits.

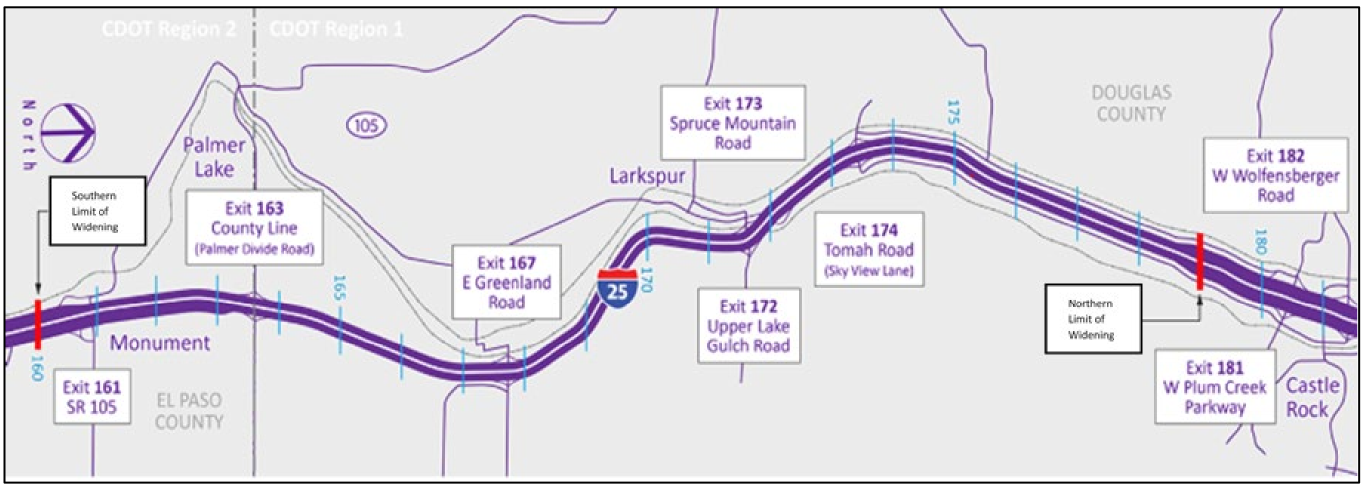


Figure ES- 1. I-25 Gap Project Area

During a construction project such as the I-25 Gap project, traffic traveling through the construction zone experiences frequent instances where construction vehicles, incidents, and recurring congestion interrupt traffic flow that result in long queues and delays as well as increased crash rates. In an effort to help mitigate the congestion and increased crashes, CDOT has deployed numerous smart work zone systems throughout the I-25 Gap construction zone including Queue Warning Systems (QWS).

This report discusses the deployment of a QWS that has been implemented in the I-25 Gap work zone. Lessons learned regarding the set up and operation of the QWS are discussed and field speed data has been analyzed to verify the system was set up and operating as intended and to quantify the effectiveness of the system. The results of this study are intended to give CDOT confidence that QWS are effective in mitigating congestion and sudden stops due to unanticipated queueing in work zones. In addition, the observations and lessons learned documented in this report will inform CDOT on how to improve deployment and the effectiveness of QWS on the I-25 Gap project and on future CDOT construction projects.

Two measures of effectiveness (MOEs) were observed and evaluated for a one month period with the Southbound I-25 Gap QWS activated (December 2019) and a one month period with the system deactivated (September 2019).

The two measurements include:

1. The average speed of vehicles during queue warning activation consisting of spot measurements of average speeds at each sensor location during QWS activation time periods.

2. The comparison of abrupt speed drop frequencies within 1 minute periods during QWS activation periods.

The following conclusions have been made based on the analysis presented in this report:

- The reliability of the operation of the QWS devices was a significant issue, especially during the early part of the monitoring. Regular visual inspections and review of detection data combined with a pay reduction penalty that was enforced was effective in significantly improving the reliability of the devices. The specification for the Queue Warning System should be revisited and the lessons learned should be incorporated.

- Comparison between field observations and the QWS data indicated good consistency between available COGNOS data and the Bluetooth travel time devices. This confirmed that the QWS performs as intended.

- The analysis indicated that average speeds were higher and there were fewer abrupt speed reductions during activation of the QWS “Slow Traffic Ahead…” and “Stopped Traffic Ahead…” messages.

- Taken together, the results of the Average Speed and Abrupt Speed Reduction measures of effectiveness demonstrate the positive impacts of the QWS on traffic flow. When activated, this system was able to significantly increase travel speeds and decrease the number of abrupt speed reductions which occurred through the Gap resulting in smoother traffic conditions for travelers.

1 INTRODUCTION

The Interstate 25 (I-25) Gap study corridor represents a crucial north-south travel artery connecting Monument to Castle Rock. The corridor serves as the main route for travelers moving between Denver, Colorado Springs, and Pueblo. Alternative routes to the I-25 study corridor include State Highways (SH) 83 and SH 105 (which becomes County Road 105 between Wolfensberger Road and Monument). These routes represent significant detours and cause increased travel time delays. Consistent population growth along the Colorado Front Range has steadily increased travel demand which correlates to increased congestion and total crashes along the I-25 Gap segment.

Prior to the beginning of construction, the facility included two through lanes in each direction. North and south of the construction segment, previous CDOT widening projects have widened the highway to three through travel lanes in each direction, resulting in the project segment being called the Gap. In response to the corridors high traffic demand, the Colorado Department of Transportation (CDOT) has prioritized the addition of one through Express Toll Lane (ETL) in each direction of the Gap to meet the growing needs of users. Travel through the I-25 Gap construction work zones presents significant challenges to both travelers and work crews, especially considering that construction work is adjacent to the highway that is open to traffic carrying high traffic volumes and/or high speed traffic. As illustrated in **Figure 1** the I-25 Gap construction work zone limits are between mile markers 161 and 181.

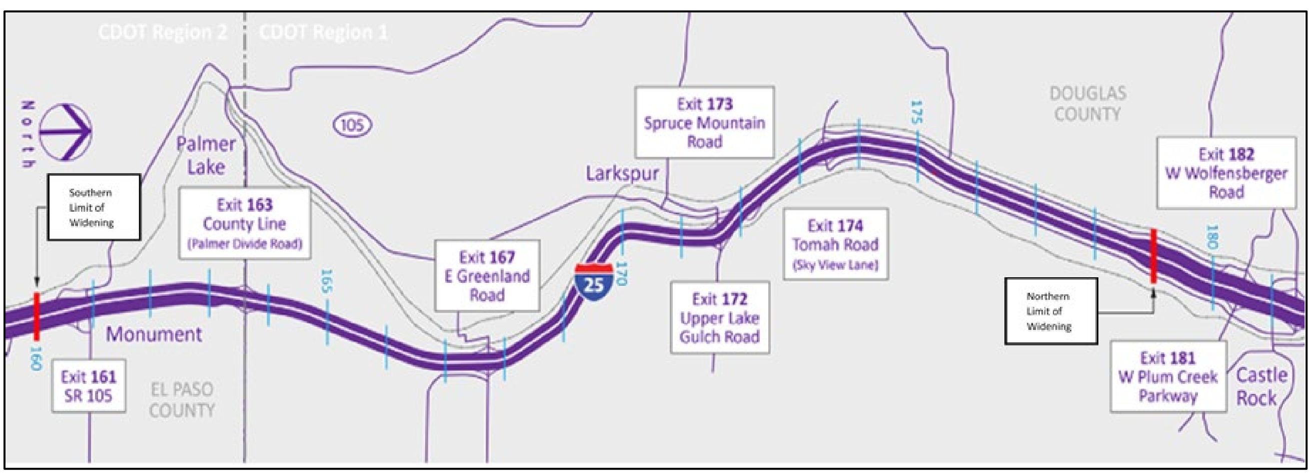


Figure 1. I-25 Gap Project Area

1.1 Project Background

As construction efforts grow in the state each year, CDOT is taking initiative to minimize the impacts of construction. CDOT Region 1 Traffic and Safety worked in coordination with the I-25 Gap Project to deploy Smart Work Zone (SWZ) technology that includes Queue Warning Systems (QWS). As shown in **Figure 1**, the I-25 Gap construction zone covers approximately 20 miles from Monument to Castle Rock with construction activity divided into 3 separate packages all of which have been scheduled to occur simultaneously until project completion in 2022.

During a construction project such as the I-25 Gap project, traffic traveling through the construction zone experiences frequent instances where construction vehicles, incidents, and recurring congestion interrupt traffic flow that result in long queues and delays as well as increased crash rates. In an effort to help mitigate the congestion and increased crashes, CDOT has deployed numerous smart work zone systems throughout the I-25 Gap construction zone including Queue Warning Systems (QWS).

1.1.1 I-25 Gap Smart Work Zone Systems and Equipment

SWZs feature the deployment of portable/temporary ITS devices within a work zone project area. In general, documentation from the device vendors show that these systems provide substantial benefits that improve overall work zone safety and mobility. Various SWZ systems were implemented along the I-25 Gap project. These systems included:

- Portable Variable Speed Limit (PVSL) systems
- Queue Warning Systems (QWS)
- Truck Entry Systems (TES)

These systems incorporated the following data measuring and public information devices:

- Doppler Sensors – these devices collect speed measurements of vehicles
- Microwave Radar Detection sensors (MVRDs) – these devices collect speed, volume and lane occupancy measurements of vehicles

- Portable Variable Speed Limit sign (PVSL) – these signs display dynamic or static speed limits programmed directly from the Project Operations Center (POC)

These devices provided continuous data collection and public information throughout the project extents. **Figure 2** provides an overview of the ITS devices used throughout the I-25 Gap construction project.

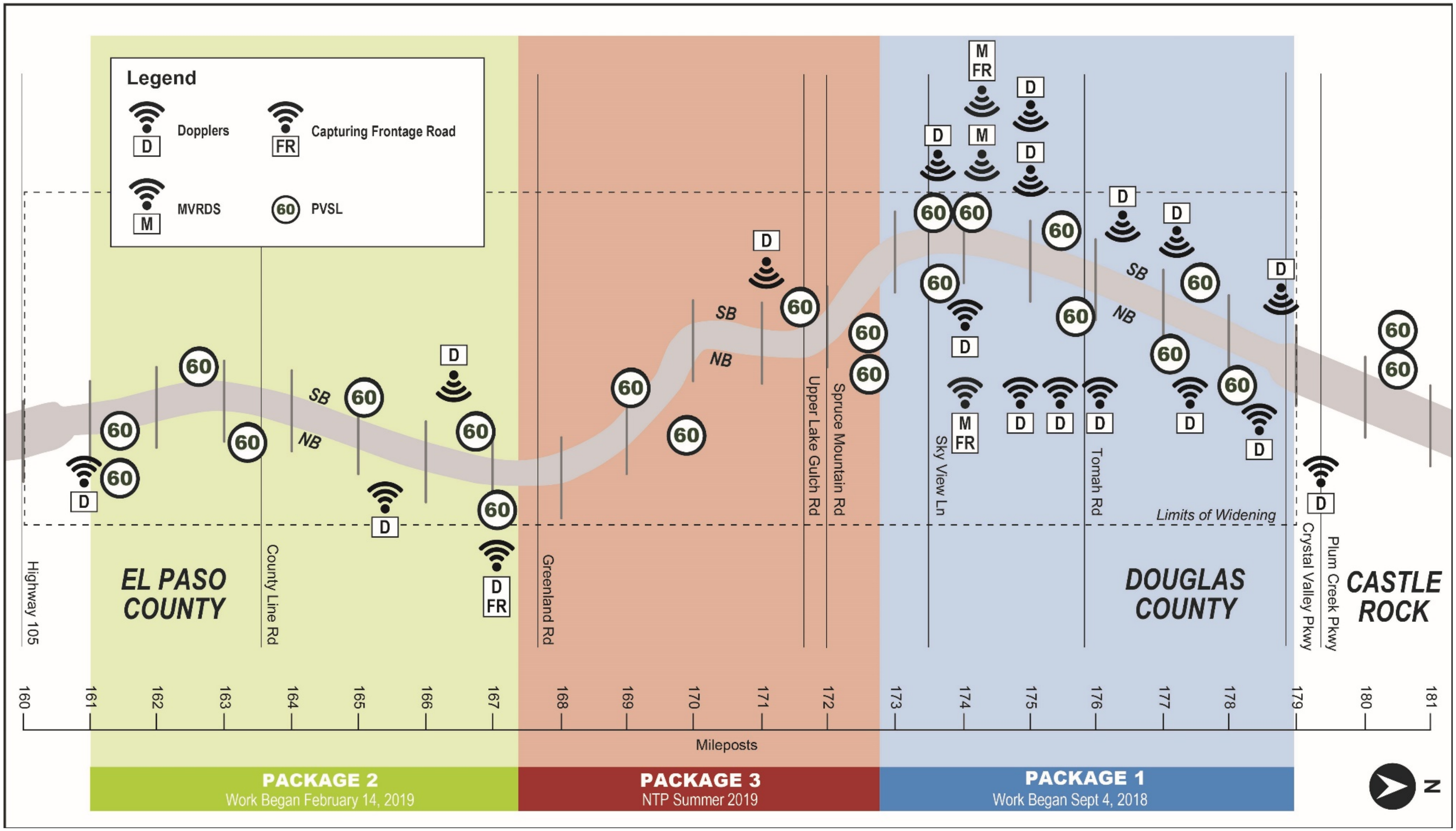


Figure 2. I-25 Gap Smart Work Zone Devices

1.2 Research Objectives

This report discusses the deployment of a QWS that has been implemented in the I-25 Gap work zone. Lessons learned regarding the set up and operation of the QWS are discussed, and field speed data has been analyzed to verify the system was set up, and operating as intended, and to quantify the effectiveness of the system. The results of this study are intended to give CDOT confidence that QWS are effective in mitigating congestion and sudden stops due to unanticipated queueing in work zones. In addition, the observations and lessons learned documented in this report will inform CDOT how to improve deployment and the effectiveness of QWS on the I-25 Gap project and on future CDOT construction projects.

This project's goals are to:

- Evaluate the effectiveness of the queue warning system to mitigate the safety and mobility impacts caused by queueing.
- Make recommendations that could result in increased efficiency of the system by changing design elements or recommending deployment and/or maintenance practices to be used in future projects.

2 QUEUE WARNING SYSTEM

A QWS is a fully automated, stand-alone system that detects the presence of real-time traffic congestion within the work zone and informs approaching motorists that traffic is either slowed or stopped ahead. **Figure 3** is an example of the Portable Changeable Message Sign (PCMS) used to inform drivers about upcoming roadway conditions. QWS benefit locations where queue lengths are anticipated to vary greatly and are used to prevent abrupt stopping and/or deceleration within the traffic flow with the goal to reduce queueing-related collisions. In addition, QWS has the potential to smooth traffic speeds so that traffic flow operates more efficiently, which can result in reduced congestion and reduced abrupt speed drops.

Figure 3. PCMS Image
(Courtesy of Street Smart)

2.1 System Logic

The southbound I-25 Gap QWS setup is illustrated in **Figure 4.** As shown, the system was composed of 4 Doppler speed sensors and 4 portable message boards. The QWS spanned approximately 8 miles of the construction zone (each pair of devices was spaced approximately 2 miles apart) from Wolfensberger Road to Tomah Road. In addition, the QWS utilized Bluetooth travel time sensors that were deployed within the work zone. The naming convention used in this report is identical to what was programmed into the JamLogic software. JamLogic is a proprietary software used to control traffic operations by connecting the data collection and public information devices in the field to inform the traveling public about nearby roadway speed conditions.

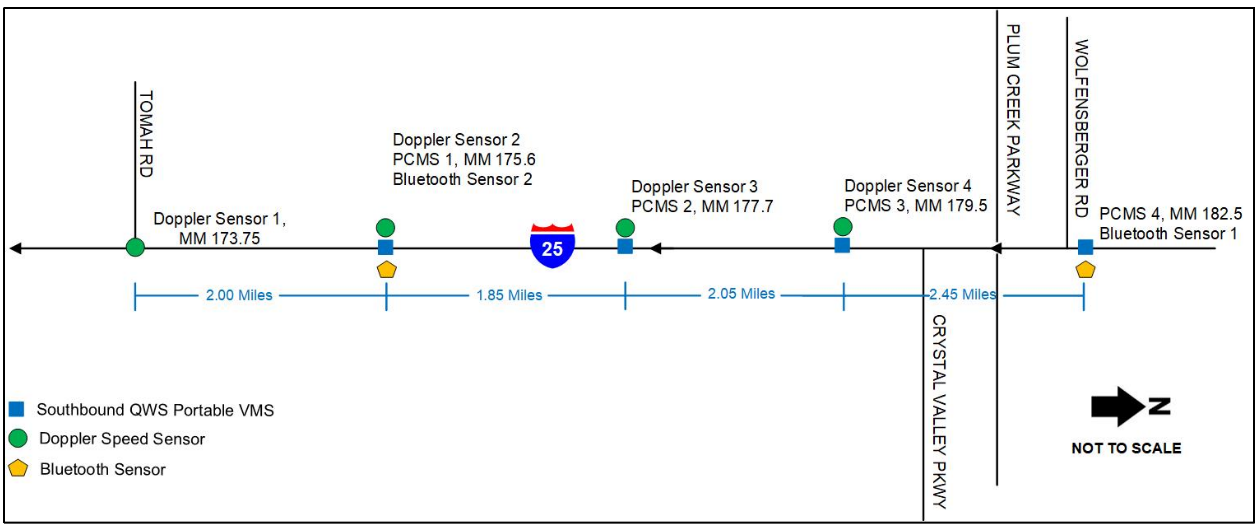


Figure 4. Southbound I-25 Gap QWS Setup

Note that PCMS 4 served as an "End of Queue" warning message board since it was located well in advance of the construction zone. This sign also displayed travel time estimates to Tomah Road and the Larkspur interchange. As **Figure 4** indicates, Sensor 2, Sensor 3, and Sensor 4 were mounted on PCMS 1, PCMS 2, and PCMS 3 respectively in the field (see Figure 3). Sensor 1, located at the Tomah Road interchange, served as a standalone sensor that provided the necessary speed information to the upstream message boards.

The QWS were setup to provide automated warning messages to travelers when downstream traffic is anticipated to be slow or stopped based on the real-time speed and travel time information collected by the Bluetooth and Doppler sensors. The following rules were established to guide traveler messaging for this project (note that the rules described here are specific to the SB I-25 Gap Queue Warning setup and QWS rules may vary for QWSs set up in different locations based on the specific locations roadway conditions):

- When the speed limit is measured to be greater than 45 MPH or the travel time is near free flow, the message board was in an inactive state.
- When the measured speed dropped below 45 MPH but was above 20 MPH (or 1.5 times normal travel time was measured), a slow traffic message was displayed.
- When the measured speed dropped below 20 MPH (or 3 times the normal travel time was measured), a stopped traffic message was displayed.

The specific message text and speed/travel time thresholds used for the I-25 Gap project are summarized in **Table 1**.

Table A. QWS Messages and Thresholds

Displayed Message	Downstream Conditions Threshold
Default (No Message)	Speed > 45 MPH or Travel Time < 15 Minutes
CAUTION SLOW TRAFFIC **PREPARE TO STOP**	Speed < 45 MPH or Travel Time > 15 Minutes
STOPPED TRAFFIC AHEAD **PREPARE TO STOP**	Speed < 20 MPH or Travel Time > 20 Minutes

Displayed Message	Downstream Conditions Threshold
TOMAH RD / LARKSPUR **9 MILES / 11 MILES** **XX MIN / XX MIN**	Displayed continuously on PCMS 4

The QWS utilized a series of speed sensors and message boards that were logically interconnected based on real-time traffic conditions. The flow chart illustrated in **Appendix A** summarizes the sensor and message board system-wide interaction when the thresholds shown in **Table 1** were met at different sensor locations. As an example, if Sensor 1 detected speeds less than 20 MPH, all PCMS boards (PCMS 1 - PCMS 4) displayed the "Stopped Traffic Ahead" message.

2.2 Data Collection

The JamLogic Fleet Management software was used to access the archived data for the QWS. In general, the software is used to manage and monitor data from the I-25 Gap SWZ devices in real-time. With the application of this software, data was exported for the desired date range into an excel file. The collected data from JamLogic was compiled for review and a data validation process was developed and applied to confirm the device reliability, data accuracy, and to ensure that the devices were functioning according to the documented logic.

2.3 Data Validation

This section describes the QWS validation process used to ensure that the sensors and automated messages were working correctly. Additionally, the data validation process used separately available data to ensure the process accurately represented actual traffic conditions. All QWS data was downloaded using 1 minute time intervals to observe the data at its highest granularity as possible. The QWS data validation process is summarized in **Table 2**.

Table B. QWS Data Validation Process

Validation Process	
Device Reliability	Review the JamLogic device "status" regularly. In addition, perform regular site visits during anticipated congested periods to confirm that the devices are correctly located and working based on the traffic conditions experienced. Summarize daily speed summaries and message activations to determine data gaps that indicate the system isn't working.
Data Accuracy	Compare the data to other traffic data sources using the project's Bluetooth travel time sensors and CDOT COGNOS devices which include: ➢ Device 025N174 Tomah Road INT ➢ Device 025S175 1.8 Mi N of Tomah RD ➢ Device 025S 177 3.8 Mi S of Plum Creek Pkwy
QWS Logic Consistency	This step confirms that the message activations follow the documented QWS logic by comparing the output data to other traffic data sources such as the Bluetooth travel time and CDOT COGNOS.

The southbound QWS was monitored monthly using the data validation process. The data validation process provided a routine opportunity to analyze the data and determine which time periods the QWS components were working successfully and when there were issues that needed to be communicated to the Street Smart vendor.

QWS device reliability was observed to be an issue and required regular communications with the vendor to address, especially during the early part of the monitoring. After several months of working with the Street Smart vendor, data reliability improved significantly. Monitoring of the QWS reliability primarily focused on the speed sensors to observe if there were extended time periods where no speed data was being collected. As shown in Figure 5, early on in the study period data from the speed sensors showed significant periods of unreliability. For example during the month of November, Sensor 2 and Sensor 1 experienced periods where there was no speed detected for more than 60 percent of a typical 24 hour period. This remained true up until mid-December 2020 when the speed device reliability increased to 90%. **Appendix B** provides sample data tables developed during this data validation process.

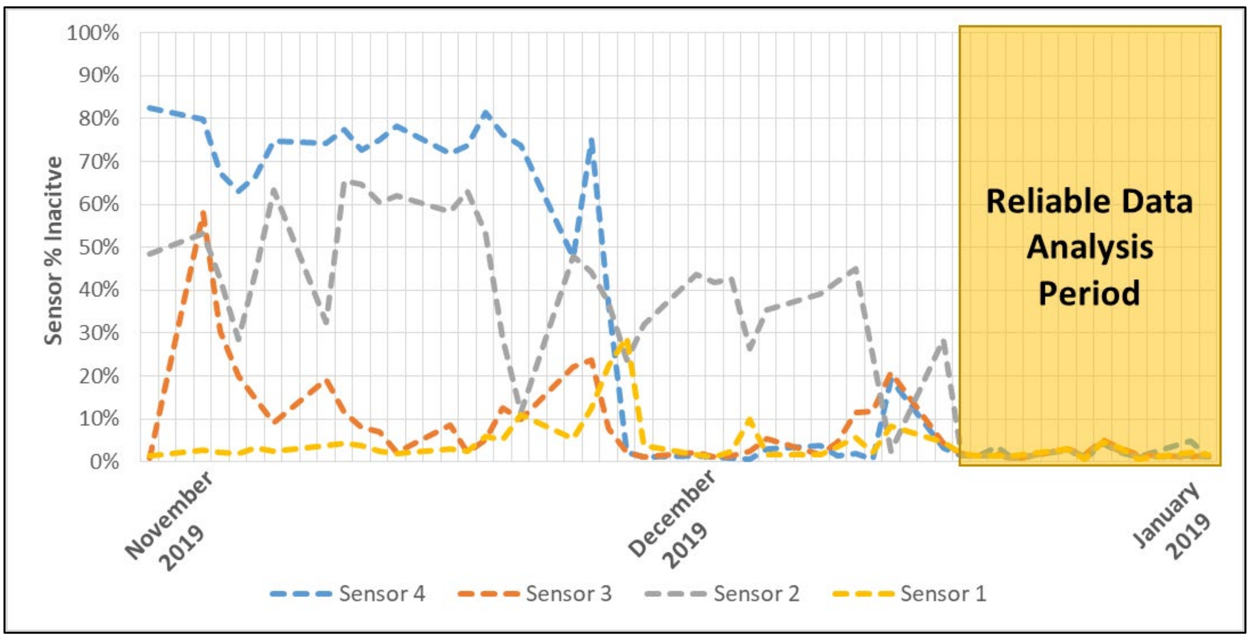


Figure 5. QWS Data Gap Reliability Profile

Before moving forward with the data analysis phase for the southbound QWS, the next step in the data validation process was to confirm the data accuracy and the QWS logic. To accomplish this task, profile charts were developed that illustrate the interactions between the sensors. These charts allowed for the messages and speed profiles to be visually mapped in order to confirm that the system was working as intended.

Figures 6 through **9** provide an example of the profile charts used to confirm the accuracy of the southbound QWS Doppler speed sensors. The speed sensor data is averaged to 15 minute periods to match COGNOS device speed outputs. COGNOS is a CDOT database maintained by the agency which records available data from field devices. The Doppler speed sensor accuracy confirmation process utilized 3 CDOT COGNOS devices. Sensor 1 was matched to Device 025N174 (Tomah Road INT), Sensor 2 was matched to Device 025S175 (1.8 Mi N of Tomah RD), and Sensor 3 was matched to Device 025S177 (3.8 Mi S of Plum Creek Pkwy). Note that Sensor 4 could not be matched to any COGNOS device. In addition, data from the southbound Bluetooth devices were included for the data accuracy confirmation. Separately, the Bluetooth devices' data accuracy was confirmed by INRIX data made available by CDOT during a concurrent task to develop work zone performance measures. INRIX data provides travel time data compiled from various data streams from local transport authorities, road network sensors, and fleet vehicles.

Figure 10 through **12** provide an example of the southbound QWS logic confirmation by illustrating the device speed profiles with the warning message displayed. These profiles allowed the project team to confirm that messages were appropriate given the corresponding speed drops.

Observation labels are provided in **Figures 6** and **7** and **Figures 10** and **11** that correspond to **Table 3**. Overall, observations indicate that the southbound QWS Doppler speed sensors generally align with COGNOS device speed profiles. In addition, the travel time shows consistent patterns as well.

Table C. Data Validation Example Observations

Observation #	Comments
1	The travel time shows a significant increase but a speed drop is not shown on Sensor 4. This is expected as the speed drop occurs at downstream sensors indicating that the congestion does not reach Sensor 4.
2	This would indicate an error with the Bluetooth travel time device.
3	There is slight variation between Sensor 3 and the COGNOS data using the MVRD device. The overall profile matches and the device locations are slightly offset (~0.7 miles). Thus, some variability can be expected.
4	This illustrates a good match between the data sources. The significant increase in travel time is indicated by a decrease in speed by both the SB QWS Sensor 3 and the COGNOS device.
5	The COGNOS data using the MVRD device shows an outage.
6	The speed profiles between the Sensor 3 and the COGNOS data using the MVRD device are significantly different. Further review of the Sensor data indicate that there are a large amount of data gaps (Sensor malfunctions).
7	This appears to be anticipated behavior of the QWS.
8	A potential QWS malfunction. The messages are observed to display; however, during this period, it the speed sensor output wasn't confirmed to be accurate due to significant data gaps.

Observation #	Comments
9	The speed at this sensor does not reach below the 45 MPH threshold. However, the downstream sensor does meet the threshold.

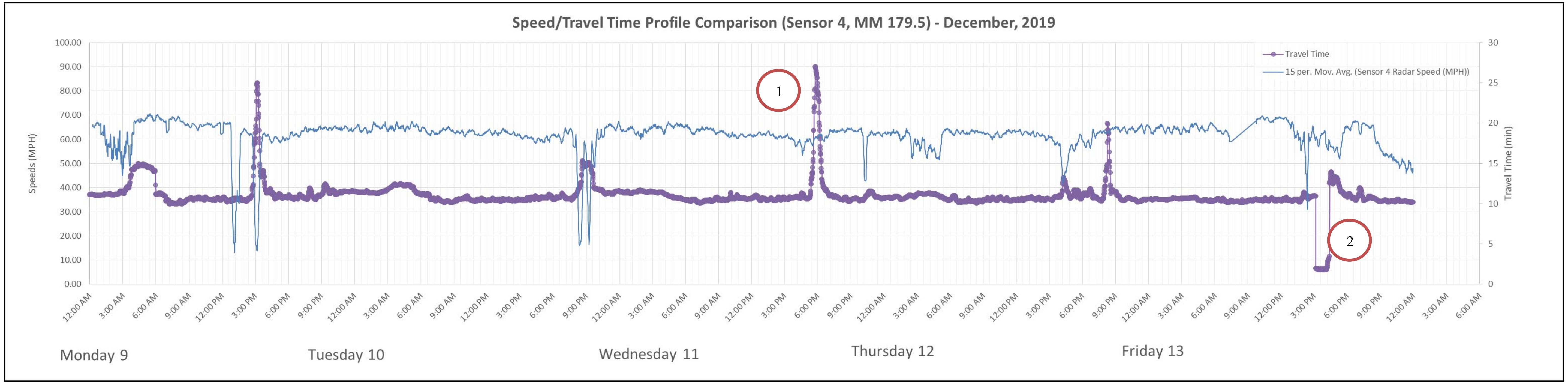


Figure 6. Data Accuracy Comparison Example (Sensor 4)

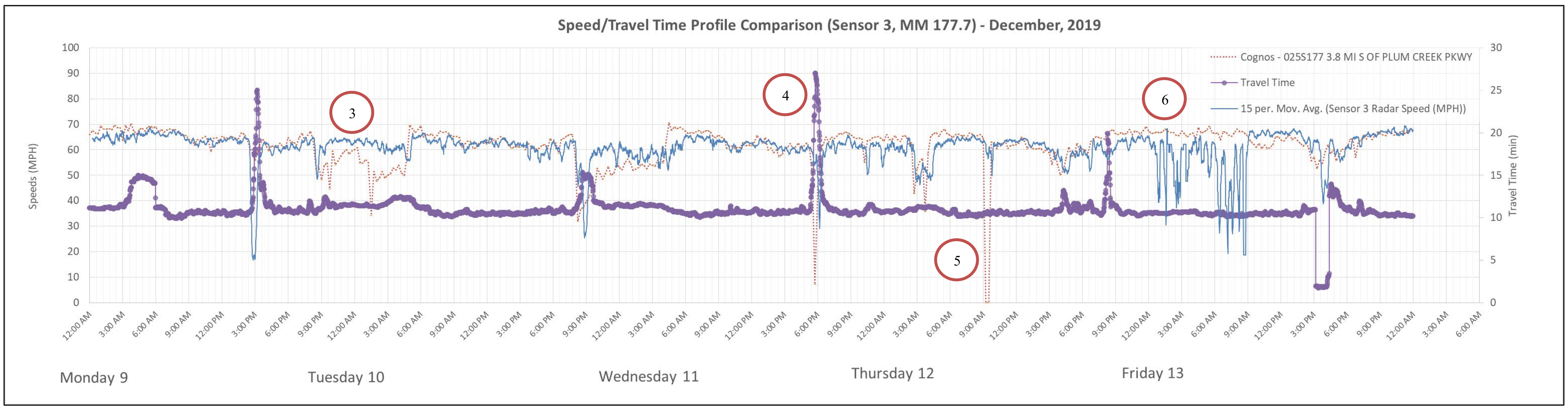


Figure 7. Data Accuracy Comparison (Sensor 3)

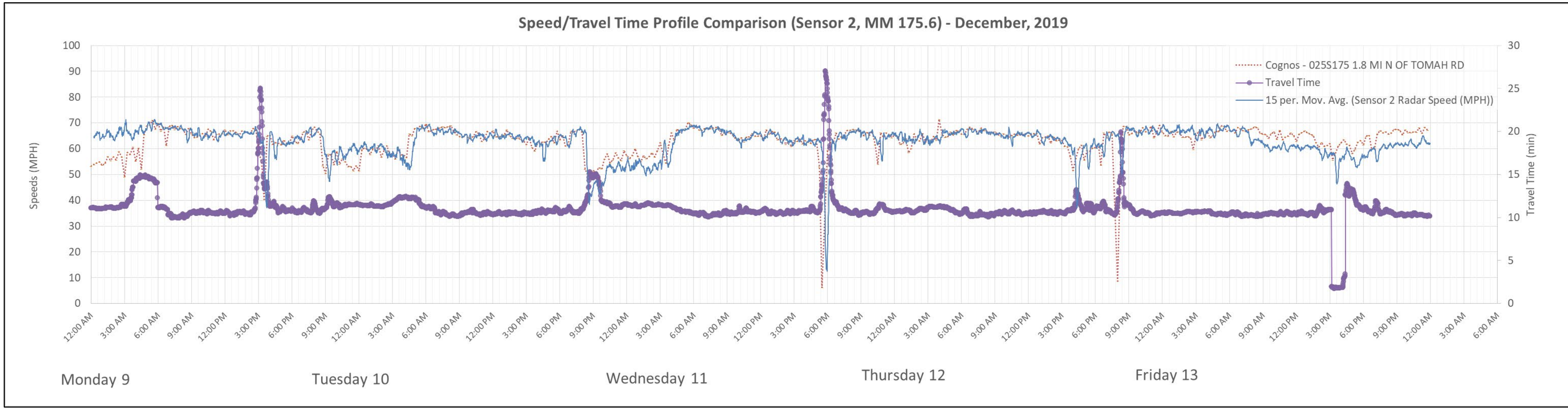


Figure 8. Data Accuracy Example (Sensor 2)

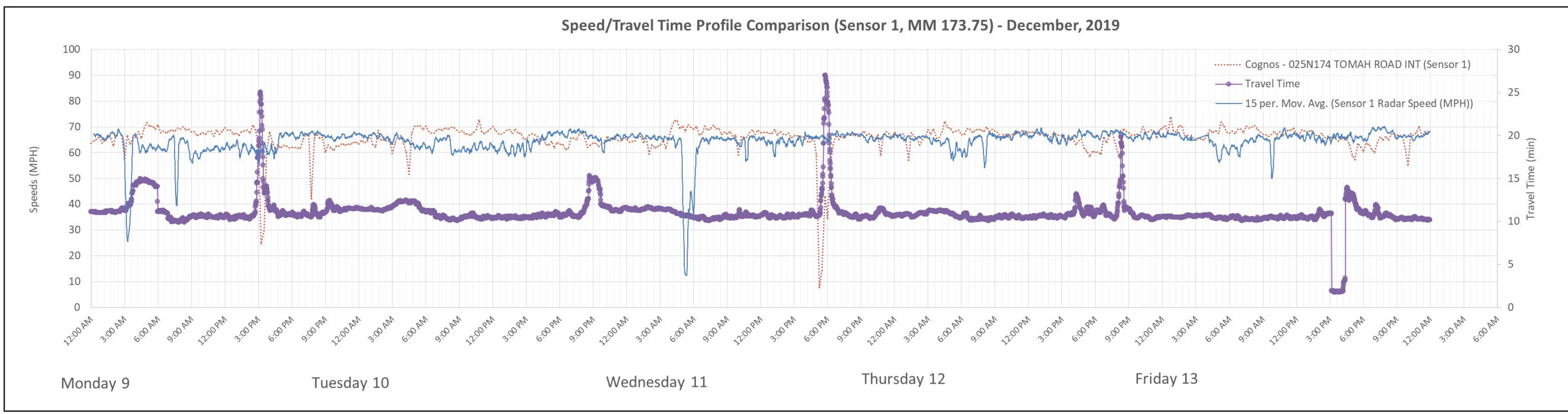


Figure 9. Data Accuracy Comparison Example (Sensor 1)

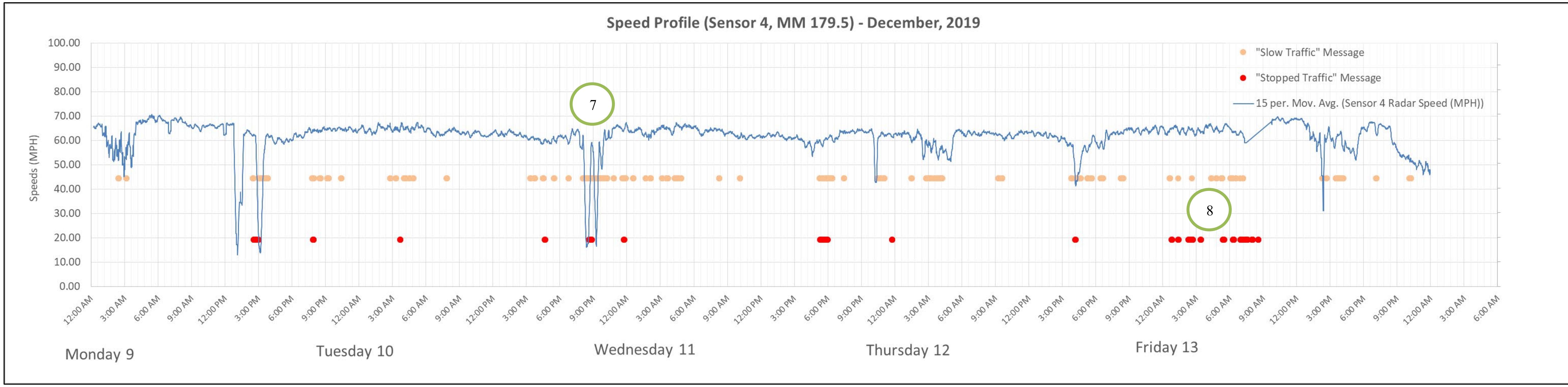


Figure 10. QWS Logic Review Examples (PCMS 3)

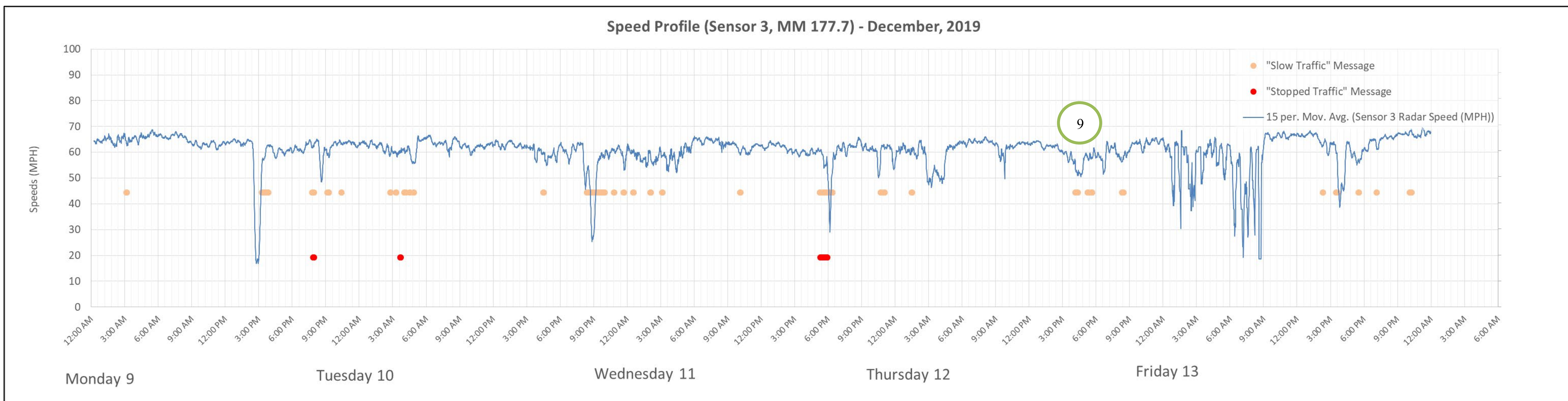


Figure 11. QWS Logic Review Examples (PCMS 2)

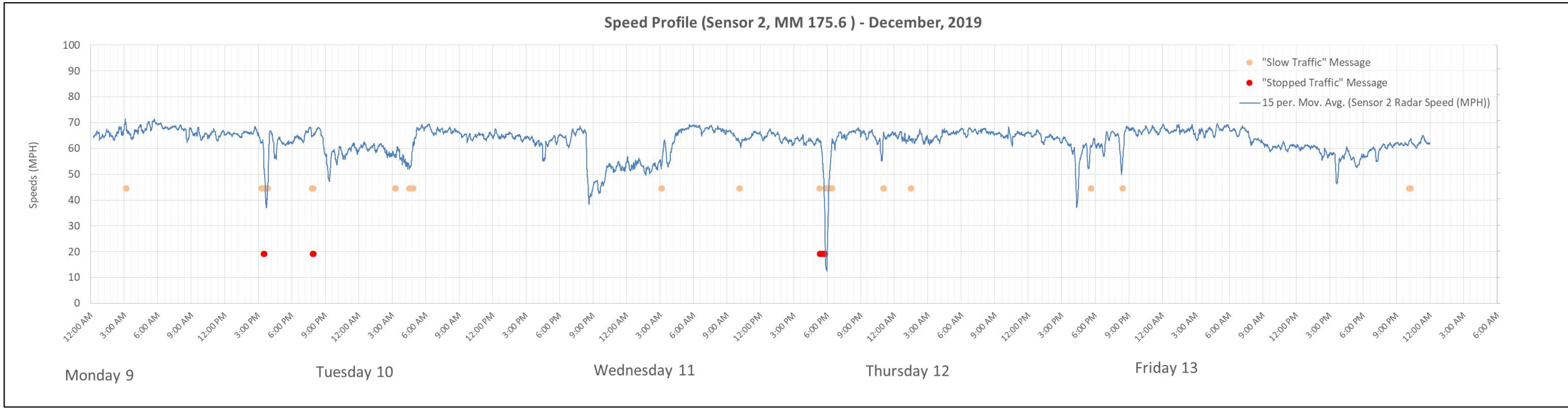


Figure 12. QWS Logic Review Example (PCMS 1)

2.4 QWS Effectiveness

This section provides a comprehensive overview of the data analysis and results based on the southbound QWS historic data. The effectiveness of the southbound QWS was evaluated using the Doppler speed sensors. Two measures of effectiveness (MOEs) were established and measured. Both MOEs include a one month period with the QWS visible to the public (December 2019) and a one month period with the system working, but message signs not visible to the public and therefore not impacting the traffic flow (September 2019). The two MOEs include:

1. Average Speed – A comparison of the average speed during the warning message activation consisting of spot measurements of average speed at each sensor location during QWS activation time periods.
2. Abrupt Speed Reduction – A comparison of abrupt speed drop frequencies within 1 minute periods during QWS activation periods.

2.4.1 Average Speed MOE

The objective of the average speed comparison is to observe how the southbound QWS messages impacts travel speeds in the area approaching the measured queue. The average speeds were measured only during message activations for a one month period with the messages visible and one month with the messages not visible to travelers. **Figure 13** through **15** illustrate the comparison between the two analysis periods. Note that the data for average speeds during the signing not visible time period at Sensors 4 and 2 is incomplete and therefore should not be considered in the analysis (although it is shown on the figures for context). These figures show that the average speed during “Slow Traffic Ahead…” and “Stopped Traffic Ahead…” messages was higher when the messages are visible to travelers compared to periods when travelers had no information about upcoming congestion. This is especially true for sensor 3 which is further from the downstream queue.

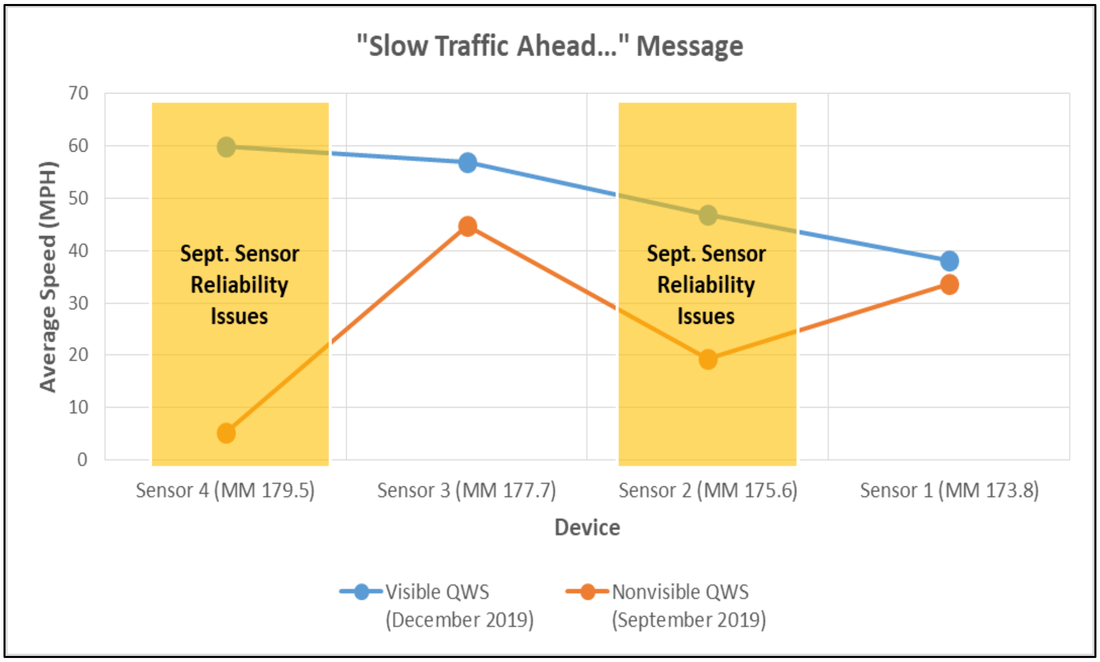


Figure 13. Average Speed Profile during "Slow Traffic Ahead…" Message

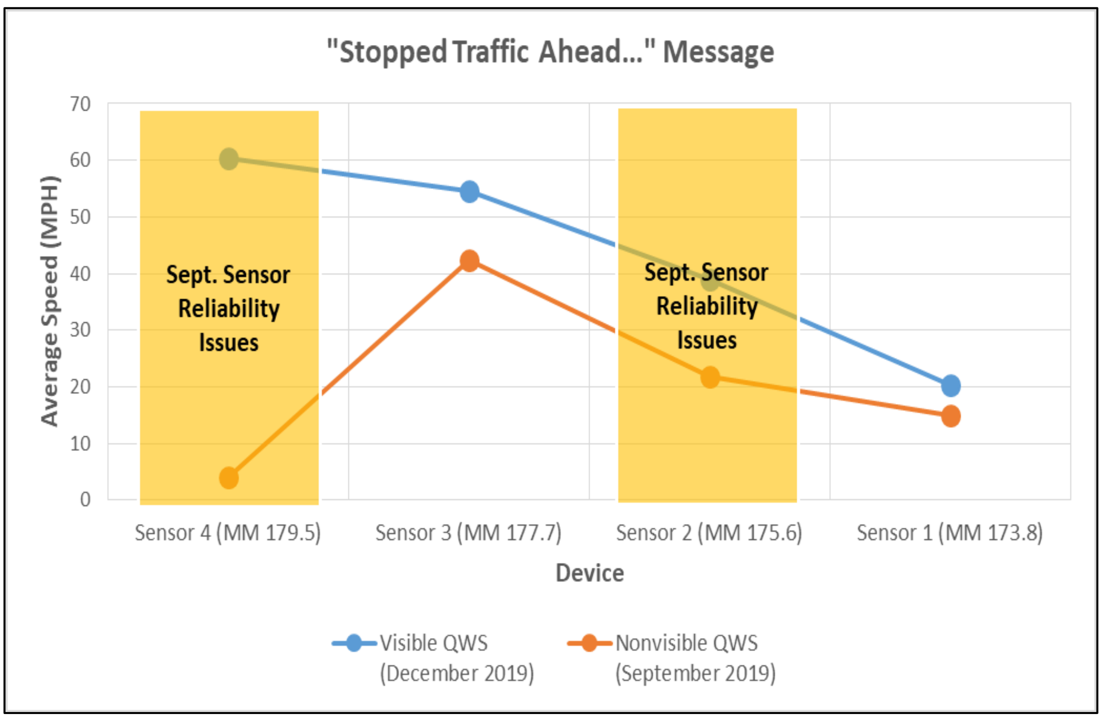


Figure 14. Average Speed Profile during "Stopped Traffic Ahead…" Message

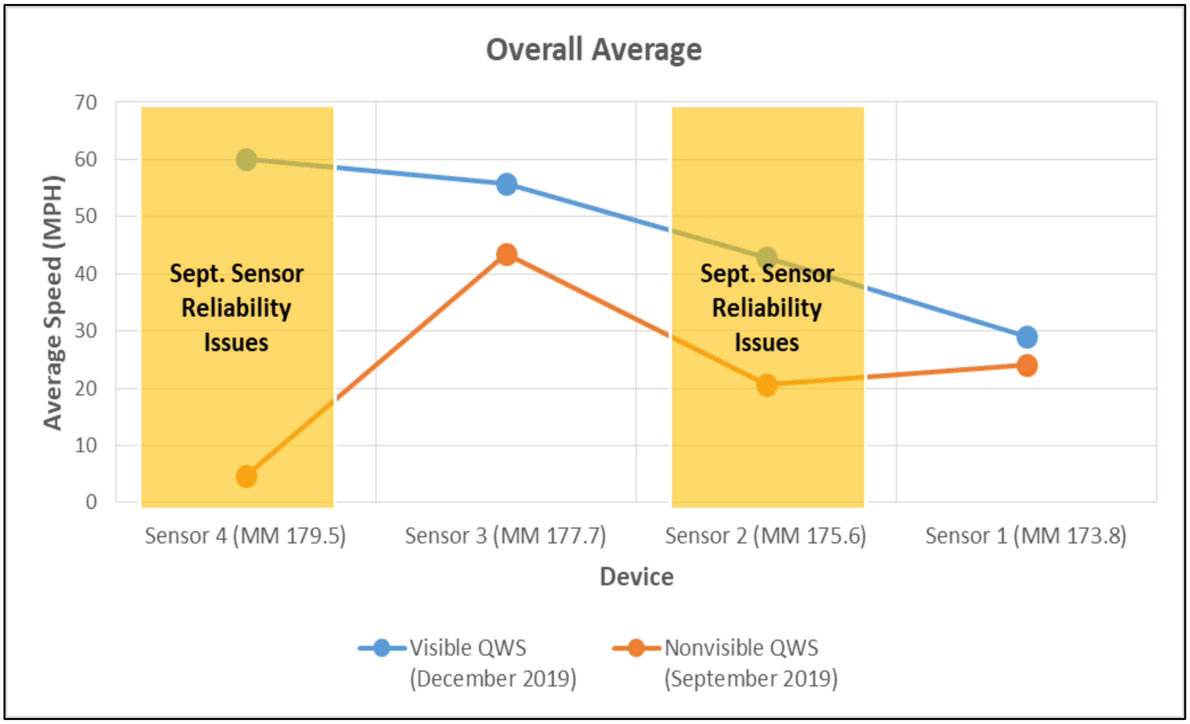


Figure 15. Average Speed Profile during Both Messages

2.4.2 Abrupt Speed Reduction MOE

The objective of the abrupt speed reduction comparison is to measure how the southbound QWS messages impact abrupt speed reductions in the area approaching the measured queues. This measure was analyzed by counting the number of 10+ and 15+ mph speed reductions recorded during message activations within a one month period with the messages visible and one month with the messages not visible to travelers. **Figures 16** and **17** illustrate the comparison between the two analysis periods. Note that the data for average speeds during the signing not visible time period at Sensors 4 and 2 was incomplete and therefore should not be considered in the analysis (although it is shown on the figures for context). As these figures show, for sensors 3 and 1, there were significantly less abrupt speed reductions counted when the messages are visible to the travelers.

Taken together, the results of the Average Speed MOE and Abrupt Speed Reduction MOE demonstrate the positive impacts of the QWS on traffic flow. When activated, this system was able to significantly increase travel speeds and decrease the number of abrupt speed reductions which occurred through the Gap resulting in smoother conditions for travelers.

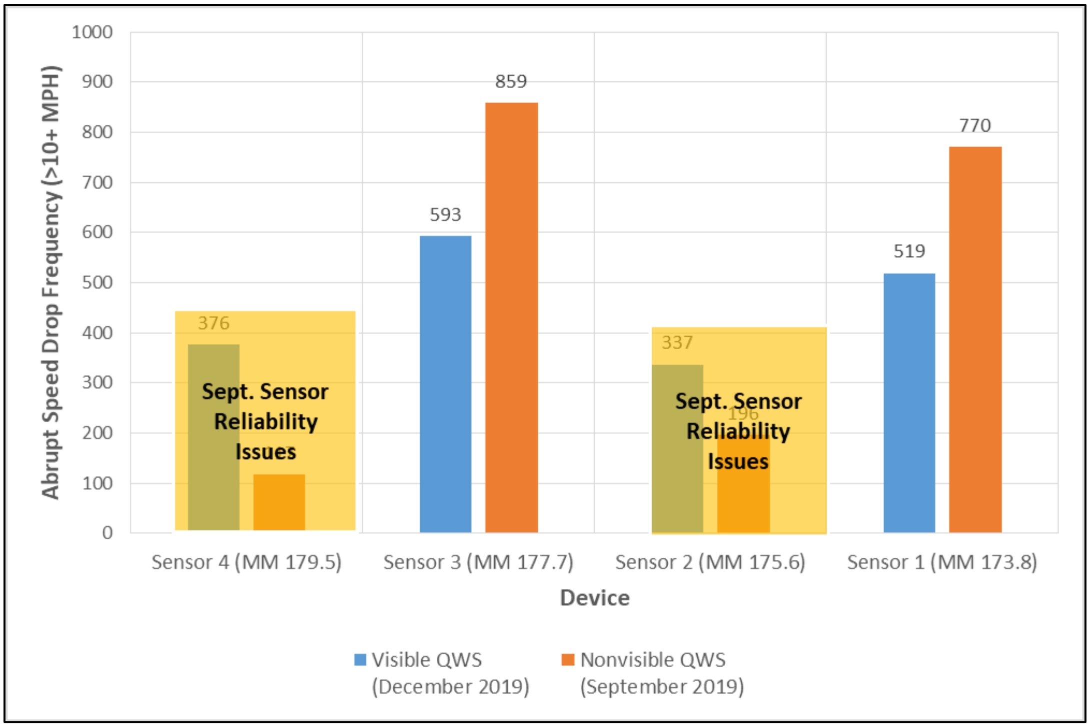


Figure 16. Abrupt Speed Drop Frequency (> 10+ MPH)

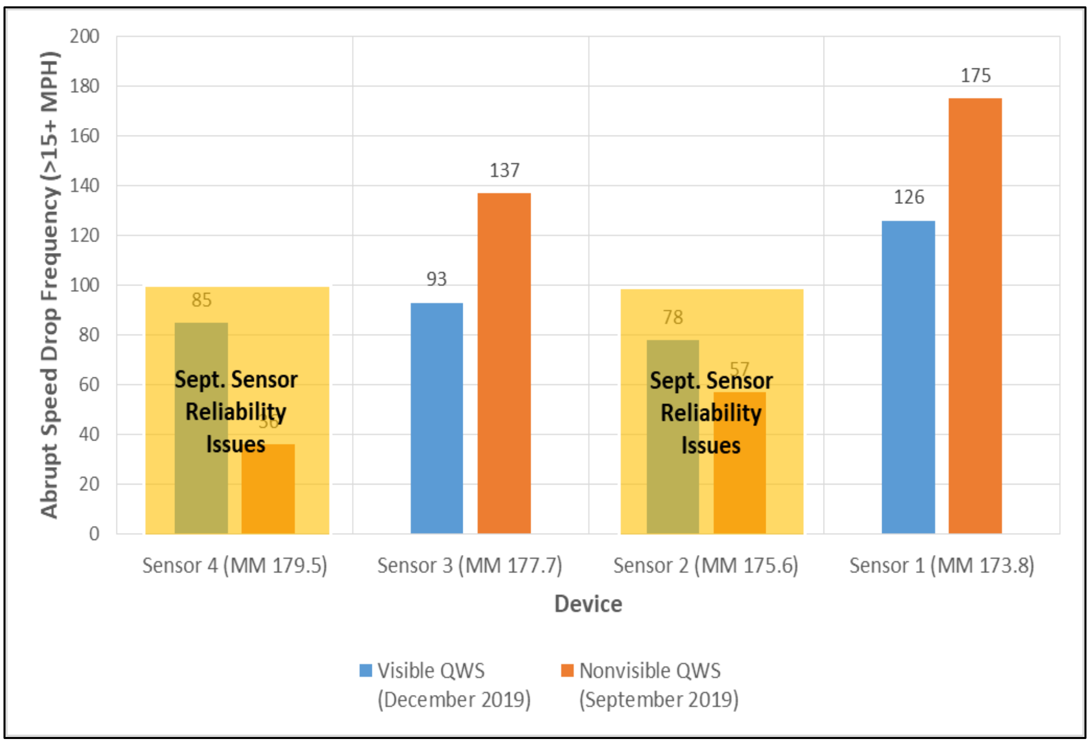


Figure 17. Abrupt Speed Drop Frequency (> 15+ MPH)

3 CONCLUSIONS AND LESSONS LEARNED

Two measures of effectiveness (MOEs) were observed and evaluated for a one month period with the Southbound I-25 Gap QWS activated (December 2019) and a one month period with the system deactivated (September 2019).

The two measurements include:

1. The average speed of vehicles during queue warning activation consisting of spot measurements of average speeds at each sensor location during QWS activation time periods.
2. The comparison of abrupt speed drop frequencies within 1 minute periods during QWS activation periods.

3.1 Conclusions

The following conclusions have been made based on the analysis presented in this report:

- The reliability of the operation of the QWS devices was a significant issue, especially during the early part of the monitoring. Regular visual inspections and review of detection data combined with a pay reduction penalty that was enforced was effective in significantly improving the reliability of the devices.
- Comparison between field observations and the QWS data indicated good consistency between available COGNOS data and the Bluetooth travel time devices. This confirmed that the QWS performs as intended.
- The analysis indicated that average speeds were higher and there were fewer abrupt speed reductions during activation of the QWS "Slow Traffic Ahead…" and "Stopped Traffic Ahead…" messages.
- Taken together, the results of the Average Speed MOE and Abrupt Speed Reduction MOE demonstrate the positive impacts of the QWS on traffic flow. When activated, this system was able to significantly increase travel speeds and decrease the number of abrupt speed reductions which occurred through the Gap resulting in smoother traffic conditions for travelers.

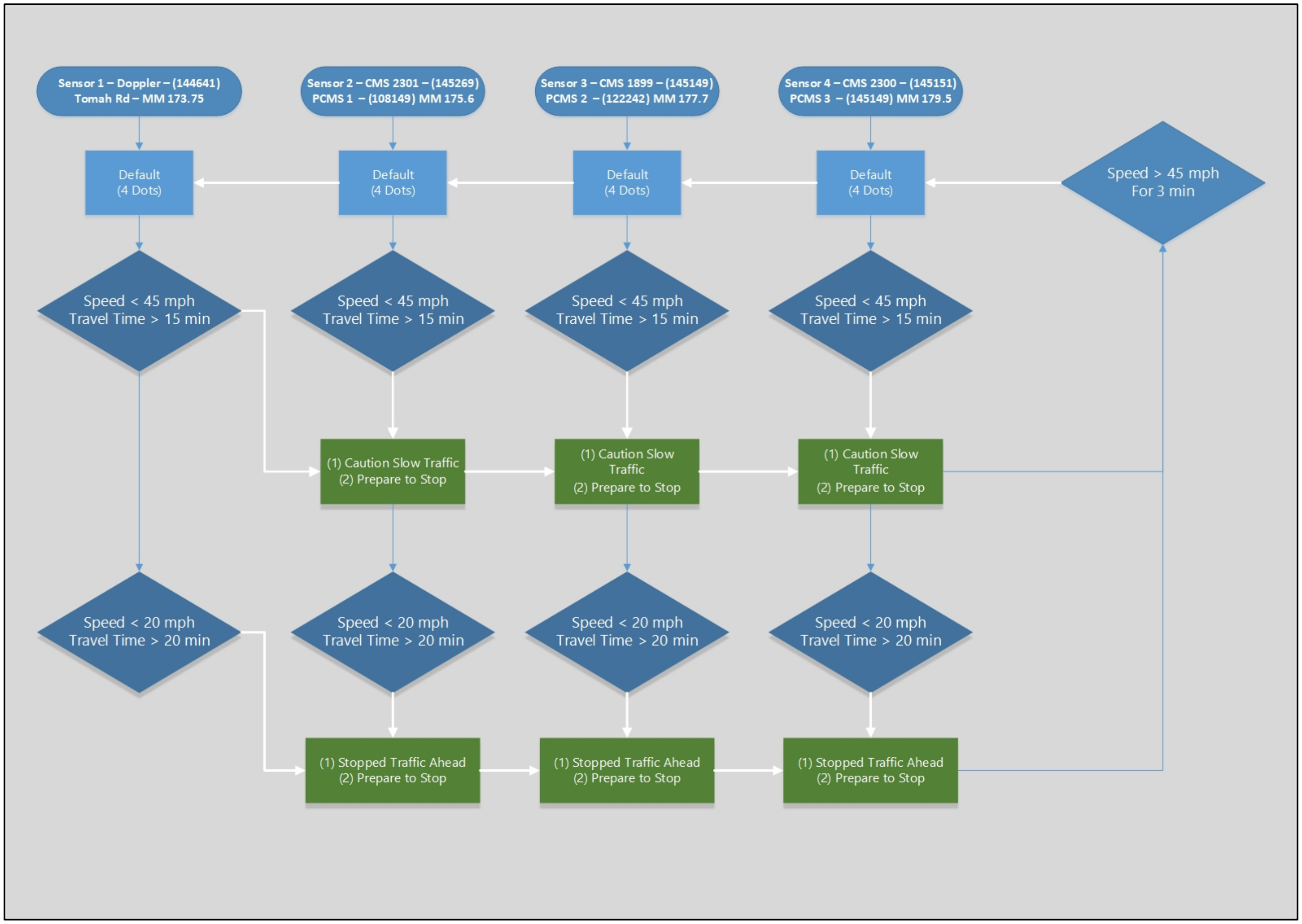
3.2 Lessons Learned

During the development of the QWS evaluation process, various lessons learned were documented to improve future processes and streamline the initial validation of the device data. These lessons learned can be divided to represent first the installation and maintenance of the QWS equipment in the field and second, to define the data validation process.

- Installation and maintenance lessons learned:
  - During installation, emphasis should be placed placement of the sensors and message boards, aiming of the sensors, visibility of the message boards and the sensitivity of the device detection to ensure that main line traffic is detected without construction activity interference.
  - Throughout the life of the project, the following measures are needed on at least a weekly basis to ensure that the QWS was set up and operating as intended:
    - Visual inspection in the field: this process should include a review of the placement of sensors and message boards. Sensors should be placed at distances close to the desired set up and all message boards should be placed to ensure a line-of-sight to oncoming travelers.
    - Data Verification: Data collected by the devices should be downloaded and reviewed for completeness and to identify if and when system devices are not measuring filed data properly.
    - Field Adjustments: If necessary, contact the vendor to make field adjustments.
    - Verification: Perform visual inspections and data review to verify that field adjustments were made successfully. Repeat the entire process if necessary.
- Data validation lessons learned:
  - Emphasis should be placed on the ability to export device data from vendor software to Microsoft Excel to facilitate data validation.

APPENDIX A – QUEUE WARNING SYSTEM METHODOLOGY

The following flow chart provides a detailed visual of the QWS methodology, specifying the activation thresholds corresponding to each message displayed on each PCMS.



APPENDIX B – QUEUE WARNING SYSTEM ACTIVATION SUMMARY

The following activation summaries depict the validation process that was conducted for the SB QWS starting at mile marker 182.5. Based on the data collected from each device, the inactivity rate was identified as the percentage of the day that a device produced no speed data. With the comparison of September 2019 and February 2020 results, great improvements were made over the course of four months to improve the accuracy and consistency of the data.

SB QWS Daily Activation Summary - September 2019

Date	Day of Week	PCMS 4			Sensor 4 Speed			
		"Slow Traffic " Message Duration (Min)	"Stopped Traffic" Message Duration (Min)	Other Message Duration (Min)	< 45 MPH Duration (Min)	< 20 MPH Duration (Min)	No Speed Data (Min)	% Inactive
9/2/2019	Mon	0	0	1440	1	0	41	3%
9/3/2019	Tue	32	20	1388	68	3	16	1%
9/4/2019	Wed	306	40	1094	118	5	17	1%
9/5/2019	Thu	0	0	1440	0	0	1018	71%
9/6/2019	Fri	19	134	1287	3	4	1433	100%
9/9/2019	Mon	44	17	1379	0	0	1383	96%
9/10/2019	Tue	46	48	1346	0	0	1440	100%
9/11/2019	Wed	62	0	1378	0	0	1440	100%
9/12/2019	Thu	288	231	921	0	0	1440	100%
9/13/2019	Fri	112	32	1296	0	0	1440	100%
9/16/2019	Mon	39	0	1401	0	0	1440	100%
9/17/2019	Tue	0	0	1440	0	0	1440	100%
9/18/2019	Wed	170	104	1166	0	0	1440	100%
9/19/2019	Thu	363	132	945	0	0	1440	100%
9/20/2019	Fri	513	48	879	0	0	1440	100%
9/23/2019	Mon	0	0	1440	0	0	1440	100%
9/24/2019	Tue	0	0	1440	0	0	1440	100%
9/25/2019	Wed	82	68	1290	0	0	1440	100%
9/26/2019	Thu	478	92	870	0	0	1440	100%
9/27/2019	Fri	523	179	738	0	0	1440	100%
9/30/2019	Mon	13	46	1381	0	0	1440	100%
September Average		147	57	1236	9	1	1159	84%

SB QWS Daily Activation Summary - February 2020

Date	Day of Week	PCMS 4			Sensor 4 Speed			
		B	C	D				
		"Slow Traffic " Message Duration (Min)	"Stopped Traffic" Message Duration (Min)	Other Message Duration (Min)	< 45 MPH Duration (Min)	< 20 MPH Duration (Min)	No Speed Data (Min)	% Inactive
2/3/2020	Mon	410	23	1007	121	0	173	**12%**
2/4/2020	Tue	83	0	1357	10	0	574	**40%**
2/5/2020	Wed	0	0	1440	0	1	38	**3%**
2/6/2020	Thu	229	83	1128	212	24	30	**2%**
2/7/2020	Fri	671	51	718	97	1	823	**57%**
2/10/2020	Mon	364	49	1027	307	1	26	**2%**
2/11/2020	Tue	252	8	1180	51	2	388	**27%**
2/12/2020	Wed	0	0	1440	0	0	24	**2%**
2/13/2020	Thu	121	0	1319	0	0	13	**1%**
2/14/2020	Fri	254	81	1105	178	24	19	**1%**
2/17/2020	Mon	209	30	1201	104	0	27	**2%**
2/18/2020	Tue	216	8	1216	29	11	585	**41%**
2/19/2020	Wed	302	2	1136	89	0	39	**3%**
2/20/2020	Thu	133	0	1307	39	0	217	**15%**
2/21/2020	Fri	1	0	1439	47	0	15	**1%**
2/24/2020	Mon	0	0	1440	14	0	21	**1%**
2/25/2020	Tue	0	0	1440	0	0	18	**1%**
2/26/2020	Wed	0	0	1440	0	0	28	**2%**
2/27/2020	Thu	24	46	1370	0	0	14	**1%**
2/28/2020	Fri	0	0	1440	0	0	420	**29%**
February Average		**163**	**19**	**1258**	**65**	**3**	**175**	**12%**