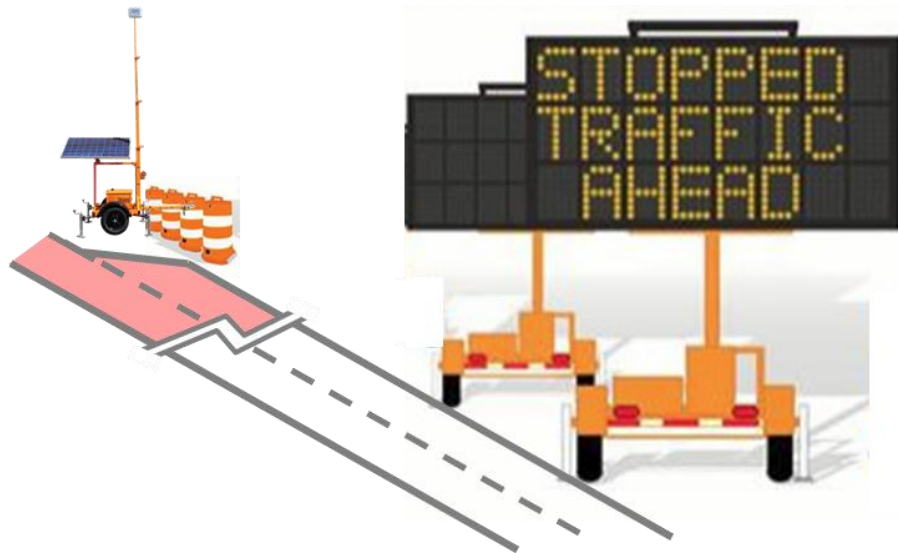


# INTELLIGENT WORK ZONE USING AUTOMATIC QUEUE DETECTION SYSTEMS

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Nebraska Transportation Center, University of Nebraska-  
Lincoln



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May 15th, 2022

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<b>16. Abstract</b> This report documents the the evaluation of the effectiveness of the Advanced Queue Detection (AQD) systems installed on Interstate work zones in Nebraska. Specifically, (1) the system performance was verified by examining whether the messages displayed on the portable dynamic message signs (PDMS) were consistent with the underlying AQD logic; (2) the system efficacy was measured by determining whether driver speeds were reduced when warning messages were provided on the PDMS; and (3) the system safety impact was modeled using statistical models. It was found that overall, the AQD systems had an error rate of 0.7% – 2.3%. Drivers reduced their speeds in response to the PDMS warning message, and the decrease was found to be statistically significant in the range of 3.5 to 7 mph. This was approximately 90% greater than the reduction in speed that occurred when the PDMS did not display any message. In summary, it was found that the AQD systems were operating correctly and, more importantly, they were effective in reducing the space mean speeds of vehicles approaching work zones. Results from the traffic crash analysis showed that most crashes occurred in the activity area of the work zone and were rear-ended. A crash was more likely to occur on weekdays, off-peak hour, in the daytime, no worker present at rural Interstate work zones. A crash was severer when drivers driving drunk, during the daytime, on weekdays, with more vehicles involved. Given that the data was obtained in the midst of the COVID-19 pandemic, its impact on the work zone traffic crashes were also studied.					
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# TABLE OF CONTENTS

EXECUTIVE SUMMARY .....	xi
1.INTRODUCTION .....	13
1.1. Intelligent Work Zone (IWZ) on Freeways .....	13
1.2. Advance Queue Detection (AQD) Systems.....	16
1.3. Objectives and Benefits .....	19
1.4. The Scope and Structure of the Report .....	20
2.LITERATURE REVIEW .....	21
2.1. Work Zone Speed Management Systems .....	21
2.2. AQD Applications among DOTs.....	26
2.3. Summary .....	29
3.DATA COLLECTION .....	31
3.1. Preliminary Studies and Test Site Selection .....	31
3.2. AQD Speed and Warning Message Data Collection .....	34
3.3. Travel Time Data Collection .....	36
3.3.1. Waco test site.....	37
3.3.2. Big Springs at PDMS 1 .....	38
3.3.3. Big Springs at PDMS 2 .....	40
3.3.4. Ogallala test site .....	41
4.DATA PROCESSING.....	42
4.1. Work Zone Speed and Message.....	42
4.2. Travel Time Measure.....	43
4.3. Travel Time Data Validation .....	45
4.4. Speed Reduction .....	48
5.CRASH ANALYSIS .....	50
5.1. Work Zone Areas.....	50
5.2. Work Zone Crashes.....	51
5.3. Variable Selection.....	54
5.4. Model Development.....	55
6.COVID IMPACT.....	56
6.1. The Impact on Traffic Volumes and Traffic Crashes .....	57
6.2. Crash Modeling under COVID Influence.....	58

6.3.	Interpretation of COVID Influence on Traffic Crash .....	60
7.	RESULTS .....	63
7.1.	Investigate whether the AQD System is Performing Adequately .....	63
7.2.	Ascertain How the Drivers React to the Messages on the PDMS .....	64
7.3.	Crash Rates at Work Zones.....	68
8.	CONCLUDING REMARKS.....	71
	REFERENCES .....	73
	APPENDICES .....	78
	A. Algorithm and Codes for Travel Time Collection and Measure .....	78
	B. Distributions of the Travel Speed.....	93
	C. Technical Memorandum .....	95

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# LIST OF FIGURES

Figure 1.1 Layout of the NDOT intelligent work zone.....	15
Figure 1.2. the framework zone an AQD system.....	16
Figure 1.3. The layout of the Nebraska AQD system (not to scale) .....	17
Figure 3.1 Data collection on queued traffic conditions at a test site .....	31
Figure 3.2. Data verification for the traffic counts at Big Spring (Shaded area indicates the data varies in a week from Sep. 14 to Sep. 20, 2020. Solid curve represents one-day data from Sep. 20, 2020, and the dotted points are field obseration at the same time and location) .....	32
Figure 3.3. Illustration of a speed and message matching example at Big Springs .....	33
Figure 3.4 Layout of the AQD systems at different test sites. The blue cross indicates lane closure. The AQD system made of speed detector and PDMS is in red triangle and rectangle, respectively...	34
Figure 3.5. Relationship between the AQD system and Miovision data collection system.....	36
Figure 3.6 The data collection system of (a) a Miovision Scout unit (b) the layout of the five Miovision stations (c) a field deployment example. ....	36
Figure 3.7 The layout of the five Miovision units at the Waco test site .....	38
Figure 3.8 The layout of the five Miovision units at the Big Springs test site.....	39
Figure 3.9 Data collection system at Big Springs test site .....	40
Figure 3.10 Data collected by sensors in the AQD systems at Big Springs test site .....	40
Figure 3.11 Data collection system at Ogallala test site .....	41
Figure 3.12 Data collected by sensors in the AQD systems at Ogallala test site.....	41
Figure 4.1 AQD speed and warning message data .....	43
Figure 4.2. Travel time of vehicles (grey dots), 15 min average (black dashed line) with the standard deviation (red lines). ....	44
Figure 4.3. Travel time obtained by MAC matching vs manual observation – no queue.....	45
Figure 4.4. Travel time obtained by MAC matching vs manual observation – with queues. ....	46
Figure 4.5. Travel time in different road segments at Waco-Utica.....	48
Figure 4.6. Travel time in different road segments at Big Springs .....	49
Figure 5.1 Component Parts of a Temporary Traffic Control Zone (MUTCD 6C-1). ....	50
Figure 5.2. The five areas that a crash takes place in a work zone in the NDOT crash dataset.....	51
Figure 5.3 I-80 work zone crashes from 2002 to 2020 (denoted by red points). Blue points are the NDOT automatic traffic recorder (ATR) locations.....	52
Figure 5.4 Crash locations in the five work zone areas .....	52
Figure 5.5 Crash composition (3095 crash samples from 2002 to 2020) .....	53
Figure 5.6 Distribution of the crashes from 2002 to 2020. Note crash location 1 – 5 represents work zone area A – E, respectively.....	53

Figure 5.7 Variable selection for crash modeling .....	55
Figure 6.1 Traffic crashes at I-80 Work Zones in 2020. ATR numbers are marked. I-80 runs through fifteen counties that are shown.....	56
Figure 6.2 Traffic volume and the crashes as a function of the week in 2020, and the comparison to the similar period in 2018 and 2019.....	57
Figure 6.3 Comparisons of CITS model result .....	62
Figure 7.1. Reduction of speeds along with the road segments. Solid lines represent the average and shaded areas represent the 95% confidence intervals. ....	65
Figure 7.2 comparison of the mean (a) and standard deviation (b) for speeds with and without warning message. ....	67
Figure B_1. Travel speed during warning message at Waco-Utica test site.....	93
Figure B_2. Travel speed during non-warning at Waco-Utica test site.....	93
Figure B_3. Travel speed during warning message at Big Springs test site.....	94
Figure B_4. Travel speed during no warning message at Big Springs test site.....	94
Figure C1_1. Data Collection Plan: Westbound I-80 Waco-Utica.....	96
Figure C1_2. Data Collection Plan: Eastbound I-80 Waco-Utica.....	96
Figure C1_3. Site Map at Waco-Utica.....	97
Figure C1_4. Westbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020.....	98
Figure C1_5. Eastbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020.....	98
Figure C1_6. Site Map at Mahoney.....	99
Figure C1_7. Westbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020.....	99
Figure C1_8. Eastbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020.....	100
Figure C1_9. Site Map at Big Springs.....	100
Figure C1_10. Westbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020.....	101
Figure C1_11. Eastbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020.....	101
Figure C1_12. Eastbound I-76: Travel speed versus Day – June 14, 2020 - July 12, 2020.....	102
Figure C2_1: Map showing approximate Miovision locations.....	103
Figure C2_2: Miovision set up.....	104
Figure C2_3: Miovision Unit with Video Portal and Battery Portal.....	104
Figure C2_4: Disconnect the video cable.....	105
Figure C2_5a: Unlock the unit.....	105
Figure C2_5b: Remove the battery.....	105
Figure C2_6a: place the battery back.....	106
Figure C2_6b: Lock the unit.....	106
Figure C2_7: Connect the video cable.....	106
Figure C3_1. AQD System installed at Waco-Utica WB I-80.....	107
Figure C3_2. AQD speed detected from sensor RDR02 and message released on PCMSs 07-10....	108



Figure C3_3. AQD System installed at Big Springs WB I-80.....	108
Figure C3_4. The list of the AQD system devices at WB I-80 test site, Big Springs.....	109
Figure C3_5. AQD speed detected from sensors MW03 & RDR13 and message released on PCMSs 02, 11, 12, 17, and 18.....	109
Figure C3_6. Data collected by the research team in 2 miles upstream of the work zone.....	110
Figure C4_1. AQD system at one test site.....	113
Figure C4_3. Unit price of the system cost.....	114
Figure C4_3. Unit cost as a function of volume.....	115
Figure C4_4. Unit cost as a function of system cost.....	115
Figure C4_5. Unit cost as a function of time (months) .....	116

## LIST OF TABLES

Table 1.1. Predefined speed and message.....	18
Table 2.1. Studies of the Speed Management Techniques Using DMS/PDMS .....	23
Table 3.1 Summary of the AQD data collection.....	35
Table 3.2. Records when PDMS displayed “SLOW” or “STOP” message.....	39
Table 4.1 t-test of the travel time at Waco-Utica on Sep. 3 <sup>rd</sup> , 2020.....	47
Table 4.2 t-test of the travel time at Big Springs on Sep. 20th, 2020 .....	47
Table 4.3 Waco Sep. 3 <sup>rd</sup> , 2020 PDMS activation periods and vehicles captured .....	48
Table 4.4 PDMS activation periods and samples at Big Springs test site on Oct. 11, 2020.....	49
Table 6.1 Model Results from Crash Rate.....	60
Table 7.1 Error rate of the AQD system operation .....	63
Table 7.2 Source and types of the AQD system errors .....	63
Table 7.3 Sample size of speed data collected at each test site.....	65
Table 7.4. Statistics summary of the speed changes .....	66
Table 7.5 Speed comparisons upstream and downstream of the PDMS.....	68
Table 7.6 Generalized Linear Model - Number of injuries.....	68
Table 7.7 Ordinal Logistic Regression – Crash Severity .....	69
Table C1_1. Technical Consultation Contact.....	102
Table C3_1. Project contractor contact.....	111
Table C4_1. Traffic volume at all test sites.....	112
Table C4_2. System cost at one test site.....	113
Table C4_3. System costs for all test sites.....	114

# EXECUTIVE SUMMARY

Work zones have become an essential and integral feature of U.S. highways. A work zone is set up when there is a need for rehabilitation and construction on an existing roadway, which usually requires the closure of a traffic lane and/or shoulder. However, if not managed properly, a work zone can become a burden or even a risk to the traffic. The goals that are set for work zone management, especially on freeways, are to maintain a safe and efficient flow of traffic, decrease the injury risk to traffic users as well as to construction forces.

Intelligent work zones have been widely adopted in the United States because they have been proven to improve traffic safety and operations. One specific work zone technology, known as automatic queue detection (AQD), is designed to measure work zone-related queuing in real-time, and inform drivers upstream so they may be prepared to slowdown or stop. This report describes an evaluation of the performance and efficacy of the AQD systems installed at four locations on Interstate 80 in Nebraska.

The AQD system involves a number of technologies. Non-intrusive speed detectors are placed at one or more locations within and/or upstream of the work zone. They are often placed at a location, or locations, where queues may be reasonably expected to form. The AQD system also has one or more portable dynamic message signs (PDMS) placed upstream of the work zone. Based on the real-time speeds measured by the speed detectors, the AQD system algorithms identify appropriate messages to display on the PDMS. The algorithms and the messages vary across vendors and states. For the AQD systems examined in this study, when the downstream measured speeds drop below specific thresholds, then the corresponding warning messages are posed on PDMS that is located upstream of the work zone. These messages indicate that there is slowing or stopped traffic ahead and the drivers should slow down and be prepared to stop.

Specifically, (1) the system performance was verified by examining whether the messages displayed on the portable dynamic message signs (PDMS) were consistent with the underlying AQD logic for the particular system being analyzed, and (2) the system efficacy was measured by determining whether driver space mean speeds were reduced when warning messages were provided on the PDMS.

It was found that the AQD systems were functioning well as evidenced by an error rate of 0.7% – 2.3%. It was concluded that drivers did reduce their space mean speeds in response to the PDMS warning display indicating that there was slow or stopped traffic ahead. The decrease was found to be statistically significant and in the range of 3.5 to 7 mph. This was approximately 90% greater than the reduction in speed that occurred when the PDMS did not display any message. In summary, it was found that the AQD systems were operating correctly and, more importantly, they were effective in reducing the space mean speeds of vehicles approaching work zones.

Results from the crash analysis show that most crashes occurred in the activity area and are rear-ended. In addition, a crash is more likely to occur on weekdays, off-peak hour, in the daytime, no worker present at rural work zones. A crash is severer when drivers driving drunk, during the daytime, on weekdays, and more vehicles are involved.

For crash occurred work zone areas, according to the model results, advance warning and transition areas need to pay attention to road conditions (e.g., worn, obstruction, debris), AADT, heavy vehicles, rural areas, and driver age younger than 25 years. Activity areas need to pay attention to work zone type, heavy vehicle, and curvature. Lastly, termination areas need to pay attention to nighttime, weekend, driving impaired (alcohol), young driver, and road conditions. Finally, the effect of the COVID intervention on I-80 crashes is evaluated.

In summary, this report first reviews the representative research on the performance of AQD systems. Next, four test sites on I-80 in Nebraska and the data collection process are described. Then, the analysis of the data is conducted, followed by a statistical analysis designed to make inferences on the efficacy of the AQD system. Crash models are developed to study the safety features at work zones, taking into account of COVID impact. Conclusions and recommendations are provided at the end of the report.

# 1. INTRODUCTION

A work zone can be described as a section of the roadway where construction or maintenance road activities are being undertaken, and they typically have driver warning signs or signals to control vehicle movement from the beginning to the end of the affected roadway section. Lane closures, especially on freeways, contravenes drivers' expectations, reduces roadway capacity, and increases the exposure of work zone workers to passing vehicles. If the controls are not properly managed, long queues may be formed that increase delays and rear-end collisions.

In 2015, work zone crashes caused 35,000 injuries and 700 fatalities (Paracha and Ostroff, 2018). The objective of work zone control signs is to manage and balance the mobility and safety challenges that typically exist in work zones (Ullman & Schroeder, 2014). Intelligent Transportation Systems (ITS) are often applied by the State Department of Transportation (DOTs) to achieve the mobility and safety objectives of work zones.

In the last two decades, ITS systems have been widely promoted in the United States. Among them, an increasingly popular option is the automated queue detection (AQD) system. The goal of AQD systems is to 1) identify locations of unstable flow, 2) provide information to upstream drivers in advance of these areas of unstable flow, and 3) based on information provided to motorists have them take the appropriate action. This action could include slowing down and/or being prepared to stop when it becomes necessary.

## 1.1. Intelligent Work Zone (IWZ) on Freeways

Work zone sites in the United States often have lower or restricted speed limits, because excessive vehicle speeds and high variations in speed have been identified as two of the major contributing factors in crashes (Li and Bai, 2009). The information on the restricted speed limits historically has been provided using standard traffic regulatory signs located upstream of the work zone.

Unfortunately, studies have shown that drivers do not always slow down in response to these upstream traffic speed signs (Garber and Patel, 1995). This could be problematic, particularly when the work zone is causing queueing that is hidden from the view of oncoming drivers. Drivers may not be aware of the queueing for a number of reasons including roadway geometry (e.g., poor sight lines due

to vertical alignment), environmental factors (e.g., snow, rain, glare, etc.), sight obstruction (e.g., large trucks), etc. When these situations occur drivers may have limited ability to reduce their speeds before encountering the queued vehicles, which increases the likelihood of a crash.

Traditionally, the construction work zone may equip with static message signs or changeable message signs that do not provide real-time information on the expected travel time, delay, or operating speed. To overcome these issues, the “intelligent work zone” system has been adopted in the work zone projects, especially on freeways.

Intelligent work zone (IWZ) system utilizes sensors, communications, and computers to get the real-time traffic conditions and provide dynamic information to the road users. In general, the system is portable and reliable and operates automatically and in real-time. The IWZ system is beneficial because the motorists are provided with real-time information so that they will not be surprised when delay, slow speed, or queue, as vehicles ahead suddenly begin to brake, which the behavior is hypothesized to contribute to rear-end accidents.

On freeways, there is often a dynamic queue detection system as part of the IWZ setup to alert approaching drivers of stopped or slow-moving vehicles and avoid rear-end collisions. In 2015, the Federal Highway Administration (FHWA) launched the IWZ initiative to assist state DOTs to better manage work zones to improve safety and mobility. Typically, the IWZ applications serve a combination of the purposes such as speed monitoring, travel time display, incident detection and surveillance, over-height vehicle warning, and end-of-queue detection.

Figure 1.1 shows a standard freeway IWZ layout in Nebraska. A typical IWZ setup that involves the advance queue detection function includes non-intrusive speed detectors placed at or near the taper of the work zone and a series of portable dynamic message signs (PDMS) placed on both sides of the road a few miles upstream of the work zone for information release.

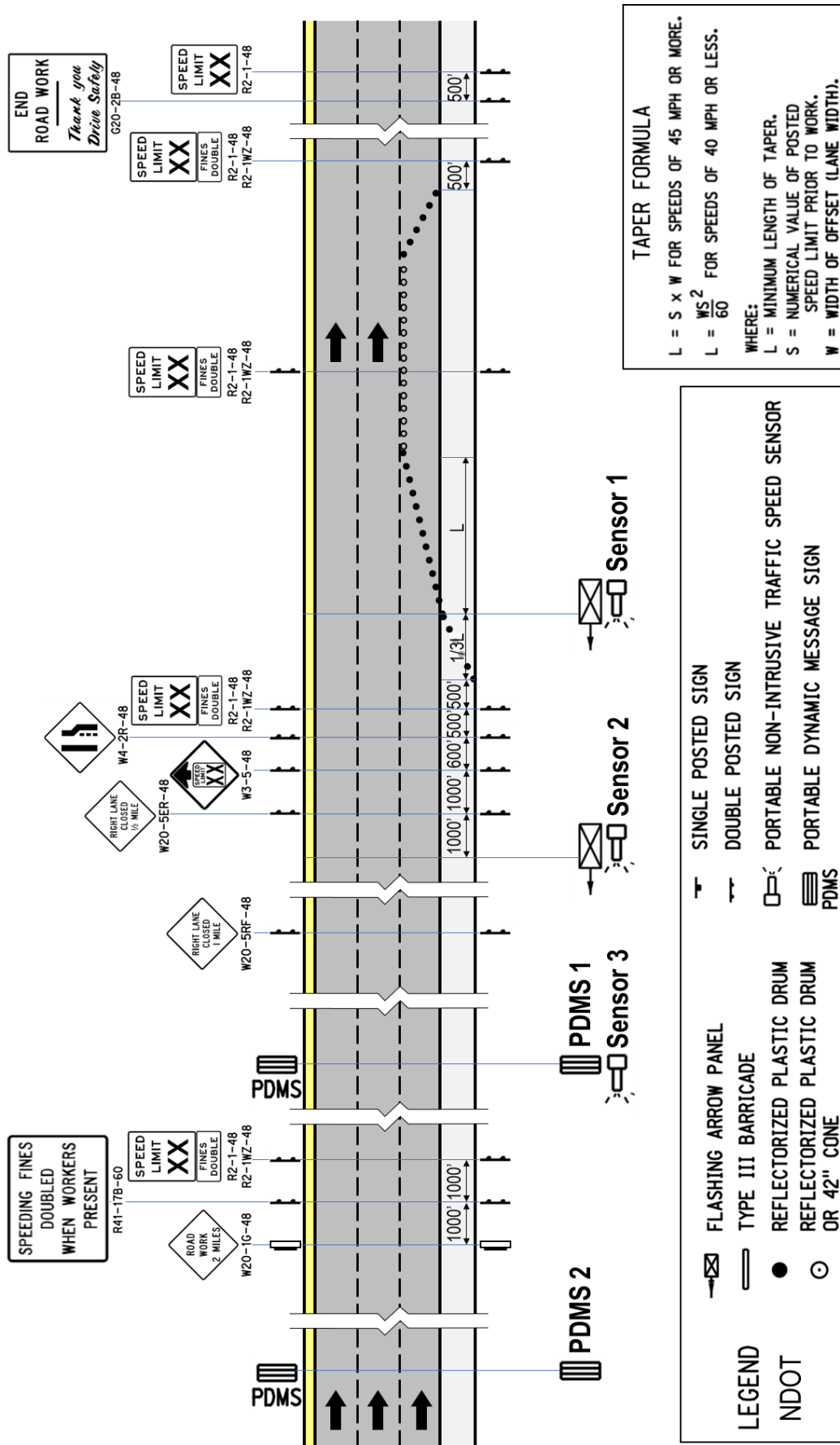


Figure 1.1 Layout of the NDOT intelligent work zone

## 1.2. Advance Queue Detection (AQD) Systems

Since 2019, the Nebraska Department of Transportation (NDOT) has implemented AQD systems on select Interstate 80 work zones. The AQD is one type of IWZ that focuses on detecting the queue, slow or stop traffic near the work zone, and informing the upstream motorists of the proper actions. Specifically, an AQD traffic management system is designed to identify critical changes in speed within or preceding the work zone and communicate this information to drivers upstream. The hope is that by providing accurate real-time information to the drivers, approach speeds will decrease, particularly during times of congestion, and safety will be improved.

The AQD system is typically installed on work zones where there is (1) significant congestion and associated slowing or stopped vehicles and (2) sight line issues that preclude drivers from identifying the slowing/stopped vehicles. These types of work zones usually have one or more lanes of traffic closed. Note that periods of peak demand often occur during holiday periods, particularly in the western, rural areas of the state. The system structures can be simplified as shown in Figure 1.2.

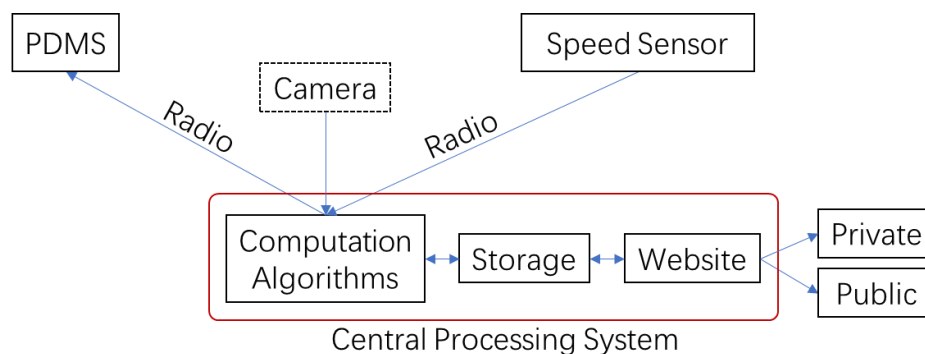


Figure 1.2. the framework zone an AQD system

The speed sensors located at the beginning of the work zone first detect the real-time speed and send it back to the central processing system. A computation algorithm of the speed (e.g., rolling average) will be used to feed the PDMS with predefined warning messages. A schematic diagram of a typical Nebraska AQD system is illustrated in Figure 1.3.



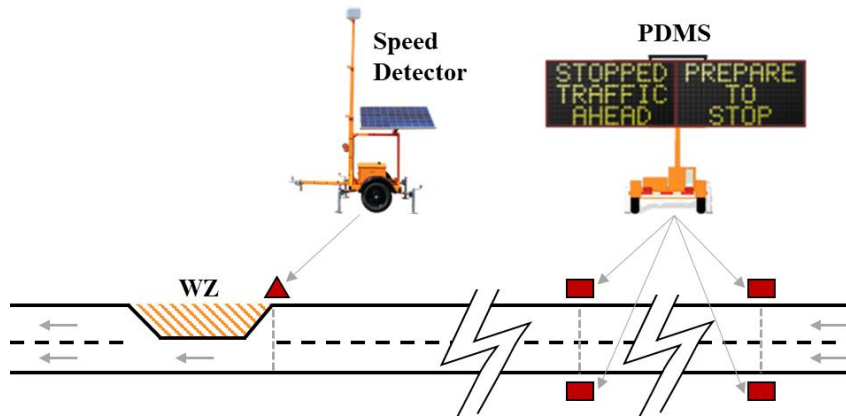


Figure 1.3. The layout of the Nebraska AQD system (not to scale)

It may be seen that the speed detector typically is placed at or near the taper of the work zone. The detector is used to measure the instantaneous speed at this location. Typically, the AQD system takes these individual instantaneous speed values and estimates a 3-minute or 5-minute rolling average speed. Intuitively, if the average speed is low (e.g., lower than a pre-defined speed threshold), it indicates a slow-moving queue has formed or is forming which represents a hazard situation for on-coming traffic.







In addition, the AQD system also includes a set of PDMS placed upstream of the work zone on both sides of the road. The AQD system provides real-time information to the drivers through the messages posted on the PDMS. For example, it may be seen in Figure 1.3, based on the instantaneous speeds measured by the speed detector in the work zone, the AQD system has detected that there is stopped traffic at the beginning of the work zone and has posted a message that approaching drivers should be prepared to stop.

Given different traffic conditions at work zones, NDOT provides a typical setting of the PDMS display in accordance with the calculated speed, as shown in Table 1.1. As a function of the estimated rolling average speeds, one of three standard warning messages will be displayed on the PDMS.

- If the rolling average speed is less than 25 mph the warning message “STOP TRAFFIC AHEAD, PREPARE TO STOP” is displayed on the PDMS. This will be referred to as “STOP” status for the remainder of the report.
- If the rolling average speed is between 25 mph and 45 mph the warning message “SLOW TRAFFIC AHEAD, SLOW DOWN” is displayed. This will be referred to as “SLOW” status for the remainder of the report.

- If the rolling average speed is greater than 45 mph, no warning message is displayed. The PDMS simply displays nothing or places four asterisks at the corners of the sign. This will be referred to as “NONE” status for the remainder of the report.

Table 1.1. Predefined speed and message

Last 3-min/5-min average speed V (mph)	PDMS message	
$V \geq 45$		
$25 < V < 45$		
$V \leq 25$		

It is important to note the warning messages follow the MUTCD guidance. In particular, the messages provided during the “STOP” and “SLOW” status are displayed in two phases. To illustrate, when the AQD is in “STOP” status the phrase “STOP TRAFFIC AHEAD” is displayed first. This is followed by the phrase “PREPARE TO STOP.” These two messages are alternated at three-second intervals until the STOP status phase is no longer active.

Note that the AQD system is adopted by the NDOT on some of their freeway work zone projects. The settings of the AQD system are location specific and depend on the traffic condition and construction intensity at the work zones. In fact, the AQD design is based on the characteristics of the work zone site. The NDOT operations engineers, in consultation with the AQD operators, may decide that for complex work zones (e.g., how many detectors and PDMS are required, where these should be placed, and the values of the operating parameters). For example, more than one speed detector may be required to provide information to the AQD algorithm. In addition, the location and number of PDMS units will be a function of the expected queue length at each test site. Intuitively, it is important to place the PDMS well upstream of the expected end of the queue so drivers will have the time to adjust their speeds in response to the information provided on the PDMS. The distance of the upstream location will be based on the characteristics of the site and the engineer’s judgment.

### 1.3. Objectives and Benefits

The first objective of the study will be to determine whether the AQD system is performing adequately. For example, the researchers will ascertain whether the correct messages are being displayed on the PDMS for given traffic conditions at the AQD detectors. For instance, if the AQD system identifies a queue, the research will confirm that the correct message is displayed on the PDMS upstream of the queue. The hypothesis that will be tested is that the correct message is displayed X percent of the time. The acceptable range used will be identified by the TAC. The hypothesis tested is shown below:

***H<sub>0</sub>: The AQD system displays the correct message within an acceptable range (e.g., X percent of the time).***

The second objective of the study will be to ascertain how the drivers react to the messages displayed on the PDMS. It is expected that when the drivers are informed that a queue is present ahead of them, they will slow down. The amount of speed reduction will be quantified as a function of distance from the PDMS. The hypothesis that will be tested is that the drivers will, on average, drive slower in response to the queue-related PDMS messages. In other words, the average speed in the vicinity of the PDMS will be lower when a “stop/slow traffic ahead” message is displayed as compared to when a “roadwork ahead” message is displayed. Also, the location of the end-of-queue will be monitored to determine whether the response of drivers is linked to the message on the PDMS and not the tail-light of vehicles at the end-of-queue. The delay associated with the work zone will also be estimated from the empirical data using the Highway Capacity Manual 6th version (HCM6) methodology [3]. The hypothesis tested is shown below:

***H<sub>0</sub>: A statistically significant decrease in average speed will occur when the PDMS indicates that the drivers should be prepared to stop because a queue has been detected ahead.***

The third objective of the study will be to determine if crash rates are lower on the SWZ equipped with the AQD system and will compare them to crashes on work zones without the AQD system using statistical theory. Note that the static signage at both types of locations will be consistent with NDOT practice. The focus will be on rear-end crashes, but all types of crashes will be examined. The hypothesis tested is shown below:

***H<sub>0</sub>: The crash rate for work zones equipped with the AQD system will be lower than work zones that are not equipped with the AQD system.***

The insights gained from this research will improve the safety and efficiency of operations at freeway work zones within the State of Nebraska. There are four main benefits:

- a. The functionality of the current AQD system will be validated using empirical data. In addition, any potential modifications and improvements will be identified;
- b. The efficacy of the systems as measured by a reduction in average vehicle speed as a function of distance from the PDMS and the message displayed on the PDMS will be quantified;
- c. The crash reduction rates associated with the AQD systems will be quantitatively identified;
- d. The NDOT benefit/cost procedure for the AQD system deployment will be validated. This will help NDOT refine the criteria used to justify the deployment of the AQD systems and determine when AQD systems should be used in work zones, etc.

The results of this project, including the validation of the NDOT benefit/cost procedures, will help NDOT engineers in deciding 1) when a lane closure may be used, 2) the length of time the lane closure should be active, and 3) whether an AQD system should be installed. The results can also provide evidence of compliance amongst drivers so NDOT may consider complementary systems. For example, enforcement may be used if the systems are found non-compliant.

#### **1.4. The Scope and Structure of the Report**

The project focuses on those IWZs on Interstate-80 in Nebraska where AQD systems are installed. Specifically, it aims to evaluate the effectiveness of the AQD systems which are designed for the application in Nebraska work zones.

The report will start with a comprehensive literature review on the engineering practices of the AQD systems applied in different states. Chapter 3 describes the data collection efforts at the selected work zone test sites, followed by data processing procedures. Crash analysis and modeling are conducted in Chapter 5, and the COVID influence on the traffic crashes is considered in Chapter 6. Results are summarized in Chapter 7 as evidence of the objectives proposed in this project. Finally, conclusions and recommendations are provided.

## **2. LITERATURE REVIEW**

Because of the dynamic nature of work zones, in terms of traffic volumes and continuous changes in lane or section locations, portable sensors that are integrated with portable dynamic message signs (PDMS) are often deployed for real-time ITS data collection and analysis (Luttrell et al. 2008) and provide actionable driver information. The integration is referred to as a smarter work zone (SWZ) or work zone ITS or Intelligent Work Zone (IWZ). The IWZs are often temporarily deployed to dynamically control traffic that is within or approaching the work zone, especially on high-speed highways (Paracha and Ostroff, 2018).

The automatic queue detection system (AQD) is an essential component of the queue warning system to alert drivers of safety issues caused by slowed or stopped vehicles on freeways at the tapers of a work zone. Essentially, the AQD system measures the speed at various locations and relays real-time information upstream to a portable dynamic message sign (PDMS). The goal of the system is to warn drivers about upcoming queues ahead. If no queues are detected, the PDMS simply informs drivers of road works ahead. The system is designed to reduce vehicle speeds as they approach the queue and/or work zone, and therefore reduce the risk of a rear-end crash (Hourdos, 2019). The following subsections summarize existing queue detection systems in some selected states in the Midwest.

### **2.1. Work Zone Speed Management Systems**

Negative driver behavior including speeding, following too closely, and suddenly slowing or stopping, has been reported as the most common contributing factor for rear-end crashes in work zones (Raub, 2001; Akepati and Dissanayake, 2011). It is assumed that if transportation agencies could reduce speed in the work zone and inform drivers of upcoming queues in real-time, it would reduce the number of rear-end crashes. This will make the work zone safer for both construction workers and the traveling public.

There are various speed management techniques that can be used in work zones such as the presence of law enforcement (e.g., police vehicle), photo-enforcement, flaggers, rumble strips, and providing real-time variable speed advisories. Using dynamic message signs (DMS), which are also called changeable message signs (CMS) or variable message signs (VMS), to provide information to

drivers upstream of the work zones has been identified in the literature as one of the most effective techniques for reducing speeds (Lin et al., 2004).

The use of the DMS to provide real-time information to drivers in order to reduce vehicle speeds can be roughly divided into two categories. In the first category, the general design involved a DMS connected to a radar unit generally in close proximity to the work zone. The radar unit was used to measure the instantaneous speeds of vehicles as they approached the work zone. The instantaneous speed was then displayed on the DMS so that the driver could see their speed and, more importantly, whether this speed was higher than the speed limit. The goal of the system was to inform drivers of their current speeds, warn drivers when they were exceeding the speed limit, and hopefully result in a lowering of the speeds of those drivers who had been exceeding the speed limit at or approaching the work zone (Wang et al., 2003).

The second category uses a Portable DMS (i.e., PDMS) as an integral part of the AQD system. The PDMS provides information on real-time speeds of the traffic downstream from the PDMS rather than speed information on an individual vehicle at the PDMS. In this system, the PDMS is located upstream of where the instability in speed (e.g., slowing or stopped vehicles) is expected to occur. Note that the exact location of the PDMS depends on the characteristics of both the vehicle traffic and the work zone. This will be discussed in detail later.

The AQD systems were first developed in the early 1970s (Kermode et al., 1970; Dudek et al., 1978a; Dudek et al., 1978b) and in recent years have been adopted by many State Departments of Transportation including those of Michigan, Wisconsin, Texas, Minnesota, Illinois (Hallmark, et. al., 2020). Their effectiveness was usually assessed by driver compliance, as measured by instantaneous speed, with the informational, advisory, or warning message that is displayed on the DMS/PDMS. In practice, a large number of studies have observed that work zone instantaneous speeds at specific locations were reduced as a result of DMS/PDMS implementation. Table 2.1 summarized the results of representative studies on the effectiveness of DMS/PDMS at high-speed intelligent work zones in literature.

Table 2.1. Studies of the Speed Management Techniques Using DMS/PDMS

Research	WZ Location & Type	Site Information <sup>a</sup>	Message Sign Location	Message Display	Speed <sup>b</sup>	Speed Variation
Richards et al., 1986	I-10 in Texas, urban 6-lane freeway	Volume = 1550 vph, Truck = 20%, PSL=60mph, RSL=40 mph	At the work zone taper	Advisory speed and/or informational message	3 - 9 mph decrease	No sig. change
Garber and Patel, 1995 <sup>c</sup>	I-81 in Virginia, urban 4-lane freeway	Volume = 24000 vpd, PSL = 65 mph, RSL = 55 mph	At the work zone taper	“High Speed, Slow Down”; “You Are Speeding, Slow Down”	0.7 - 5.6 mph decrease	Decrease
McCoy et al., 1995	I-80 in Nebraska, urban 4-lane freeway	Volume = 38000 vpd, Truck = 21%, PSL = 75 mph, RSL = 55 mph	At the work zone taper	Current speed display	4 - 5 mph decrease	No sig. change
Fontaine and Carlson, 2001	US-62 in Texas, rural 2-lane highway	Volume = 1000 vpd, PSL = 70 mph	0.439 – 0.587 mile upstream of the work zone taper	Current speed display	Car: 2 - 9 mph decrease ; Truck: 3 - 10 mph decrease	-
Wang et al., 2003	Georgia, rural 2-lane highway	Truck% = 35%, RSL= 45 mph	At the work zone taper	“You Are Speeding, Slow Down Now”; “Active Work Zone, Reduce Speed”	7 - 8 mph decrease	Decrease

King et al., 2004	I-70 in Missouri, urban 4-lane highway	PSL = 70 mph	2 and 5 miles upstream of the work zone	“Actual Speeds Ahead/xx mph”; “Slow Traffic/xx miles Ahead”; etc.	7 mph decrease	Decrease
Mattox III et al., 2007	SC219, SC290, SC72 in South Carolina, 2-lane highway	Volume = 122-250 vph; PSL = 45 mph	within work zone	Speed-activated sign: “You Are Speeding If Flashing”	2 – 6 mph decrease	-
Zech et al., 2008	I-90 in New York, rural four-lane freeway	PSL = 65 mph RSL = 45 mph	0.29 – 0.857 mile upstream of the work zone	i. “Right Lane Closed, Keep Left”; ii. “WZ Max Speed 45 MPH, Prepared to Stop”; iii. “Left Lane Closed, Keep Right”	3.3 - 6.7 mph decrease for ii; No sig. change for i and iii	0.2 - 2.0 mph increase for ii; -2 to 1.13 mph change for i and iii
Li et al., 2010	US-36 and US-73 in Kansas, rural two-lane highway	Volume = 3400 – 3630 vpd, PSL = 65 mph, RSL = 45 mph	0.284 mile upstream of the work zone	“Road Work Ahead, Slow Down”	4.7 mph decrease	-
Huang and Bai, 2014	K-13 in Kansas, rural two-lane highway	Volume = 1200 vpd, PSL = 65 mph	0.1 mile upstream of the work zone	“Work Zone Ahead, Slow Down”; “Flagger Ahead Prepare to Stop”	8 mph decrease	-



Domenichini et al., 2017 <sup>d</sup>	Four-lane highway using simulator	PSL = 80 mph	0.43 mile upstream of the work zone	“Reduce the Speed”	5.7 mph decrease	1.8 mph increase
Bham and Leu, 2018	I-44 in Missouri, rural 4-lane highway	PSL = 70 mph	1.5, 2.3, 3.9, and 5.6 mi upstream of WZ	Caution, WZ Ahead, Reduce Speed, etc.	9.35 - 48.91 mph decrease	Increase

<sup>a</sup> PSL = post speed limit at non-work zone; RSL = Regulatory speed limit at work zone.

<sup>b</sup> The speed evaluated in the literature refers to the time mean speed (spot speed).

<sup>c</sup> Seven sites were tested in total at I-81 and I-64 with other messages of “Excessive Speed, Slow Down” and “Reduced Speed in Work Zone.”

<sup>d</sup> The change of mean speed and speed variation is calculated using values at Site B minus values at Site A.

Although extensive empirical research on the performance of PDMS has been done, there are still gaps in the literature. For example, while all of the studies listed in Table 1 reported a reduction in work zone time mean speeds, the magnitude of the speed reduction varied across the sites. More importantly, the few studies that did examine the variability of speeds in the work zone arrived at conflicting conclusions. In other words, it is still an open question on whether the use of PDMS to provide real-time information impacts the variability of work zone speeds.

Furthermore, studies in literature analyzed the effectiveness of the system by comparing the time mean speeds upstream and downstream from the PDMS locations. By definition, time mean speed, which is measured at a particular point in the work zone, may not capture driver speed changes along the entire road segment. This is particularly true when traffic is congested (Kim et al., 2013). In this situation using space mean speed, which is taken over a definite length of roadway, may provide more meaningful results as it won't be as susceptible to transitory effects that can occur when measuring the speed at one location.

In addition, some studies found that the PDMS was no more effective than traditional speed management techniques (e.g., static signage) in reducing speeds (McCoy and Pesti, 2002; Huebschman et al., 2003). In these situations, the authors attributed this to a number of factors including PDMS location (e.g., too far from work zone), traffic flow conditions (e.g., uncongested), and/or road geometry restrictions. Therefore, while the AQD system has been shown to be effective, many authors have indicated that these systems have to be designed for the specific work zone conditions in order for them to achieve maximum effectiveness (Middleton et al., 2011; Ullman et al., 2014; Azimi et al., 2021).

This study investigates AQD systems that have been implemented on Interstate Highway work zones in Nebraska. These AQD systems consist of a downstream speed detection system that feeds real-

time speed estimates to upstream PDMS. First, the operation of the AQD system was verified by examining the measured space mean speeds at the AQD detector locations and ensuring that the associated PDMS messages were consistent with the underlying system logic. Second, the behavior of drivers, as a function of the message on the PDMS, was studied by comparing empirical travel times (e.g., space mean speed) of vehicles on the freeway segments immediately upstream and downstream of the PDMS. Note that individual vehicle travel time information is not collected as part of the AQD system. To the authors' knowledge, this is the first study that evaluates the effectiveness of an AQD system using travel time (e.g., reciprocal of space mean speed) over roadway segments rather than time mean speed at select locations.

## **2.2. AQD Applications among DOTs**

Several state DOTs have deployed IWZ applications provided by the state themselves or through various private suppliers over the years. The characteristic features of the IWZ are that they should be portable, automated, and reliable to obtain and analyze traffic data in real-time. Examples of IWZ systems include but are not limited to the following: Traffic Information and Prediction System (TIPS), Advance Speed Information System (ASIS), Computerized Highway Information System (CHIPS), ITSWorkzone, Automated Data Acquisition and Processing of Traffic Information in Real-time (ADAPTIR), the Automated Information Management System (AIMS), etc. A detailed description of some of the existing IWZ can be found elsewhere (Pant, 2017). A review of the literature shows that all IWZ works with the objective of one or more of the following functions:

- Construction Equipment Alerts – Intended to inform motorists about a construction vehicle in the traffic stream.
- Travel Time Display – Provides travel time information to assist motorists to make informed route choice decisions.
- Incident Detection and Surveillance – The objective is to provide incident information to motorists as they happen and enable faster response times to incidents.
- Over-Height Vehicle Warning – Provides warning alerts to motorists in advance for work zones with low structures.
- Speed Monitoring – To enhance the compliance of speed reductions and facilitate uniform speeds.
- Queue Detection – The objective is to address the safety issues caused by slowed or stopped vehicles on freeways at the approaches to a work zone.

Over the past two decades, there have been several studies on the benefits of IWZ applications. This section gives a review of the efforts by the Federal Highway Administration, state DOTs, and academia. The FHWA website describes IWZ applications and provides reports that overview concepts, guidance, and benefits of IWZ. According to Pant (Pant, 2017), these reports outline the characteristics

of an IWZ system and provide motorists with actionable information in real-time within a work zone (Scriba and Atkinson, 2014) outlined costs of deployment, troubleshooting, different ITS equipment in existence, and of course the variation of the needs of work zones.

In 2014, the FHWA developed an IWZ Implementation Guide to assist in the design and implementation of IWZ (Ullman et al., 2014). This was followed by the IWZ initiative as part of round three of the Every-Day Counts program (Paracha and Ostroff, 2018). The FHWA launched the SWZ or IWZ initiative in 2015 to encourage and assist state DOTs/agencies to produce better work zone operating plans. According to the FHWA, this initiative has contributed to minimizing travel delays, enhancing safety, and maintaining access to business and residential facilities. Also, the FHWA has developed an IWZ implementation Tool as a software application to the Guide that supports independent decision-making on IWZ deployment. These documents can be accessed via the FHWA website (FHWA, 2022).

Many state DOTs have undertaken studies to evaluate IWZs and produced guides to help achieve mobility and safety metrics in the implementation of IWZs. A good summary of the IWZ applications and results from case-by-case study efforts can be found in a project report completed by the Arizona DOT, where it may be seen that the installation of IWZs result in mobility and safety improvements (ADOT, 2019).

Currently, many state DOTs are implementing IWZs in an integrated way to achieve two or more objectives within the same system implementation. For example, the Kansas DOT implemented an IWZ system that has both dynamic lane merge and queue warning systems at an approximate cost of \$840 a day (KDOT, cited in ADOT, 2019). There is a growing recognition that one of the major safety measures in freeway work zones is to address the issue of the back of queue crashes by installing automatic queue warning systems.

- **Illinois DOT**

Illinois DOT (IDOT) began the installation of queue detection systems in the early 2000s because of the incidents of a severe crash on the I-57 (Hallmark et al., 2020). IDOT has two queue detection system approaches used for long-term and short-term projects. The latter is usually on-call and used for projects that span two weeks or less. It is a low-cost alternative to the long-term system setup. More importantly, the specific equipment for the queue detection systems is determined by the traffic control company that wins the bid and not by IDOT. The interstate or highway selection criteria for a queue detection system are based on conditions that cause more than five minutes of delay, a mile of the backup queue, and other traffic patterns. According to Ullman & Schroeder (Ullman & Schroeder, 2014), the evaluation of a queuing system in Illinois resulted in a 14% decrease in queuing crashes and an 11% decrease in injury crashes. Another study resulted in a 13.8% reduction in rear-end crashes (Roelofs and Brookes, 2014).

- **Iowa DOT**

In Iowa, Traffic Management Centers (TMC) are used in the IWZ operations. Real-time travel data is collected using sensors and cameras and sent to the TMC via a machine learning algorithm (Kinckerbocker et al., 2018). The TMC Operators then sent actionable messages to PDMS, social media, and the 511 system. There are four levels of speed limits that the logic is being implemented: at 70 mph (normal conditions, no message), at 55 mph (advised), 45 mph (advised), and 35 mph (advised). Iowa uses the TransSuite transportation management system for queue alerts. A typical message displayed on the PDMS relating to the estimated speed is as follows - (1) below the free-flow speed at a given threshold - 'Slow Traffic Ahead,' (2) below the speed threshold - 'Stopped Traffic Ahead,' and (3) when speeds are regained – 'Traffic Delays Possible for up to xx minutes' depending on the conditions of the work zone (Hallmark et al., 2020).

- **Kansas DOT**

In addition to the actionable information on PDMS, traffic and video data are supplied to the Kansas City Traffic Management Center (<http://www.kcscout.net/>) to assist early incident detection and traffic flow conditions. In Kansas, the general public is able to obtain work zone real-time traffic information online using JamLogic's platform (Bledsoe, 2014). According to (Hallmark et al., 2020), there was a 50% traffic diversion when the PDMS displayed a delay of 7 minutes or more.

- **Michigan DOT**

Michigan DOT started implementing IWZ over a decade (ADOT, 2019). The study on the queue warning system in Michigan DOT started in 2012 and has then been standardized (Hallmark et al., 2020). The placement of queue warning systems is based on the following roadway characteristics (e.g., peak hour lane closure, one or more-mile queue length) and at least an automatic queue advisory and speed-based IWZ systems are deployed. The evaluation of the impact of the queue warning systems in Michigan has resulted in a 60% to 40% percent reduction of total rear-end crashes (Hallmark et al., 2020).

- **Minnesota DOT**

Minnesota DOT uses an IWZ Toolbox that provides the basis for various ITS work zone system selection (MnDOT, 2008). Similar to the operation of the queue warning systems in the other states, the MnDOT system provides congestion notifications and alerts motorists of a traffic stop or slow-moving traffic. The MnDOT system requires PDMSs to be incrementally spaced and automatically activated when the queue is within a mile away from the PDMS location. The messages on the PDMS switches from "Prepare to Stop" when queues are detected otherwise it stays blank or is used for other purposes. According to Hallmark et al., (2020), an evaluation of the system set up in Minneapolis showed that the queue detection was within  $\pm 5$  seconds from when the empirical queue was observed. The overall true

positive queue detection rate was 84% which ranges from 74% to 96.7%. Another study resulted in a 22% and 54% decrease in crashes and near-crashes (Hourdos et al. 2017).

- **Missouri DOT**

In Missouri, queue length detectors in combination with other ITS equipment are used to monitor and provide actionable information to motorists via PDMS. The system uses the TransSuite software in combination with HERE probe speed data to monitor speeds and display information to motorists at varying speed thresholds. According to Clark et al. (2017), the system is effective in supporting smooth traffic flow, advising motorists, and providing warnings.

- **Texas DOT**

In Texas, an integrated system developed by the Texas Transportation Institute is used to monitor the work zone and disseminate motorist information. The system aims to automatically detect and predict queue formation and disseminate actionable information such as ‘slow and stopped traffic ahead.’ According to Habermann (2015), before the deployment of the system – there is an agreed concept of operations with stakeholders and the public. An evaluation of one of the queue warning systems set up in Houston resulted in a decrease in speed variance, a 55% reduction in forced lane changes, and a 2% to 3% reduction in erratic maneuvers (Pesti et al. 2008).

- **Wisconsin DOT**

The Wisconsin DOT completed a study to evaluate a work zone queue warning system in Manitowoc County along I-43. This study was initiated because of the spike in work zone crashes and fatalities in 2015. The main objective was to collect and analyze speed data in and on the tapers of the work zone to determine driver behavior. The study compared crashes from a similar project without the queue warning system. According to the Wisconsin DOT cited in Hallmark et al. (2020), it was found that there were 15% and 65% decreases in queue-related crashes and injury crashes, respectively.

### **2.3. Summary**

The literature review has shown that there is a growing interest in the use of smart work zones during road construction, especially on interstates. There are numerous settings employed by several state DOTs. However, the basic characteristics of these smart systems are that they need to be automated, reliable, and portable to obtain and analyze traffic data in real-time, and then communicate actionable information to motorists.

Intelligent work zones are designed with the goal to enhance safety and mobility by employing sensors, estimation algorithms, and traffic management strategies. The evaluation of these intelligent work zones has resulted in considerable positive results on safety and mobility through the back of

queue management, safe lane merging, speed reductions, facilitating uniform speeds, route diversion, and other traffic control techniques.

One of the major safety measures in freeway work zones is to address the issue of back of queue crashes. State DOTs have deployed automatic queue warning systems to provide visual warnings and actionable information to ideally help drivers to prepare for slow-moving or stopped traffic in and around the work zone.

It is the hope of many state DOTs that, drivers comply and take the needed actions. However, drivers are often distracted and may fail to read alerts or recognize warning signs especially when signs are a few miles away from the tapers of the active work zone. In other cases, drivers just fail to comply with the warning signs they receive. This report evaluates the effectiveness of the automatic queue detection system and estimates the compliance rate of drivers approaching the work zone after displaying actionable information.

### 3. DATA COLLECTION

To evaluate the effectiveness of the AQD system, one of the critical traffic conditions is there should be slow-moving traffic, or queues, in the work zone so that a type of warning message will be displayed and conveyed to upstream drivers. Therefore, on one hand, high-volume traffic is expected during the data collection period to form queues at the beginning of work zones. On the other hand, the queues should be far from reaching the upstream PDMS locations so drivers would see the warning message before seeing the end of the queue. This was not that difficult to reach in normal conditions since at least one lane will be closed at the test site, which will naturally generate a merging bottleneck, as shown in Figure 3.1.



Figure 3.1 Data collection on queued traffic conditions at a test site

However, under the influence of the COVID-19 pandemic and its interventions, traffic flow was dramatically reduced during the work zone activation seasons. Heavily congested traffic scenarios were rarely observed. Therefore, the data collection of travel times at PDMS has to be conducted in a two-phase manner. Note the impact of COVID-19 on the traffic performance of the work zone test sites will also be studied later in this report.

#### 3.1. Preliminary Studies and Test Site Selection

Before conducting holistic data collection, preliminary studies were performed to understand the function of the AQD systems and select the work zone test sites. AQD systems provided speed at the taper of the work zone merging area (i.e., beginning of the work zone) at a 1-min interval, which activates a warning message with the time and content information to the PDMS. Depending on different settings, more speed detectors at 1-mile and/or 2-mile upstream of the work zone may also be

available, although these speeds are not used to feed the warning message according to the AQD algorithm. In addition, the AQD systems also provided vehicle counts, large vehicle counts, etc.

To this end, data from the AQD systems at Big Springs (Westbound I-80) test site was obtained. The traffic volume and heavy vehicle percentage data in the week of September 14 to September 20, 2020, were compared to manually observed data from cameras on September 20, 2020. Figure 3.2 shows the verification of the traffic counts.

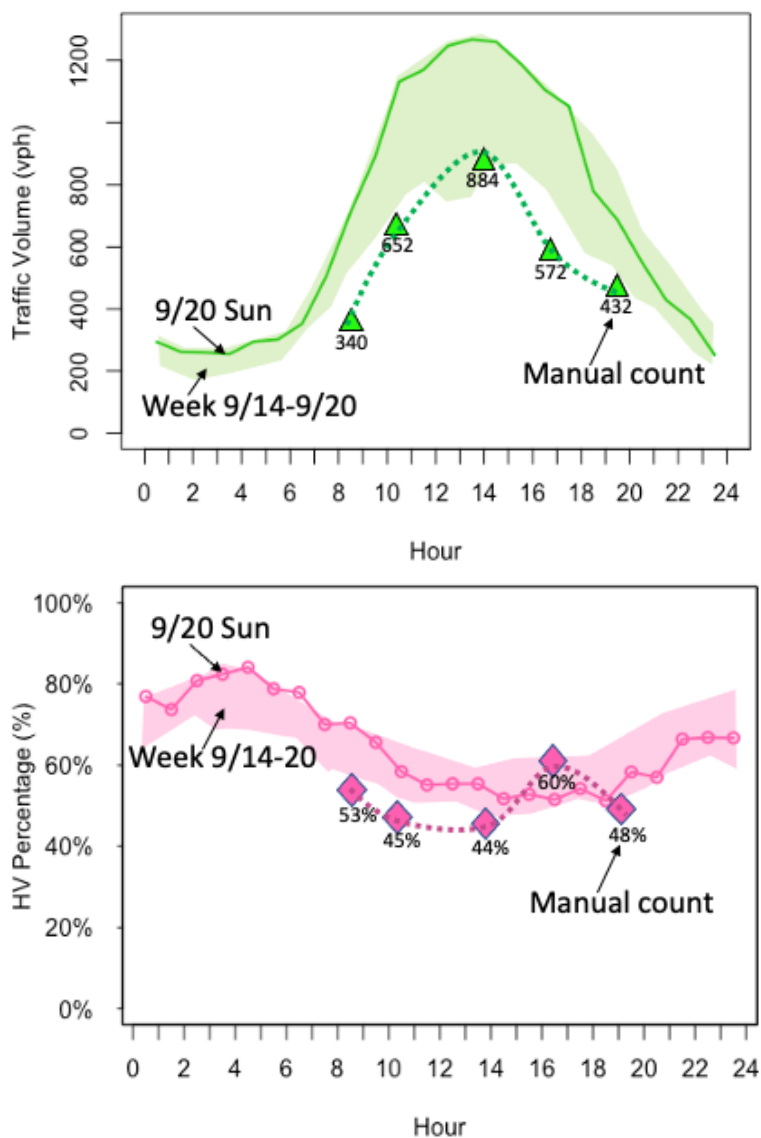


Figure 3.2. Data verification for the traffic counts at Big Spring (Shaded area indicates the data varies in a week from Sep. 14 to Sep. 20, 2020. Solid curve represents one-day data from Sep. 20, 2020, and the dotted points are field observation at the same time and location)

As the core algorithm of the AQD systems, average speed and warning messages are obtained and studied. Figure 3.3 provides an example of the AQD data with sporadic slow or stop traffic at the work



zone, which green, yellow, and red colored timeframes indicating the display content on the PDMS were STAR, SLOW, and STOP, respectively.

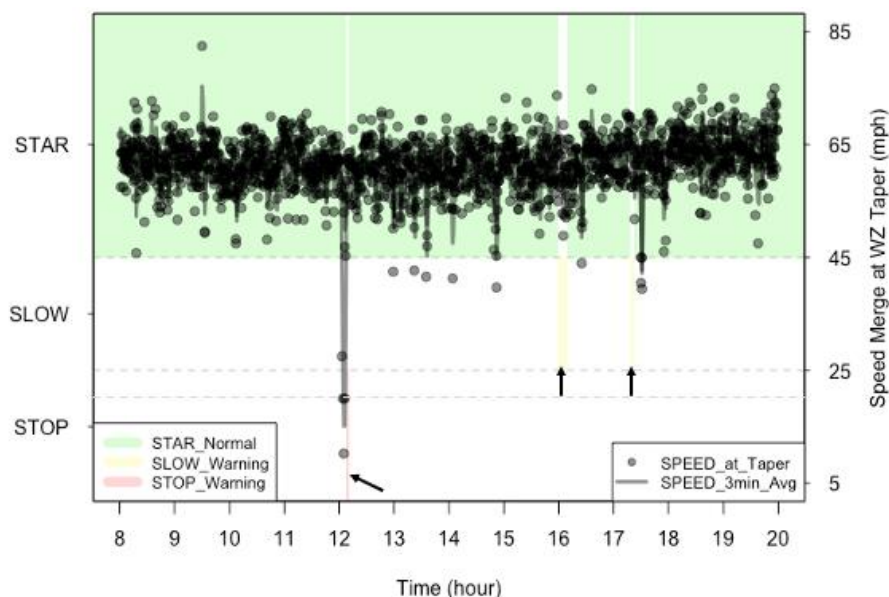


Figure 3.3. Illustration of a speed and message matching example at Big Springs

Intuitively, Figure 3.3 shows the released message matches the detected speed very well. There may be inconsistency (i.e., error) where the warning message was displayed however it shouldn't, according to the calculated average speed, as arrows marked in Figure 3.3 错误!未找到引用源。 . In those cases, the speeds were above 45 mph, however, during these periods the PDMS displayed the SLOW warning message (timeframes were indicated in yellow color).

Note all the speed and warning message data are provided from AQD systems. A further statistical study will report a quantitative result of the matching rate at different locations. The preliminary studies help to identify possible problems that need attention.

It is anticipated that the criteria used to select the test sites will include:

- a) Work zone location (e.g., urban, rural),
- b) Number of lanes (e.g., 3-to-2, 2-to-1),
- c) Traffic density,
- d) Truck percentage,
- e) Road geometry (e.g., grade, curvature), and
- f) Presence of existing AQD systems.

Although listed in the last, many time the presence of existing AQD systems that are available as test site is critical. This is due to the fact that NDOT has not widely installed AQD systems for the construction work on Interstate. Finally, all the study sites are identified in consultation with the TAC and NDOT traffic engineers.

### 3.2. AQD Speed and Warning Message Data Collection

Based on the preliminary results of the AQD data from all available IWZs on I-80 in Nebraska, four test sites were selected to study the effectiveness of the functionality of the AQD systems. Specifically, the goal was to make sure the AQD systems work functionally as expected. Data from the four selected test sites, as shown in Figure 3.4, were obtained to analyze the system errors during the study period.

Test site 1, located near Wood River, NE, involved a reduction from two lanes to one lane in the eastbound direction. As shown in Figure 3.4 (a), the AQD system consisted of a speed detector that was located at the taper of the lane closure. It also included two sets of PDMS. The first and second PDMS was located approximately 1 mile and 5 miles upstream of the speed detector, respectively.

Test site 2, located near Ashland NE, had a reduction from three lanes to two lanes in the westbound direction. Similar to Test Site 1, the speed detector was located at the taper of the work zone. As shown in Figure 3.4 (b), the test site also utilized two sets of PDMS, which were located approximately 1.5 miles and 2.5 miles upstream of the speed detector, respectively.

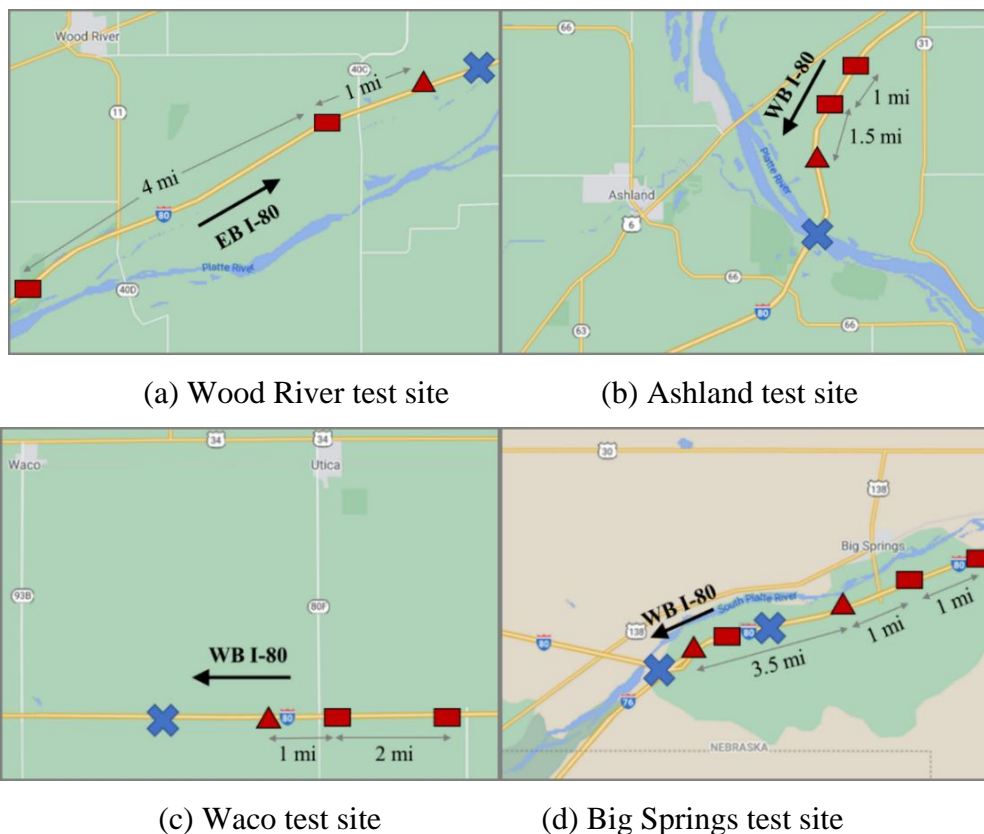


Figure 3.4 Layout of the AQD systems at different test sites. The blue cross indicates lane closure. The AQD system made of speed detector and PDMS is in red triangle and rectangle, respectively.

Figure 3.4 (c) shows the Waco test site. This work zone had a reduction from two lanes to one lane in the westbound direction. It also utilized two sets of PDMS located upstream of the speed detector.

The first was located approximately 1 mile upstream and the second was located approximately 3 miles upstream.

The AQD systems at the Big Springs test site, as can be seen in Figure 3.4 (d), were more complex because the work zone was located at the interchange of two Interstate highways (e.g., I-80 and I-76) and was approximately 5 miles long. This work zone had a reduction from two lanes to one lane in the westbound direction. Because this work zone included multiple construction activities, the designers chose to utilize two speed detectors. The first detector was installed at the taper of the Work Zone. The second detector was installed approximately 3.5 miles downstream from the first detector and was used to measure vehicle speed within the work zone.

The AQD logic was such that the lowest rolling average speed from the two speed detectors was used at the input to the AQD algorithm. In other words, the lowest rolling average speed was used to identify which message to display on the upstream PDMS. This test site also utilized two sets of PDMS located upstream of the speed detector. The first and second PDMS sets were located approximately 1 mile and 3 miles upstream of the work zone, respectively. Both sets of PDMS were designed to display the same message simultaneously.

The summary of the AQD data collection at the four locations is shown in Table 3.1.

Table 3.1 Summary of the AQD data collection

Test site	Wood River	Ashland	Waco	Big Springs
AADT (vpd)*	21811	43074	25245	15070
Heavy vehicle percentage*	36.6%	17.4%	33.5%	47.1%
Lane configuration	2-to-1	3-to-2	2-to-1	2-to-1
Work zone length (mi)	5	6	4	11
AQD data collection (0:00 am – 11:59 pm)	8/14/2019 – 11/15/2019	4/15/2020 – 7/22/2020	4/8/2020 – 9/11/2020	6/16/2020 – 10/19/2020

\*Annual Average Daily Traffic (AADT) and truck percentage were obtained from the NDOT website. NDOT conducted counts before the work zone construction in 2020 and the AADT from the nearest collection station on I-80 was used in this table.

As mentioned previously, the AQD system is designed to capture speed data from the speed detectors as well as the message data posted on the PDMS. Each speed detector captured individual vehicle speeds and vehicle type information and all data had time stamps. From this, the vehicle volumes, disaggregated by vehicle type, could be estimated. Each PDMS stored the start time, end time, and text for each message displayed. All this data was available to the research team.

### 3.3. Travel Time Data Collection

As introduced previously, a typical NDOT AQD system comprises a speed sensor located at the merging taper of the WZ, and two sets of PDMS that are one mile and two miles away from the speed sensor, respectively. The Miovision data collection system is a five Miovision Scouts which are roughly even spaced upstream and downstream of the PDMS locations. The relationship between the AQD system and the Miovision data collection system can be found in Figure 3.5. Note that the Miovision data collection system can only be in either one of the PDMS locations at a time.

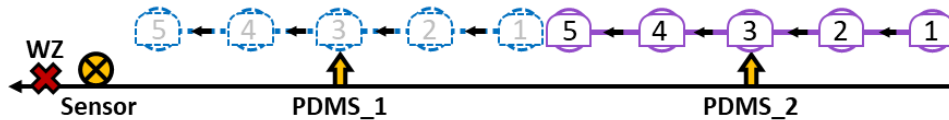


Figure 3.5. Relationship between the AQD system and Miovision data collection system

The Miovision Scout portable units, as shown in Figure 3.6 (a), consist of two types of detectors (e.g., cameras and WiFi receivers), and both were used to capture traffic data. Cameras within the portable units were used to obtain video data of traffic traversing the roadway. The WiFi receivers were used to capture Media Access Control (MAC) addresses, and their associated time stamps, from passing vehicles. Any electronic unit in a passing vehicle that has (1) short-range communication capabilities, and (2) is enabled, would provide MAC addresses. These electronic units could include laptops, tablets, mobile/cell phones, and communication systems within the vehicle.

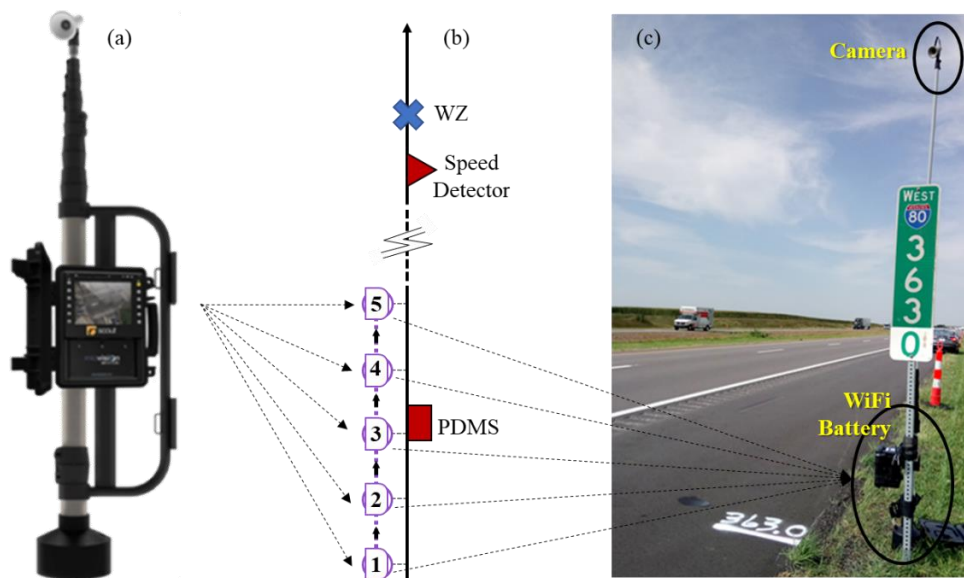


Figure 3.6 The data collection system of (a) a Miovision Scout unit (b) the layout of the five Miovision stations (c) a field deployment example.

Five Miovision Scout units formed the travel time data collection system, as shown in Figure 3.6 (b). The five Miovision Scout stations, labeled stations 1 through 5 were placed at approximately 0.5 mile spacing in the vicinity of the PDMS being analyzed. The goal was to place Station 3 as close to the PDMS, as was practical. Stations 1 and 2 were placed approximately 0.5 and 1 mile upstream of the PDMS. Stations 4 and 5 were placed approximately 0.5 and 1 mile downstream from the given PDMS.

As shown in Figure 3.6 (c), each Miovision Scout unit was attached to a mile-marker sign. The research team ensured the WiFi antenna was pointed perpendicular to passing traffic and the camera faced oncoming traffic.

Because it was necessary to attach the devices to a mile-marker sign, the exact location of the Miovision units varied from work zone to work zone. After the research team placed the five Miovision Scout portable detectors in the field they measured the distances between them using the embedded GPS, which is accurate to within a 23 ft radius (Miovision Website). The measured distances were then compared to the distances on the mile-marker signs. The average difference between the distances measured by the GPS and the distances indicated on the mile-marker signs was 1.1%. Consequently, the measurements obtained from the GPS were used for all further calculations.

It should be noted that before setting up the data collection systems at Waco-Utica and Big Springs, the AQD system had been operational for several weeks and had been well tested. Therefore, it was assumed any commuter drivers were familiar with the AQD system operating as part of the work zone.

It was also assumed that the data collection system had minimal or no effect on driver behavior. This was because the data collection units are relatively small and are attached to existing mile-marker signs which help hide their profile as shown in Figure 3.6 (c). The data collection was scheduled for the same period each day from 8 AM to 8 PM. No information was collected when the research team was setting up the system or changing out the batteries.

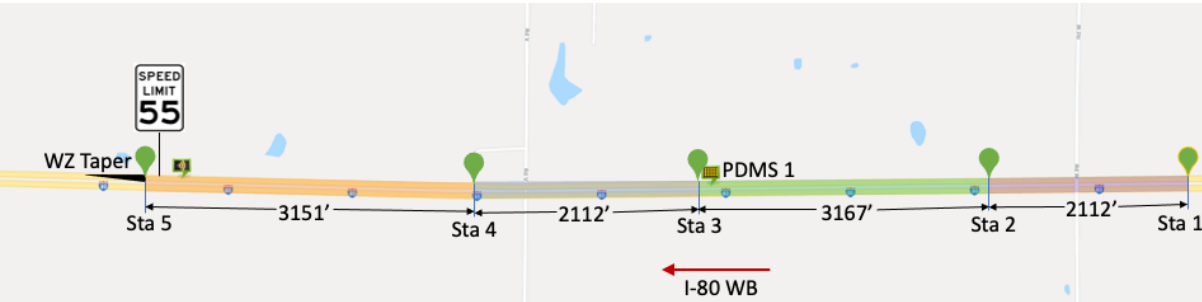
Data collection was conducted in two phases. The first phase was during September through November in 2020, and the second phase was in July 2021. Four work zone test sites were selected for travel time data collection. The speed limit at all four test sites was reduced from 75 mph to 55 mph in the work zone, which began about 2 miles upstream of the work zone and ended just past the end of the work zone. The deployment of the data collection systems at these four test sites is described below.

### 3.3.1. Waco test site

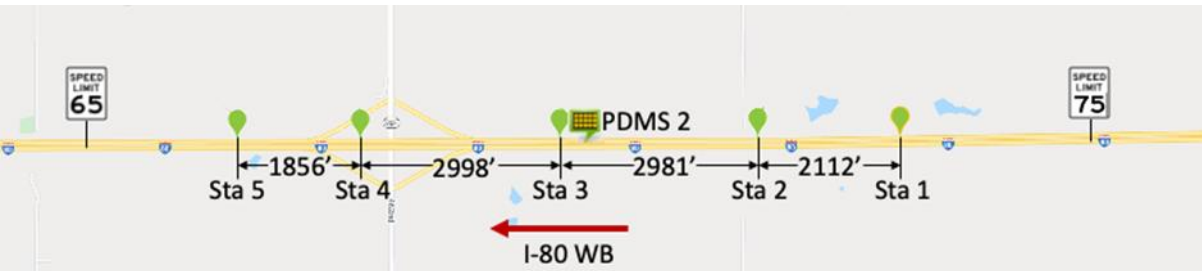
Data were collected at the I-80 Waco work zone in September 2020 and lasted about 2 weeks. Five Miovision stations were attached to the mile marker poles. The deployment of the Miovision data collection system is shown in Figure 3.7.



(a) Work zone test site located between Waco and Utica



(b) Data collection stations at PDMS 1



(c) Data collection stations at PDMS 2

Figure 3.7 The layout of the five Miovision units at the Waco test site

### 3.3.2. Big Springs at PDMS 1

Data collection at Big Springs was conducted during September and October 2020 and lasted about 3 weeks. The target PDMS (PDMS 1) is located at mile marker 108, WB I-80. Figure 3.8 showed the settings of the Miovision data collection system, which were located at mile markers 107, 107.5, 108, 108.5, and 109, respectively. In other words, the five Miovision units were 0.5-mile spaced and covered 1 mile upstream and 1 mile downstream of the PDMS.

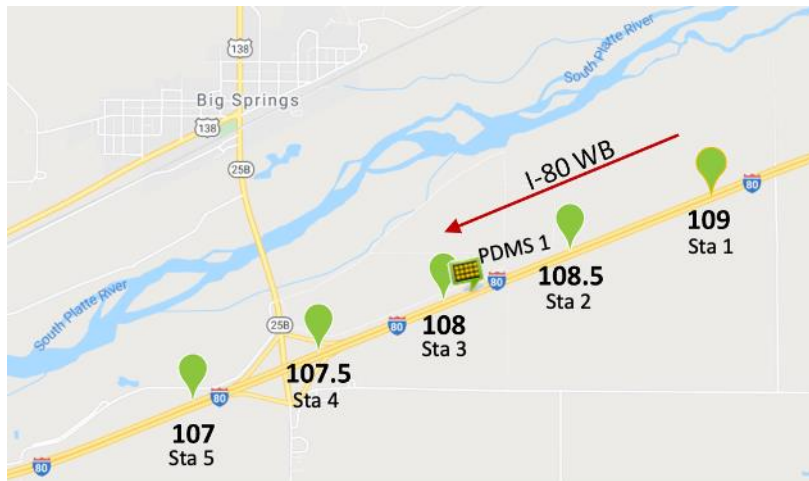


Figure 3.8 The layout of the five Miovision units at the Big Springs test site

Data were collected every day from 8 AM to 8 PM at each location. Table 3.2 listed the “SLOW” and “STOP” warning messages displayed on the PDMS. Other periods not listed are normal traffic conditions with a “STAR” message (four asterisks were displayed in the corners of the PDMS as placeholders). As indicated in Table 3.2, the slow/stop traffic duration is very short, and the majority of these durations occurred on weekends.

Table 3.2. Records when PDMS displayed “SLOW” or “STOP” message

Date	Begin	End	Message	Duration
Thu, Sep 17, 2020	9:08 AM	9:12 AM	slow	4 min
Sat, Sep 19, 2020	4:01 PM	4:07 PM	slow	6 min
Sun, Sep 20, 2020	12:07 PM	12:11 PM	stop	4 min
Sun, Sep 20, 2020	3:59 PM	4:09 PM	slow	10 min
Sun, Sep 20, 2020	5:18 PM	5:23 PM	slow	5 min
Wed, Sep 23, 2020	11:48 AM	11:54 AM	slow	6 min
Sat, Sep 26, 2020	2:42 PM	2:58 PM	slow	16 min
Sun, Sep 27, 2020	2:08 PM	2:16 PM	slow	8 min
Sun, Oct 11, 2020	3:43 PM	5:05 PM	slow	82 min

Unfortunately, there is no queue and longer time of slow-moving traffic at the work zone during the entire data collection period. Thus, more data collection efforts may be required and will be conducted in a second phase.

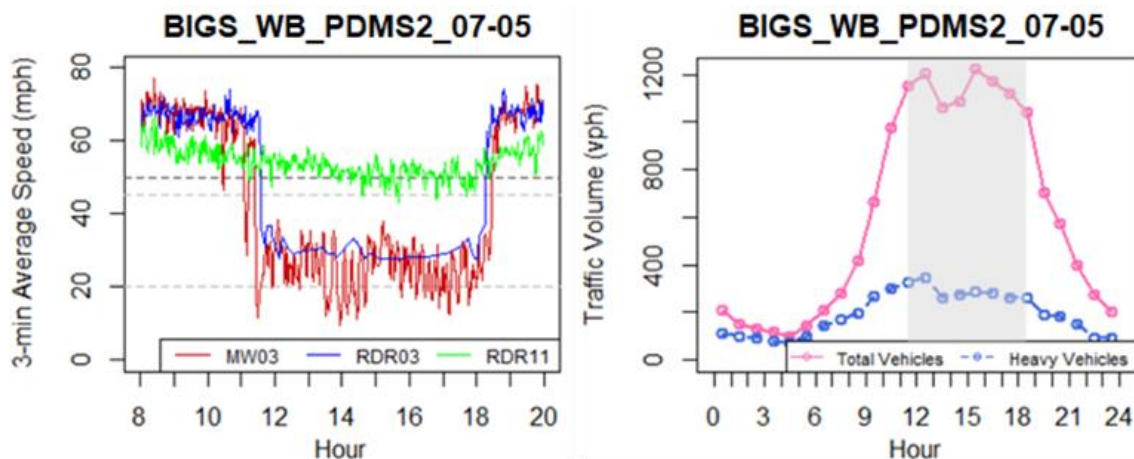
### 3.3.3. Big Springs at PDMS 2

The second phase of data collection at the Big Springs test site was on July 3rd through 6th 2021 at the same AQD settings as the first phase. Three Miovision units were installed 0.5-mile before, at, and 0.5-mile after the PDMS, as can be seen in Figure 3.9.



Figure 3.9 Data collection system at Big Springs test site

In Figure 3.10 (a), as the speed at the work zone merging area (Sensor # MW03) shows, up to seven hours of afternoon congestion from 11:30 AM to 6:30 PM was under slow-moving traffic. Meanwhile, the speed at 1-mile upstream of the work zone merging area (Sensor # RDR11) shows that, although slightly affected, the impact of the work zone slow traffic was diminished. A further check of the Miovision cameras at the PDMS2 location confirmed that no slow-moving or queued traffic was reached up to PDMS2. In other words, rather than being forced to slow down or stop due to the end-of-queue, drivers are free to react to the warning message at PDMS2.



(a) Speeds at three locations

(b) traffic count from sensor MW03

Figure 3.10 Data collected by sensors in the AQD systems at Big Springs test site

Figure 3.10 (b) indicates the traffic volume during the day, which was counted by Sensor # MW03 at the work zone merging area. The shaded area indicates the observed period of slow-moving traffic.



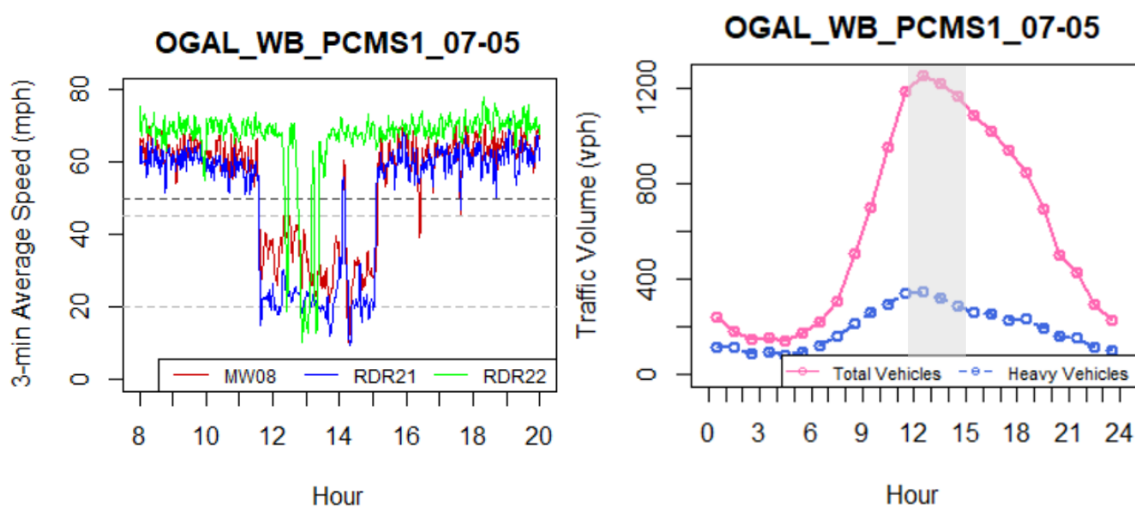
### 3.3.4. Ogallala test site

The work zone of westbound I-80 at Ogallala was a 2-to-1 test site (i.e., two lanes in mainline while one open lane in a work zone). Data collection was conducted from July 3rd through 6th 2021. Three Miovision units were installed 0.5-mile before, at, and 0.5-mile after the PDMS, as can be seen in Figure 3.11.



Figure 3.11 Data collection system at Ogallala test site

The speed of the day at the work zone test site and the volume that the work zone experienced over the day can be found in Figure 3.12.



(a) Speeds at three locations (b) traffic count from sensor MW08

Figure 3.12 Data collected by sensors in the AQD systems at Ogallala test site

Note that the Miovision data collection system in Phase 2 at Big Springs test site and Ogallala test site was reduced from 5 units to 3 units for the purpose of reducing data collection efforts. It was found in previous studies in Phase 1 that the data (i.e., travel time) from first two stations, as well as the last two stations, do not show statistically significant differences. Therefore, the data collection systems can be simplified.

## 4. DATA PROCESSING

### 4.1. Work Zone Speed and Message

To verify the AQD system operated as designed, the correlation between the rolling average traffic speed estimated from the speed detector data and the message displayed on the PDMS was examined. Note the researchers only had access to the raw speed data, which is provided in a 1-minute average format. Consequently, Equation (4.1) was used to calculate the 3-minute rolling average speed as a function of time for each of the test sites.

$$\bar{v}_t = \frac{\sum_{i=t-k}^{t-1} v_i}{k} \quad \forall i = 1, \dots, I \quad (4.1)$$

Where,  
 $\bar{v}_t$  = 3-minute rolling average speed at time period  $t$  (mph)  
 $v_i$  = instantaneous speed of vehicle  $i$  (mph)  
 $i$  = count of vehicles when their front bumpers go through the detector  
 $k$  = duration of rolling average speed (minute), e.g., 3 minutes

It should be noted that if any of the 1-minute average speed values are missing, the algorithm uses the last three 1-minute average speed data points in Equation (4.1). If no speed values are measured for five minutes in a row, the speed detector is considered to be in a “No Data” condition. Under this condition, the AQD systems will continue to release the most recent traffic status as “message” displayed on the PDMS until additional 1-minute average speeds are obtained. These time durations are set based on engineering judgments.

Figure 4.1 presents one day of sample data from each of the four test sites, which the instantaneous speed measured at the taper of the work zone as a function of time of day. Specifically, the left y-axis in Figure 4.1 represents the average speed detected at the work zone taper area. The dots are raw speed data at 1-min intervals, and the 3-min rolling average is calculated, as indicated in the black line. According to the AQD systems providers at this site (e.g., Salander), the 3-min rolling average speed is used to feed in the PDMS with the corresponding message (i.e., STAR, SLOW, and STOP) indicating the traffic status in work zone.

It should be noted that, at the Big Springs test site, the speed below 20 mph (instead of a typical 25 mph) is defined as stop traffic, and the slow traffic is when speed is between 20 mph and 45 mph. However, the rest three of the test sites follow the typical NDOT AQD systems settings, which adopted speed thresholds of 25 mph and 45 mph for defining the “STOP” and “SLOW” traffic conditions at work zones, respectively.

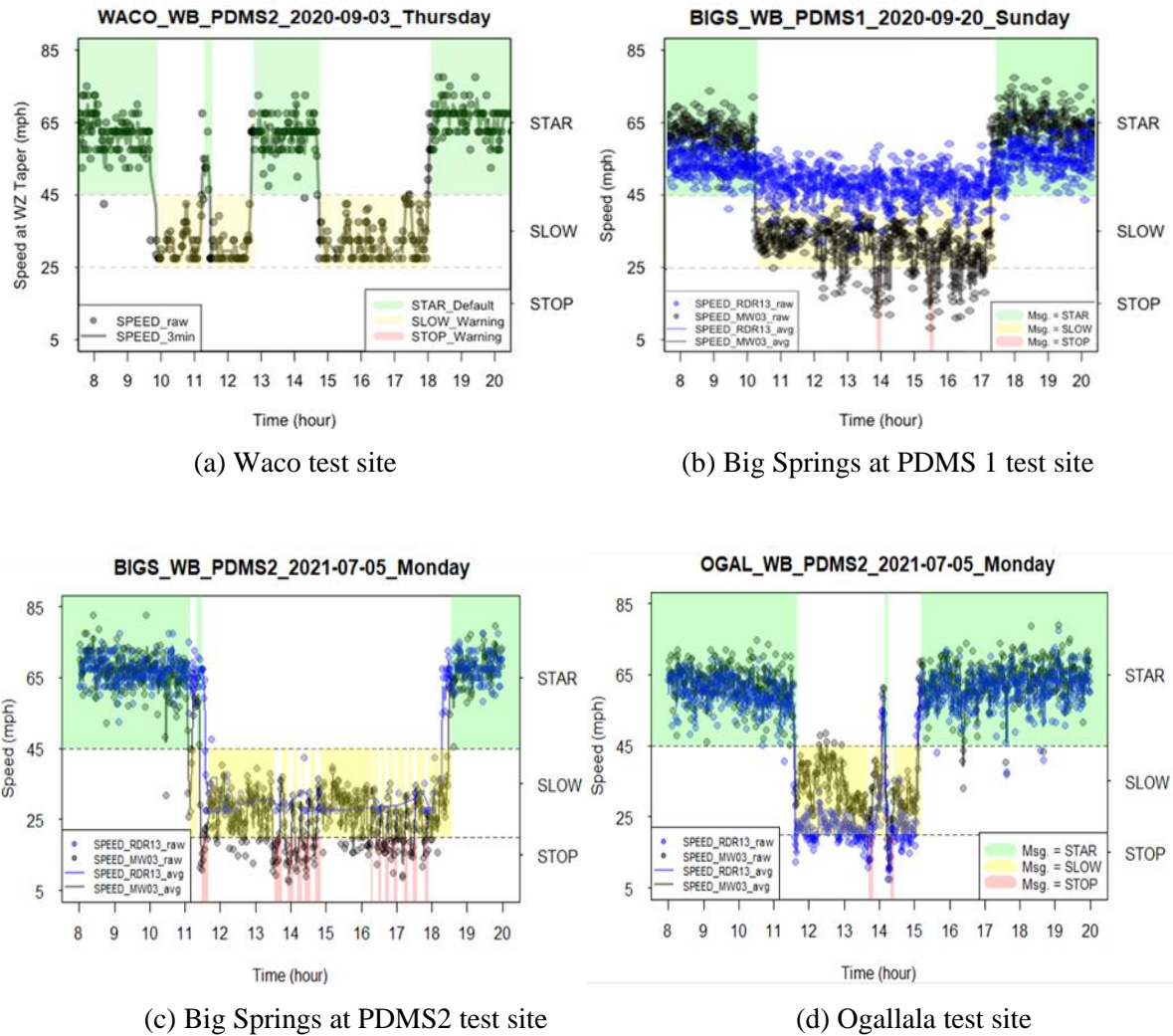


Figure 4.1 AQD speed and warning message data

The right y-axis in Figure 4.1 represents the message posted on the PDMS, which the green color represents the message of four “stars” at each corner of the PDMS (short for “STAR”); the yellow color represents the message of “Slow Traffic Ahead, Slow Down” (short for “SLOW”); and the red color represents the message of “Stopped Traffic Ahead, Prepare to Stop” (short for “STOP”).

Statistical summaries and conclusions regarding the AQD system error are the evidence to the first objective of this project, which will be presented in the Results in Chapter 7.

## 4.2. Travel Time Measure

To verify the AQD system was operating correctly, segment travel time data at the Waco and Big Springs test sites were collected by the research team. The five Miovision Scouts record the MAC address of vehicles traveling through them. Therefore, travel time in four road segments can be obtained. They are Segment 12, Segment 23, Segment 34, and Segment 45 (e.g., Segment 12 measures from Miovision Scout 1 to Miovision 2). As an example, travel time measured at the Waco test site on September 9, 2020, is shown in Figure 4.2.

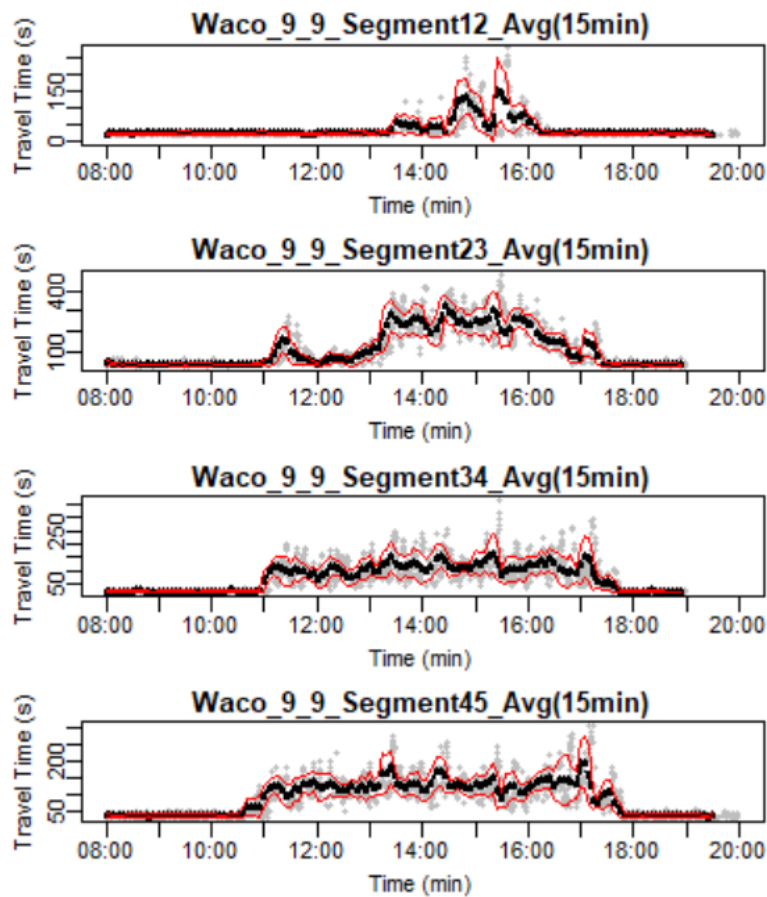


Figure 4.2. Travel time of vehicles (grey dots), 15 min average (black dashed line) with the standard deviation (red lines).

The algorithm of data cleaning and MAC address matching is constructed in three steps as described below. Codes can be found in Appendix A.

- The first step was to match MAC addresses across the different Miovision units. When a match was found, the time difference was calculated. Using the known distances and the time difference, the travel time and space mean speeds between Miovision unit locations were estimated. The MAC address matching algorithm was programmed using the R statistical software package.
- In the second step, the resulting segment travel times were verified by manually matching randomly chosen vehicles from the cameras at each station. The video footage was played at a rate of 1/100 seconds, and a well-trained assistant identified a sampling of vehicles and then recorded the moment when a given vehicle from the sample passed each Miovision station. In addition, the video from the camera was used to visually verify vehicle types, speed reductions, precipitation conditions, and queuing conditions, on an “as needed” basis.
- Once the samples of segment speeds were obtained, they were correlated to the messages being displayed on the PDMS. The goal was to identify whether drivers were responding to the messages (e.g., reducing their space mean speeds downstream of the PDMS units) and, if so, whether these reductions were statistically significant.

### 4.3. Travel Time Data Validation

Miovision units collected the MAC address of vehicles and the timestamp when it travels through their detection range and video footage at each unit. The MAC address is unique to each vehicle. Algorithms are set up to clear the raw data and filter out outliers. Matching MAC address between two successive Miovision units and the time difference is the travel time on the segment. Video footage is used to verify the travel time calculation and check traffic status if any abnormal data were obtained.

The camera at each Miovision Scout location recorded footage during the data collection time. Videos were used to verify the validity of the travel time automatically measured by the MAC address matching. Figure 4.3 and Figure 4.4 show the travel time obtained by automatically matching the MAC addresses (i.e., grey color) and the travel time obtained by manually checking the corresponding video (i.e., blue color) for uncongested and congested traffic conditions, respectively.

Note that September 9, 2020, at the Waco test site, is selected as an example to show the travel time patterns of the day as the queue accumulated. Unfortunately, the camera of the Miovision Scout 1 was not functioning during the data collection, therefore, the comparison of the Segment 12 was missing in Figure 4.4.

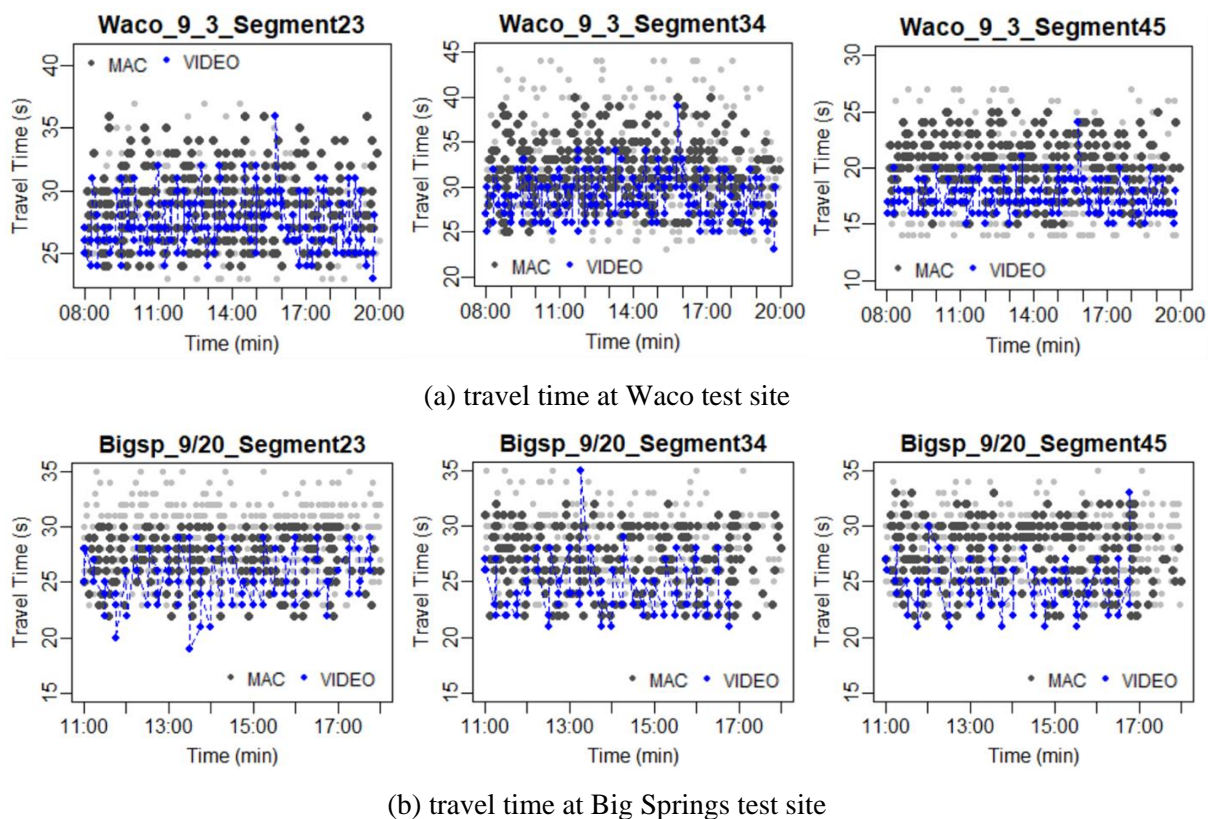


Figure 4.3. Travel time obtained by MAC matching vs manual observation – no queue.

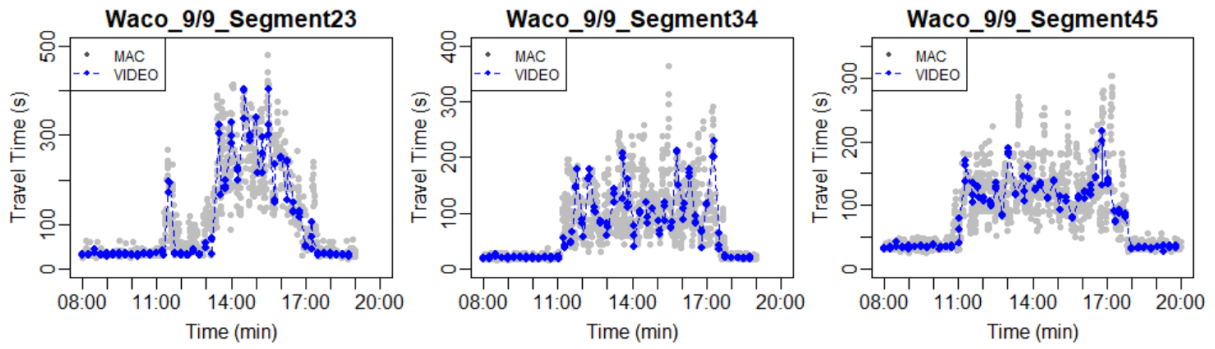


Figure 4.4. Travel time obtained by MAC matching vs manual observation – with queues.

The accuracy of travel times obtained from the MAC data were manually validated using three days of video data collected from three test sites. Figure 4.4 shows the relationship between travel time and time of day for three segments (Segments 23, Segment 34, and Segment 45) on the Waco-Utica test site for September 9, 2020. are shown in Figure 4.4. Unfortunately, the manual travel time on Segment 12 could not be obtained because the camera at Station 1 had technical issues during the data collection period. The grey dots represent the vehicle travel times estimated using the matching algorithm with MAC address data input from the Miovision Scout devices. A total of 2216, 2640, and 2363 travel times were obtained for Segments 23, 34, and 45, respectively. The blue dots represent the manual travel times, which were collected by randomly selecting three vehicles during every 15-min interval and estimating their travel times as described earlier. For this example, a total of 144 vehicles during the data collection period (e.g., 8 am - 8 pm) were matched using the video data.

It may be seen from Figure 4.4 that traffic at I-80 around the tested PDMS was relatively congested. More importantly, it may be seen that the vehicle travel times developed from the MAC addresses and those developed manually track each other relatively well in that both capture the variability in travel time as a function of time of day. Intuitively, if the mean travel time as a function of time of day from one system was considerably higher or lower than from the other system, it would indicate a discrepancy in one of the systems.

While the travel time data passed the visual test, it was important to test whether there were statistical differences in the data. A Shapiro-Wilk of normality (significant level = 0.05) was conducted. It indicated the travel times were not normally distributed. Therefore, a non-parametric two-samples Wilcoxon rank test was used to compare the distributions of the travel time obtained from the MAC address and Video for each segment. The p-values from the Wilcoxon test for Segment 23, Segment 34, and Segment 45 are 0.168, 0.249, 0.490, respectively. These are greater than the significance level for  $\alpha = 0.05$ . Therefore, it was concluded that for this site the travel times derived from the MAC process and that from the manual process are not statistically different.

Note that the same statistical comparison procedure was followed using data obtained from September 3, 2020, at the Waco-Utica test site and from September 20, 2020, at the Big Springs test site. These sites did not experience congestion. It was found the differences in the travel time

distribution derived from the MAC addresses and the travel time distributions derived manually from the video were not statistically different at the 5% level of confidence. Specifically, Welch Two Sample t-test is conducted to test the following null hypothesis:

*H<sub>0</sub>: true difference in means between the travel time obtained using MAC and the travel time obtained manually is equal to 0.*

Thus, the alternative hypothesis is that the true difference in means is not equal to 0, with the significance level alpha = 0.05. Statistic results are shown in Table 4.1 for the Waco-Utica test site and in Table 4.2 for the Big Springs test site, respectively.

Table 4.1 t-test of the travel time at Waco-Utica on Sep. 3<sup>rd</sup>, 2020

	Segment_23		Segment_34		Segment_45	
	MAC Match	Video Observation	MAC Match	Video Observation	MAC Match	Video Observation
Mean (s)	28.7	27.4	31.5	28.8	20.1	17.4
Adjust (s)	-1	0	-2.5	0	-2.5	0
t statistic	1.3959		0.96077		0.32433	
df	323.8		316.69		401	
p-value	0.1637		0.3374		0.7459	
95% CI	(-0.139, 0.816)		(-0.280, 0.815)		(-0.288, 0.401)	

Table 4.2 t-test of the travel time at Big Springs on Sep. 20th, 2020

	Segment_23		Segment_34		Segment_45	
	MAC Match	Video Observation	MAC Match	Video Observation	MAC Match	Video Observation
Mean (s)	26.7	25.4	27.1	24.5	27.7	24.7
Adjust (s)	-1	0	-2.5	0	-2.5	0
t statistic	1.2776		0.18215		1.7991	
df	86.178		73.069		73.011	
p-value	0.2048		0.856		0.07613	
95% CI	(-0.182, 0.839)		(-0.538, 0.646)		(-0.054, 1.055)	

Based on the above analyses, the larger and more comprehensive travel time data set from the Miovision system was used for all further analyses. Note that it would be simply too expensive to replicate the manual travel time process on a large scale. This was why the automatic data collection system was used to collect travel times and the manually calculated times were used only to validate the accuracy of the automatic system.

#### 4.4. Speed Reduction

The Waco test site, September 3, 2020, was selected for data analysis on the speed reduction because there was slow-moving traffic at work zones. On this day, there were 7 periods that the PDMS was activated and a “SLOW TRAFFIC AHEAD, SLOW DOWN” message (short for “SLOW”) was posted on the PDMS. During the PDMS activation periods, the number of vehicles that traveled through the road segments where the Miovision sensors were installed was extracted. The start and end times of the 7 periods of the “SLOW” message and the corresponding vehicles are provided in Table 4.3.

Table 4.3 Waco Sep. 3<sup>rd</sup>, 2020 PDMS activation periods and vehicles captured

No	Message	Start time	End time	Duration (minutes)	Number of vehicles captured			
					Segment_12	Segment_23	Segment_34	Segment_45
1	SLOW	9:52	10:09	17	15	12	23	52
2	SLOW	10:11	11:18	67	67	46	81	209
3	SLOW	11:32	12:46	74	87	68	105	289
4	SLOW	14:47	15:11	24	20	16	28	86
5	SLOW	15:15	16:31	76	75	55	93	279
6	SLOW	16:32	17:03	31	62	23	41	76
7	SLOW	17:05	18:06	61	76	43	83	280
Total				350	402	263	454	1271

The travel time of each vehicle is obtained. The distances of Segment\_12, Segment\_23, Segment\_34, and Segment\_45 are 2112 ft, 2981 ft, 2998 ft, and 1856 ft, respectively. Hence, a vehicle’s travel speed can be calculated. The travel speed before and after the PDMS for the seven activation periods is shown in Figure 4.5. It should be noted that the Miovision travel times were measured at the PDMS which is 3 miles away from where the queue was not reached to the detection segments.

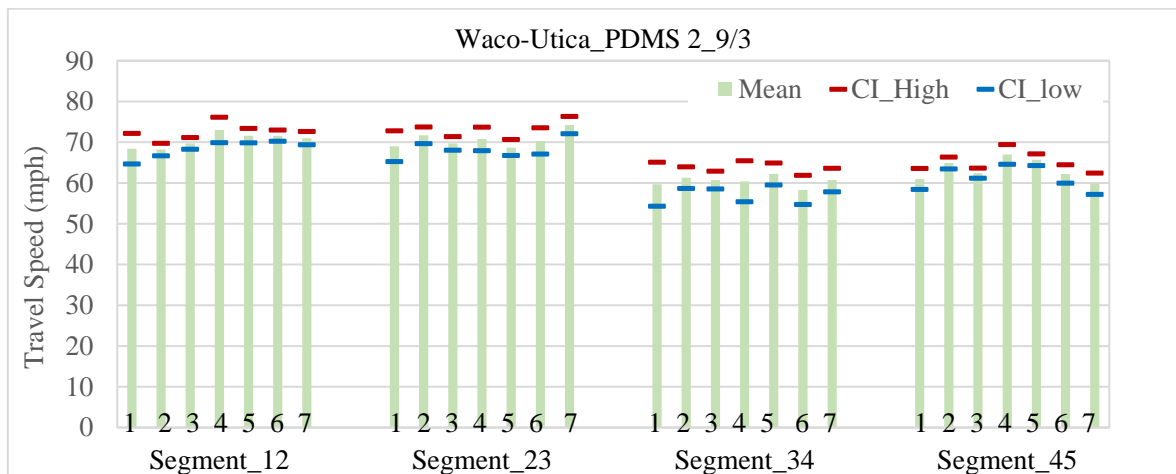


Figure 4.5. Travel time in different road segments at Waco-Utica



Similarly, data collected on October 11, 2020, at Big Springs (PDMS 1) was selected for speed analysis at this test site. On this day, there are 3 periods that the PDMS was activated and a “SLOW TRAFFIC AHEAD, SLOW DOWN” message (short for “SLOW”) was posted on the PDMS. During the PDMS activation periods, the number of vehicles that traveled through the road segments where the Miovision sensors were installed was extracted. The start and end times of the 3 periods of the “SLOW” message and the corresponding vehicles are provided in Table 4.4.

Table 4.4 PDMS activation periods and samples at Big Springs test site on Oct. 11, 2020

No	Message	Start time	Start time	Duration (minutes)	Number of vehicles captured			
					Segment_12	Segment_23	Segment_34	Segment_45
1	SLOW	7:33	7:39	6	0	0	0	0
2	SLOW	15:16	17:15	119	150	89	151	381
3	SLOW	19:09	19:24	15	6	7	13	10
Total				140	156	96	164	391

The travel time of each vehicle passing through the PDMS 1 at Big Springs was obtained. The Miovision stations at the Big Springs test site were equally spaced at a distance of 0.5-mile when attaching the device to the roadside mile-markers. Therefore, the distances of Segment\_12, Segment\_23, Segment\_34, and Segment\_45 are all 2640 ft. The travel speed before and after the PDMS for the seven activation periods is shown in Figure 4.6.

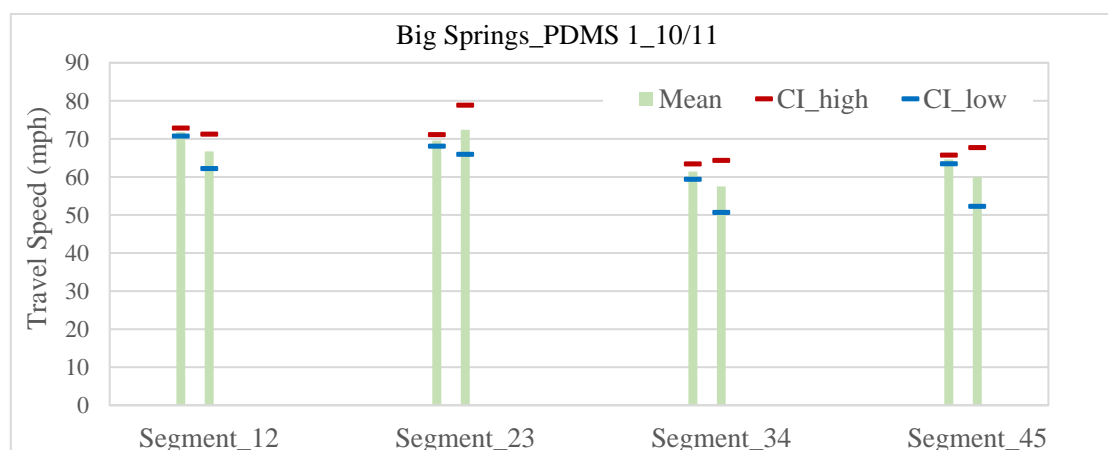


Figure 4.6. Travel time in different road segments at Big Springs

It should be noted that the data processing for data collected in Phase 2 (on July 5<sup>th</sup>, 2021) at Big Springs and Ogallala test sites follows the same procedure as that in Phase 1. The statistical results of the speed reduction at different test sites are evidence of the second objective of this project, which will be summarized and discussed in the Results in Chapter 7.

## 5. CRASH ANALYSIS

The purpose of the crash analysis was to compare crash data from the freeway work zones where the AQD systems are operational to those work zones that are not equipped with AQD systems. The hypothesis was that the frequency of crashes, and in particular rear-end crashes, will be significantly reduced when the AQD system is installed. Unfortunately, due to the lack of sample size and missing information (e.g., the time and location of the AQD systems), the crash models are developed using the crash data from all work zones (without differentiating the AQD work zones) on I-80 to study the characteristics of work zone crashes in Nebraska.

It should be noted that when the sample size of crashes at AQD equipped work zones becomes large and readily available, the methods used in this section can be easily repeated, and the results can be compared to those traditional work zones (i.e., without AQD systems) to verify the effectiveness of AQD systems in safety improvement at freeway work zones.

### 5.1. Work Zone Areas

The Manual on Uniform Traffic Control Devices (MUTCD, 2009) divided the temporary traffic control zone, i.e., the work zone, into four areas in the traffic direction: (1) advance warning area, (2) transition area, (3) activity area, including a buffer space and a workspace, and (4) termination area. These four areas can be found in Figure 5.1.

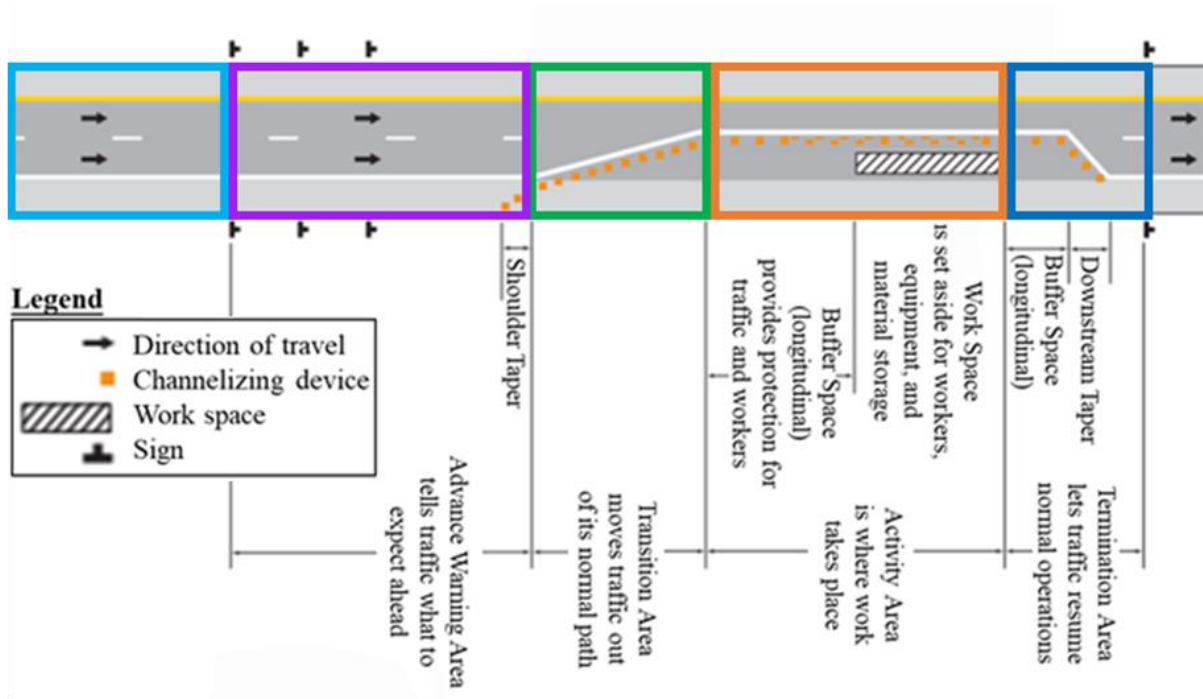


Figure 5.1 Component Parts of a Temporary Traffic Control Zone (MUTCD 6C-1).

According to the accident locations in the work zone, there are five areas that a crash is recorded in the NDOT crash dataset, which are (1) the area before the first sign of the work zone; (2) the advance

warning area, which starts at the first message sign of work zone ahead and ends at the start of the lane taper; (3) the transition area, which covers the lane taper of work zone merging; (4) the activity area, which starts from the end of lane taper to the end of the workspace; (5) the termination area; which starts at the end of workspace and ends at the last message sign of work zone. These five areas are marked as A to E in the model for simplicity purposes, which is shown in Figure 5.2.

- A - area before the first sign,
- B - advance warning area,
- C - transition area,
- D - activity area, and
- E - termination area.

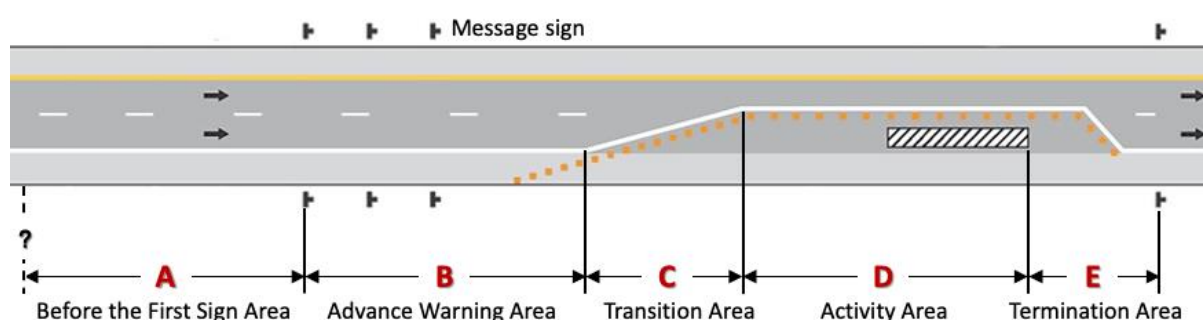


Figure 5.2. The five areas that a crash takes place in a work zone in the NDOT crash dataset

Note that it was assumed that the NDOT crash dataset has the same definition as the MUTCD for B to E areas, as can be seen in Figure 5.1. However, the start point of the first area A was not defined anywhere. It was assumed that the “before the first sign” area, labeled in the NDOT crash dataset, covers the road segment that is close to the work zone. Whether the crash occurrence location is associated with area A, depends on the judgment of the police officer who filled the crash report form. A reasonable guess for the distance of the “before the first sign” area is the sight distance from upstream (indicated as the question mark in Figure 5.2) to the first warning sign where drivers are noticed with work zone ahead for the first time.

## 5.2. Work Zone Crashes

NDOT traffic crash data used in this study ranged from 2002 to 2020. Crashes that occurred on the I-80 work zone are extracted, as indicated in Figure 5.3 (crashes are marked as red points). As expected, most of the crashes occurred near the urban area (e.g., City of Omaha, City of Lincoln).

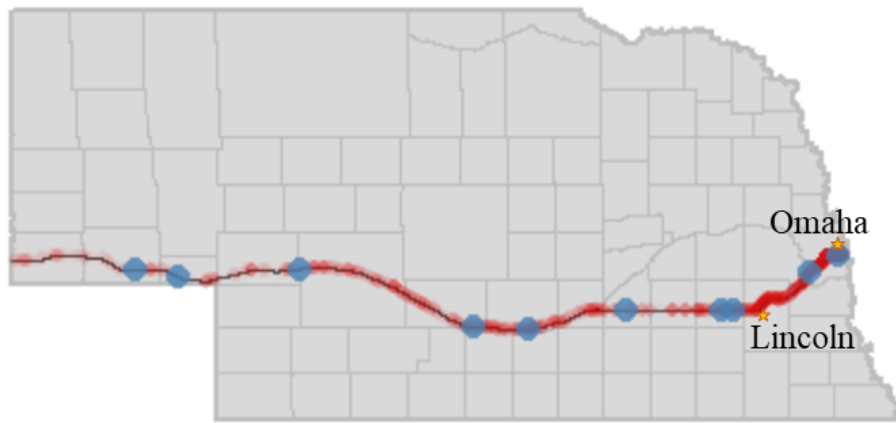


Figure 5.3 I-80 work zone crashes from 2002 to 2020 (denoted by red points). Blue points are the NDOT automatic traffic recorder (ATR) locations.

In the 19 years NDOT crash dataset, 3095 crashes occurred in work zones. The distribution of the crashes locations in the five areas is shown in Figure 5.4. Note among the five areas, A and B are areas that the PDMS may be installed in an IWZ system.

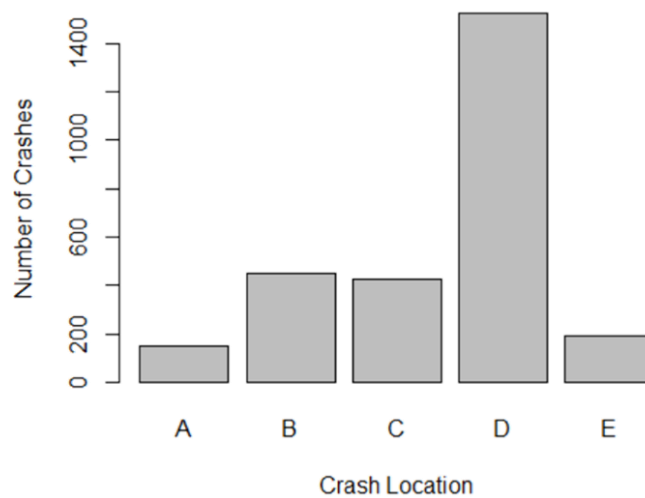


Figure 5.4 Crash locations in the five work zone areas

Meanwhile, the proportion of crashes locations in the five work zone areas is shown in the first pie chart in Figure 5.5. Other types of the composition of the work zone crashes are also shown in Figure 5.5. Specifically, the proportion of injuries is 71% for non-injury crashes, 18% for one injury crashes, and the rest 11% crashes are for two or more injuries. Also, the crashes are grouped according to their severity, from property damage only (54%), different levels of injury, all the way to fatal (2%). For the freeway crashes involving two vehicles, the main types are rear-end crashes (41%) resulting from car-following behavior and sideswipe (25%) resulting from, for example, lane-changing behavior.

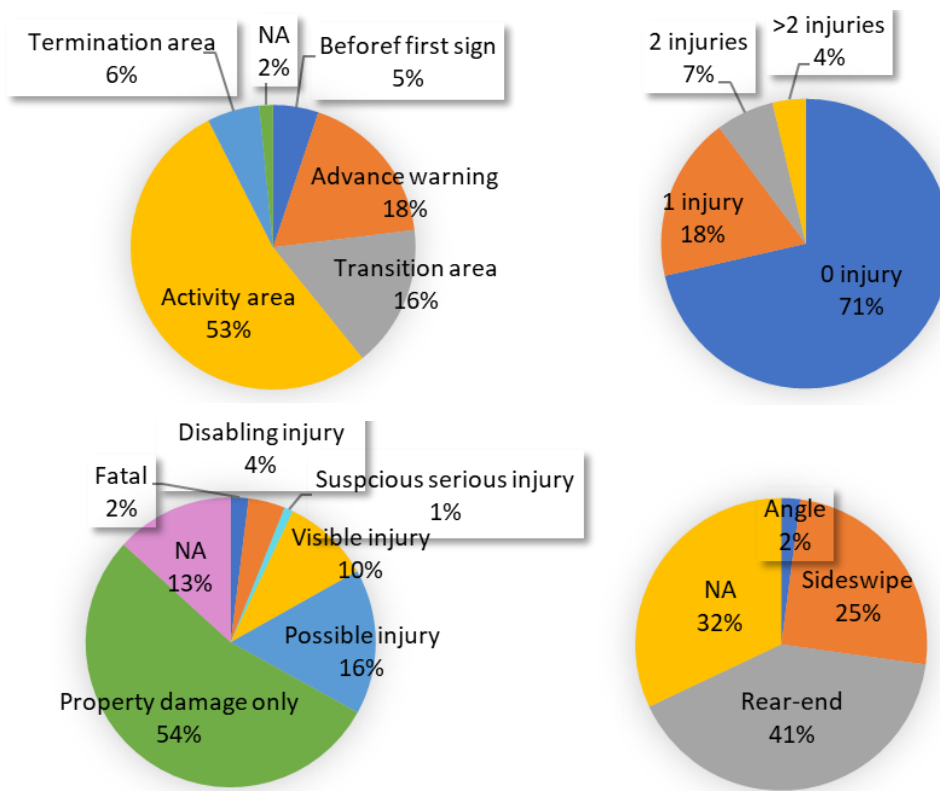


Figure 5.5 Crash composition (3095 crash samples from 2002 to 2020)

The temporal distributions of crashes, i.e., year, month of year, day of week, and hour of day, are shown in Figure 5.6.

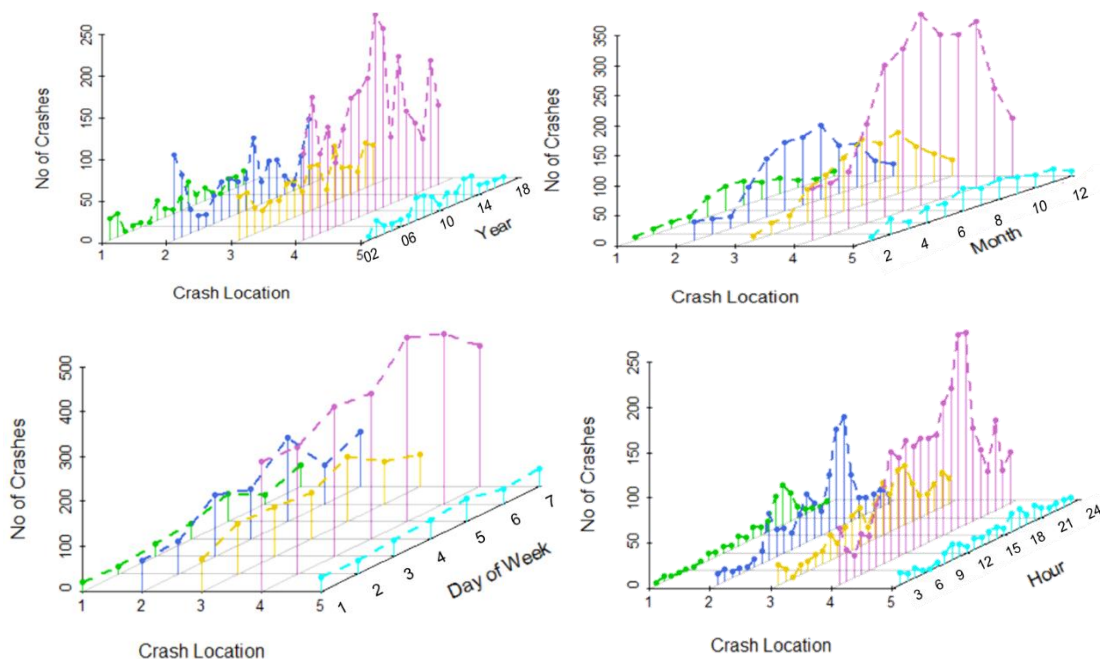


Figure 5.6 Distribution of the crashes from 2002 to 2020. Note crash location 1 – 5 represents work zone area A – E, respectively.

As can be seen in Figure 5.6, despite escalating safety measures at Interstate WZ, traffic crashes did not continuously decrease but fluctuated over years. Crashes increased in construction activity seasons of the year, usually from April to October in Nebraska. In addition, Fridays and afternoon rush hours (4-6 PM) are those times when crashes are more frequent.

### 5.3. Variable Selection

Considering the sample size, data in each category is divided into limited levels for each variable used in the model, as listed below.

- Six types of traffic accidents in the crash records are grouped into three levels according to their severity: 1) property damage only, which includes no people are injured, 2) minor injury, which includes possible injury and visible injury, and 3) serious injury, which includes suspicious serious injury and fatal.
- The crash type is categorized into sideswipe and rear-end types.
- The crash location is grouped into urban (including municipal) and rural areas.
- The crash time is labeled either on a weekday or a weekend.
- Driving behavior is grouped into either normal driving, which is labeled as no improper driving in the crash report, or improper driving such as driving distracted, driving too fast, followed too closely, operating vehicles erratically, etc.
- Driver age is grouped into 25 years or younger, between 25 and 65 years, and 65 years or older.
- Vehicle type is divided into passenger cars, which include sedan, van, and motorcycle, and pickup truck; and large trucks, which include single-unit truck, truck trailer, and multi-unit truck trailer, etc.
- Light conditions are divided into daylight which illuminates with natural light, and darkness (including dark, dawn, and dusk) that may illuminate with auxiliary light.
- Weather conditions are labeled as favorable weather (e.g., clear and cloudy) and adverse weather (e.g., fog, rain, snow, etc.).

The variable selection is conducted using the random forest method. In total, of the 33 variables examined, there are 18 variables that showed importance on both MSE and Node Purity, as can be seen in Figure 5.7. These variables generally cover six types of data, which are:

- Road condition: road class, number of lanes, road grade, pavement type, median type
- Traffic condition: speed limit, AADT
- Vehicle condition: vehicle type, airbag ejection, total vehicles and trucks involved
- Driver condition: driver age, mental condition
- Environmental condition: weather, light
- Work Zone condition: WZ area, WZ type, WZ person present

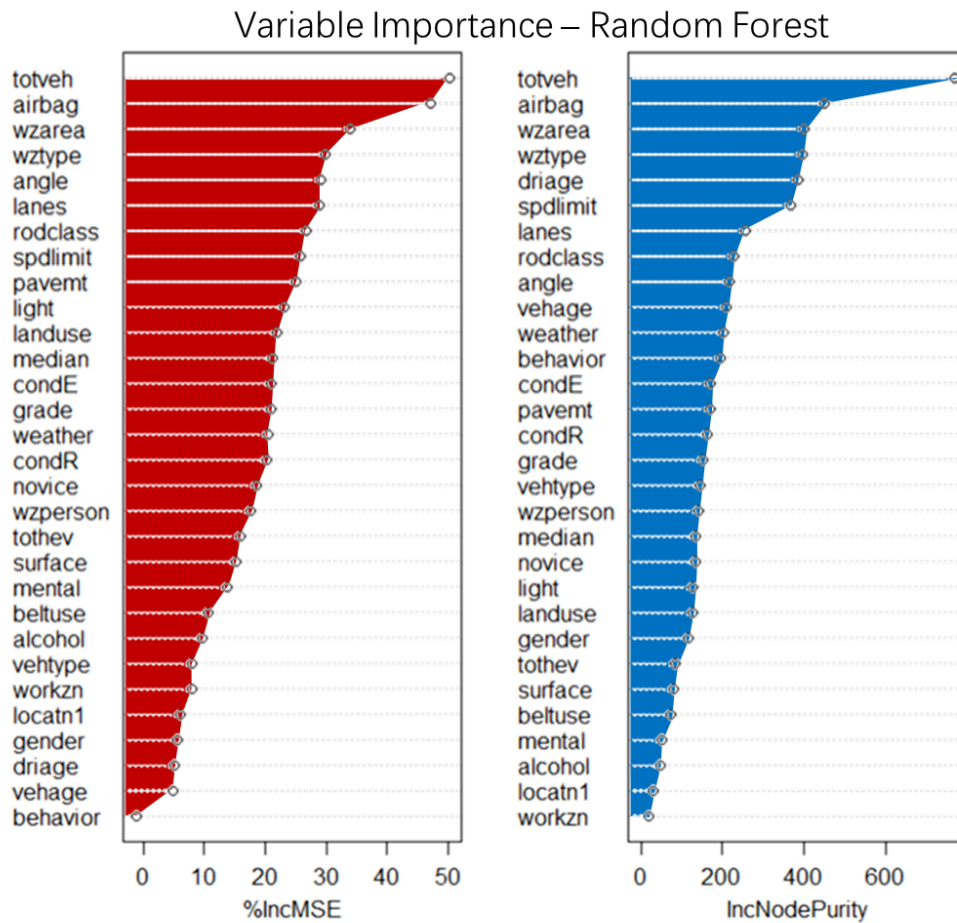


Figure 5.7 Variable selection for crash modeling

All the selected variables are used in developing the crash models, given different model structures, which will be described in the next section.

#### 5.4. Model Development

Firstly, a Generalized Linear Model (GLM) is used to estimate the number of injuries as a function of various contributory factors such as traffic conditions, road conditions, driver conditions, and vehicle conditions. The factor “work zone areas” (i.e., approaching advance warning area, transition area, activation area, termination area) where the crash occurred act as a “moderator” or an intersection term in the GLM model.

Second, an Ordinal Logistic Regression (OLR) is used to estimate the crash severity, which is categorized into No injury, Minor injury, and Sever injury. Similarly, the work zone area is an intersection of the selected contributory factors in the OLR model.

Model results and conclusions regarding the crash data on all the Nebraska I-80 work zones will be presented in the Results in Chapter 7.

## 6. COVID IMPACT

Since the first case reported at the end of January 2020, coronavirus disease 2019 (COVID) has been swept across the United States and abroad. This still ongoing pandemic is unprecedented in modern history. Its impact is not only measured by the number of cases and deaths, but also overloaded health services, undesirable quality of life, and interrupted social and economic activities. In response to this public health crisis, the states responded quickly to formulate and enact various appropriate orders. Without exception, these orders were designed to discourage non-essential travel, practice social distancing, and ultimately expect to slow down the spread of the virus.

To this end, Nebraska issued a series of policies to restrain the spread of the pandemic. Rather than implement a statewide stay-at-home order, Nebraska employed a framework named "Directed Health Measures" (DHM) to minimize in-person interactions during COVID in 2020 [Nebraska DHHS, 2020]. As anti-epidemic strategies, DHM benefits from its flexibility that they were phased in the county by county based on active infections. It is, therefore, hypothesized to affect the population of the jurisdictional counties at different stages. Specifically, the critical timeline for the affected population is below.

- 3/19, 2020 – 41.5% affected – 3 counties: Douglas, Cass, Sarpy
- 3/25, 2020 – 62.3% affected – 4 counties: Lancaster, Dodge, Saunders, Washington
- 4/03, 2020 – 100% affected – All counties
- 5/31, 2020 – 0% affected – All DHM lifted

The immediate impact of the DHM intervention was a sharp drop in traffic demand on I-80. Because of this, the number of traffic crashes has decreased, especially at those I-80 work zones. Figure 6.1 shows the crash locations (marked as yellow dots). For example, there were 57 crashes that occurred at I-80 work zones in the first half of 2020 (week 1 to week 27), which is more than twice lower than the number of crashes that occurred during the same period in 2018 (crashes = 108) and 2019 (crashes = 132).

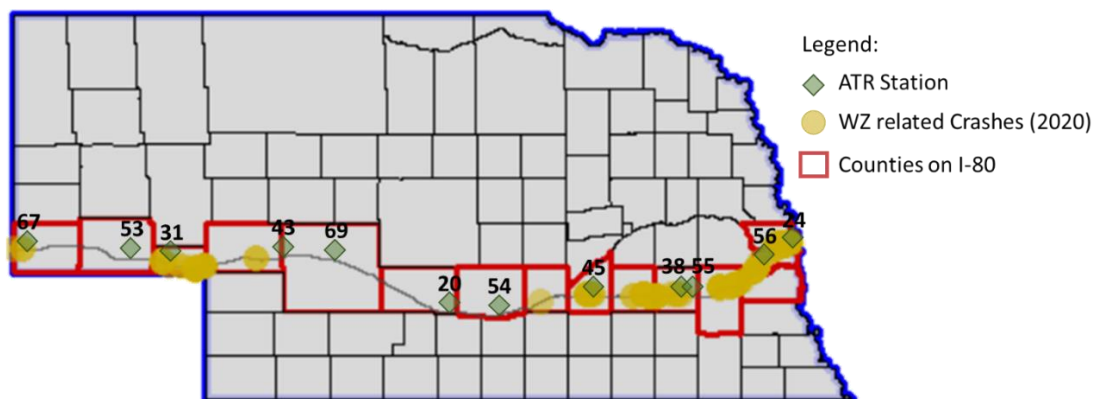


Figure 6.1 Traffic crashes at I-80 Work Zones in 2020. ATR numbers are marked. I-80 runs through fifteen counties that are shown.



To know the impact of COVID restrictions on essential travels. Traffic volumes on Interstate 80 are collected at the NDOT Automatic Traffic Recorder (ATR) stations, as can be seen in Figure 6.1. It is hypothesized that these ten ATR measure the traffic demands of I-80 in both urban areas and rural areas in Nebraska.

### 6.1. The Impact on Traffic Volumes and Traffic Crashes

Figure 6.2 (a) shows the weekly traffic volume, accumulated using all the ten ATR data, as a function of time from Week 1 to Week 27 in 2020. As for comparisons, traffic volumes are identified using the same period of data in 2018 and 2019.

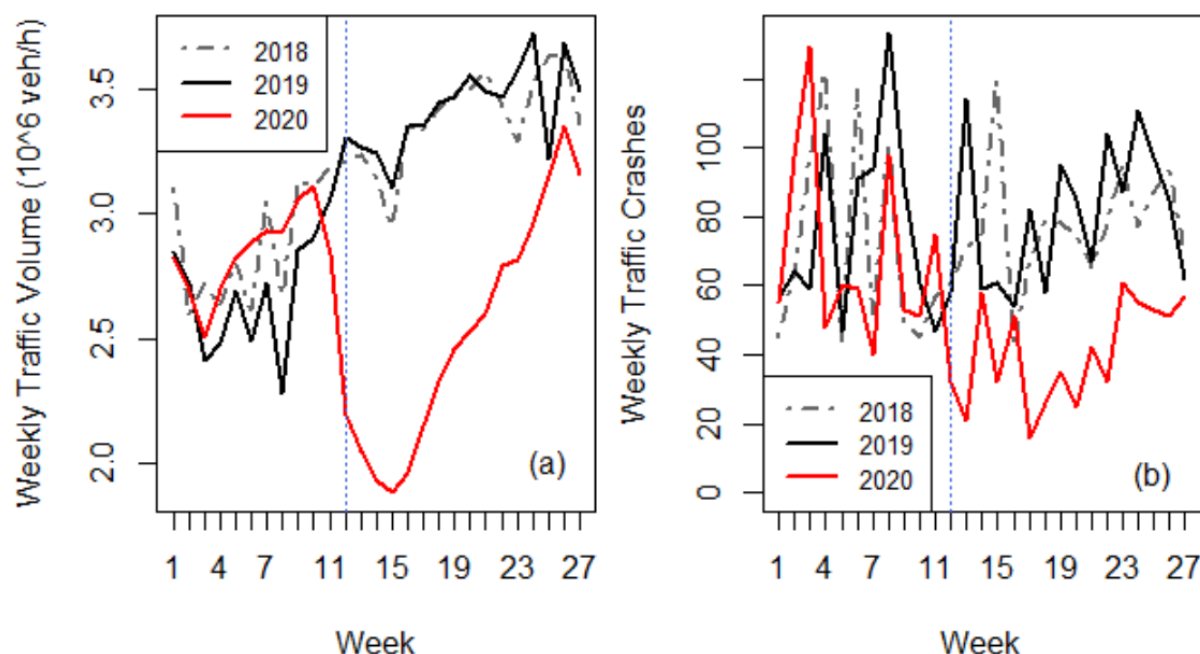


Figure 6.2 Traffic volume and the crashes as a function of the week in 2020, and the comparison to the similar period in 2018 and 2019.

As can be seen in Figure 6.2 (a), the overall trends of the weekly traffic volume for 2018 and 2019 consistently increase, while the volume for 2020 drastically dropped and then rebounded. Specifically, traffic volume in 2020 (1) was seen a significant decrease starting from Week 9, (2) kept reducing about 7 weeks (Week 9 -15), at the time when the entire Nebraska counties were put into DHM restrictions, (3) reached the lowest on Week 15 (i.e., 30%-35% lower compared to the levels of 2018 and 2019), and (4) continued to rebound since after. Until Week 22 when all the DHM are lifted, traffic volume had returned to about 85% of its full capacity, compared to the traffic levels at the same time in 2018 and 2019. Note that it took 4 more weeks (week 23-27) for the traffic volume in 2020 to get back to roughly similar levels (as of 2018 and 2019), presumably due to residual fears after the reopening of the community (Ghader et al., 2020),

Naturally, the week of March 19, 2020, when the Nebraska governor's first major DHM intervention was implemented, as marked by the blue dot line in Figure 6.2, cuts the 27 weeks (7 days a week) into 11 weeks pre-intervention and 16 weeks post-intervention. As comparison groups, data are prepared using the same treatment as if the DHM order was issued on March 19 (Week 12) in 2018 and 2019.

Figure 6.2 (b) shows the number of weekly crashes in 2018, 2019, and 2020. They were at a similar level during the pre-COVID intervention period (i.e., Week 1 to Week 11). During the post-COVID intervention period (i.e., Week 12 to Week 27), the number of weekly crashes in 2018 and 2019 maintained a slight increase, while decreasing in 2020.

Statistical test results show that there are no statistically significant differences in the number of crash counts between 2018 and 2019. This implies that the traffic crash pattern did not change over a year. Thus, it may be safe to assume that if there was no special event, the traffic crash pattern will remain the same from 2019 to 2020. However, when compared the number of weekly crashes in 2020 to 2019, it was significantly lower at a 5% significance level (t-stat = 4.028,  $p < 0.001$ ). It is hypothesized that the reduction in the number of crashes is a result of the impact of COVID interventions.

A count of the number of crashes is often inadequate when comparing multiple roadways of varying levels of traffic exposure. Based on the assumption that the more exposure to road traffic, the greater chances a crash occurs, this study used crash rate as an effective metric for relative safety measures when it is exposed to traffic at a given location. The crash rate is defined as the quotation of crash frequency (crashes per week) and vehicle exposure (e.g., traffic volumes) at the location where the crashes occurred. (6.1 shows the calculation of the crash rate defined in this study.

$$r_{c,i} = 10^6 * \frac{\sum_{d \in i} N_{c,l,d}(t)}{\sum_{d \in i} V_{c,\tilde{l},d}(t-1)} \quad (6.1)$$

Where  $r_{c,i}$  represents the crash rate for a certain category  $c$  of interest at week  $i$ .  $N_{c,d(t)}$  represents the number of crashes for a certain category  $c$  of interest occurred at location  $l$  and on date  $d$  associated with a specific hour  $t$ .  $V_{c,d(t-1)}$  represents the traffic volume, veh/h, on hour  $(t-1)$  of date  $d$  at location  $\tilde{l}$ , the nearest ATR station on I-80. To facilitate the readability and interpretability of the model outcome, the crash rate is calculated per million vehicles, indicating the number of crashes that occurred per  $10^6$  traffic volume exposure.

## 6.2. Crash Modeling under COVID Influence

The purpose of this study is to understand the influence of the COVID restrictive interventions implemented in Nebraska (i.e., phased DHM) on the rate of traffic crashes that occurred on I-80. To this end, the changes of distributive patterns of crash rates and the main contributing factors are modeled

using the comparative interrupted time series (CTIS) method. Specifically, the CTIS model is applied to evaluate the impacts of COVID by looking at whether the treatment group deviates from its “baseline” by a significant amount than the comparison group. In other words, in developing the CITS model of the 2020 crash data, crash data in 2019 are used as the baseline. The CITS can be specified in Equation (6.2).

$$Y_i = \beta_0 + \beta_1 T + \beta_2 D_i + \beta_3 T * D_i + \beta_4 P + \beta_5 T * P + \beta_6 D_i * P + \beta_7 T * D_i * P + \varepsilon_i \quad (6.2)$$

Where,

$Y_i$	Outcome of interest at time $i$ (i.e., crash rate per million veh/h for the week $i$ )
$T$	Continuous variable representing time by week
$D_i$	Dummy variable indicating untreated and treated groups, i.e., prior (code = 0) and post (code = 1) enact of the DHM intervention.
$P$	Categorical variable indicating the comparison year or treatment year (i.e., 2018, 2019, or 2020).
$\varepsilon_i$	Error term capturing the residual variation not explained by time

In this study,  $\beta_0$  is the interception that represents the initial level of the outcome.  $\beta_1$  is the pre-intervention slope.  $\beta_2$  is the immediate level change when the intervention is issued.  $\beta_3$  is the sustained trend change which is the difference in slopes between pre-intervention and post-intervention.  $\beta_4 - \beta_7$ , represents similar meaning as  $\beta_0 - \beta_3$ , respectively, except the comparison group data, is referred to as the baseline. In other words,  $\beta_0 - \beta_3$  are coefficients describing the initial level, pre-intervention trend, immediate effect, and sustained effect for the comparison group (crash data in 2018, 2019), while  $\beta_4 - \beta_7$  are coefficients indicating the differences of the initial level, pre-intervention trend, immediate effect, and sustained effect between the treated group and the comparison group, respectively. In this regard, the interested coefficients are  $\beta_6$  and  $\beta_7$ .

Some hypotheses are made beforehand. For example, reports speculated that traffic crashes have become severer during the pandemic (Camille Kamga et al., 2020; Vingilis et al., 2020). Given the sharply reduced traffic demand, which means lane became emptier, both lane-changing and car-following tasks are assumed to be more efficient and less risky. The changes in crash rate patterns may also be reflected in different locations. Intuitively, I-80 through urban areas is mostly affected because the restrictive measures have the greatest impact on the drop of traffic demand. The demand for large trucks to transport essential supplies during COVID may not necessarily decrease, instead, it may increase to meet the supply needs (Maoh and Anderson. 2021). All these hypotheses will be verified through the model output, which will be presented next.

### 6.3. Interpretation of COVID Influence on Traffic Crash

The above concerns are examined through the significance of the factor coefficients of each CITS model. In other words, a significantly positive estimate of the coefficient indicates that this factor is positively correlated with, or has increased, the crash rate, and vice versa. The model outcomes are given in Table 6.1 and are interpreted one by one subsequently.

Table 6.1 Model Results from Crash Rate

Model	Variable	Est.	S.E.	t value	Pr(> t )	Model significance
Serious injury (N=236)	β6:2018	96.6	194.1	0.50	0.620	Residual SE: 0.168 Adjusted R <sup>2</sup> : 0.048 F-statistic: 0.869 p-value: 0.574
	β7:2018	19.3	27.6	0.70	0.487	
	β6:2020	248.9	190.6	1.31	0.196	
	β7:2020	40.4	26.0	1.55	0.125	
Minor injury (N=1440)	β6:2018	38.4	32.5	1.18	0.242	Residual SE: 0.029 Adjusted R <sup>2</sup> : 0.391 F-statistic: 5.66 p-value: <b>2.1e-06</b> ***
	β7:2018	-1.4	4.4	-0.31	0.761	
	β6:2020	61.0	32.5	1.88	0.065`	
	β7:2020	-12.8	4.4	-2.89	0.005**	
Property damage only (N=3593)	β6:2018	28.5	23.1	1.23	0.222	Residual SE: 0.020 Adjusted R <sup>2</sup> : 0.642 F-statistic: 14.05 p-value: <b>1.1e-13</b> ***
	β7:2018	2.3	3.2	0.74	0.460	
	β6:2020	136.1	23.1	5.89	<0.001***	
	β7:2020	-4.9	2.7	-1.82	0.074`	
Rear-end (N=2396)	β6:2018	7.1	22.0	0.32	0.749	Residual SE: 0.019 Adjusted R <sup>2</sup> : 0.456 F-statistic: 7.013 p-value: <b>8.8e-08</b> ***
	β7:2018	-1.4	3.0	-0.48	0.632	
	β6:2020	76.1	22.0	3.46	0.001**	
	β7:2020	-5.5	3.0	-1.83	0.072`	
Rural Area (N=2962)	β6:2018	44.5	27.9	1.59	0.116	Residual SE: 0.025 Adjusted R <sup>2</sup> : 0.498 F-statistic: 8.211 p-value: <b>5.6e-09</b> ***
	β7:2018	2.0	3.8	0.54	0.595	
	β6:2020	129.3	27.9	4.63	<0.001***	
	β7:2020	-5.6	3.8	-1.48	0.144	
Large Truck (N=1824)	β6:2018	18.9	34.5	0.55	0.587	Residual SE: 0.030 Adjusted R <sup>2</sup> : 0.329 F-statistic: 4.557 p-value: <b>3.5e-05</b> ***
	β7:2018	-2.4	4.7	-0.51	0.613	
	β6:2020	87.0	34.5	2.52	0.014*	
	β7:2020	-7.1	4.7	-1.52	0.134	

Reference year = 2019. Significant codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '`' 0.1 '`' 1

The significance of the model specification is firstly checked. As shown in the last column in Table 6.1, the model for serious injury crash rate does not show statistical significance (p-value = 0.574), due to the small sample size (N=236 for three years). In addition, model for sideswipe crash is also not significant (p-value = 0.192). Therefore, these two models and the corresponding hypotheses are excluded from this study. The rest of the models are accepted as they all have the lower residual standard error, higher adjusted R-square, higher F-statistic, and p-value below the significance level 0.05.

As shown in Table 6.1, none of the 2018 coefficients in all models, i.e.,  $\beta_6$  for the immediate effect and  $\beta_7$  for the sustained effect, are significant, indicating that there is no significant in crash contributing factors of 2019 compared to 2018. The purpose of examining the historical data in the comparison of 2018 and 2019 is that it provides evidence of the crash trend in Nebraska. It can be assumed that if there is no special event (e.g., COVID pandemic), the crash pattern and distribution in 2020 may not be significantly different compared to 2019.

Importantly, it is found in Table 6.1 that, compared to the previous years, crash rates in 2020 have been greatly altered as a result of the anti-COVID policy intervention. Specifically, each research hypothesis and the corresponding model result are interpreted as below.

- During the COVID intervention, the increase in minor injury crash rate is marginal significant ( $\beta_6 = 61.0$ ,  $p = 0.065$ ), however the trend was decreasing significant ( $\beta_7 = -12.8$ ,  $p = 0.005$ ). similarly, the increase in property damage-only crash rate is significantly increased by the COVID intervention ( $\beta_6 = 136.1$ ,  $p < 0.001$ ) while the increased levels decreased as time passed by ( $\beta_7 = -4.9$ ,  $p = 0.074$ ). Unfortunately, the serious injury crash rate is unclear due to the insufficient sample size. These together indicate that under the intervention of COVID, the severity of the crashes on Nebraska I-80 may or may not have worsened.
- The main affected crash type was the rear-end, which has significantly increased ( $\beta_6 = 76.1$ ,  $p < 0.001$ ) and gradually flat off ( $\beta_7 = -5.5$ ,  $p = 0.072$ ) after the COVID intervention.
- The increases in crash rate levels in rural areas were significant ( $\beta_6 = 129.3$ ,  $p < 0.001$ ) immediately after the COVID intervention is released.
- Large trucks are increased in crash rate levels significantly ( $\beta_6 = 87.0$ ,  $p = 0.014$ ) immediately after the start of the DHM.

The model results can be visually seen in Figure 6.3.

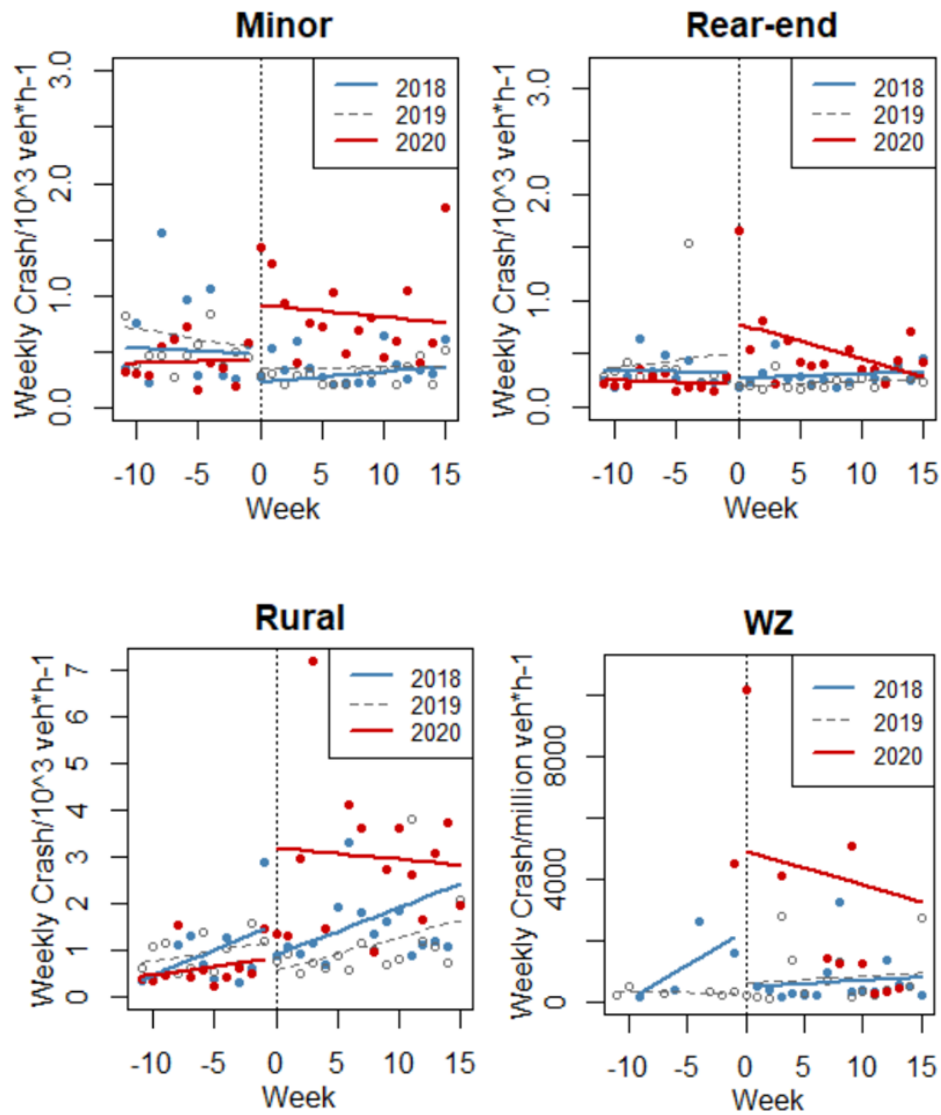


Figure 6.3 Comparisons of CITS model result

In general, results show that the decrease in traffic volumes outpaced the reduction in crashes, resulting in a higher crash rate. Therefore, the COVID intervention, for most cases, increased the crash rate (i.e., positive effects) as concluded from modeling the Nebraska I-80 crash data, rather than lowering the crash rate (i.e., negative effects) as hypothesized based on existing studies.

## 7. RESULTS

Results in response to the three objectives proposed in this project and the correspond discussions are presented below.

### 7.1. Investigate whether the AQD System is Performing Adequately

The error rate of the AQD system was calculated using a week of data (i.e., 10080 minutes) at each test site to study the first objective in this project: *H0: The AQD system displays the correct message within an acceptable range (e.g., X percent of the time).* Table 7.2 summarizes the total error rate and sources of the error rate from different traffic conditions (i.e., free-flow and congested traffic) and under different warning statuses.

Table 7.1 Error rate of the AQD system operation

	Wood River	Ashland	Waco-Utica	Big Springs
Total examined time	10080 min	10080 min	10080 min	10080 min
Total time in SLOW status	333 min	173 min	847 min	227 min
Total time in STOP status	631 min	155 min	0 min	4 min
Total error time (all types)	232 min	166 min	66 min	92 min
Total error rate	2.3%	1.6%	0.7%	0.9%

It can be seen from Table 7.2 that the Wood River test site has the highest error rate (2.3%), and Waco-Utica has the lowest error rate (0.7%). The total error rate may be further disaggregated based on the severity of the error in Table 7.2 and are explained below.

Table 7.2 Source and types of the AQD system errors

	Wood River	Ashland	Waco-Utica	Big Springs
<b>Error in traffic conditions</b>				
Free-flow traffic (Category 1 error)	44.0%	8.7%	97.3%	36.9%
Congested traffic (Category 2 error)	56.0%	91.3%	2.7%	63.1%
Sum	100%	100%	100%	100%
<b>Error in congested traffic condition</b>				
SLOW status	95.4%	88.1%	100%	100%
STOP status	4.6%	11.9%	0%	0%
Sum	100%	100%	100%	100%

For example, at the Wood River test site, 44% of the 2.3% total errors occurs when the work zone experienced free-flow traffic. In other words, the PDMS displayed a warning message when it should not have. This situation is known as a category 1 error. In the long-term, the category 1 error may cause drivers to have less confidence in the AQD system because the drivers were told they needed to slow down due to slow traffic ahead (which did not exist). However, these errors do not put the driver at immediate risk. They merely encourage drivers to slow down as they approach the work zone.

Another situation is a category 2 error which may be considered much more problematic. This error occurs when the PDMS does not display a warning message even though the systems identified there is congested traffic and/or queuing downstream from the PDMS. While category 2 errors are rare, there was variability across all four sites as evidenced by the fact that category 2 errors ranged from 0.02% (i.e., 2.7%\*0.7%) at Waco-Utica to 1.46% (i.e., 91.3%\*1.6%) at Ashland. The low error rates indicate the system performed well.

Category 2 errors may be further analyzed by concentrating on the times when there are congested traffic conditions in the work zone, as listed in Table 7.2. In these situations, the errors tend to take place during the SLOW status, rather than STOP status, condition. When average across the four test sites, the error rates in the SLOW status and the STOP status account for 96% and 4% shares, respectively. This result is not surprising due to the fact that the average time of the work zone traffic examined in SLOW status (e.g., 1580/4=395 minutes) is twice as great as the average time of the work zone traffic examined in STOP status (e.g., 790/4=198 minutes).

Various factors may account for the category 1 and category 2 errors identified above. First, the complexity of the work zone and its associated AQD system may play a part. It is hypothesized that larger distances may cause errors in system operation due to potential signal loss. Second, if the traffic volumes are low, there will be a lower number of speed samples. In this situation, the PDMS may be sensitive to switching between two different message displays when the speed is approximately the same as the predefined thresholds, i.e., 25 mph and 45 mph for the STOP and SLOW status, respectively. Third, the rolling average calculation may be different in this study from the AQD application in the field. However, a detailed analysis of the root causes of the errors was beyond the scope of the report.

## **7.2. Ascertain How the Drivers React to the Messages on the PDMS**

By definition, the effectiveness of the AQD system is directly related to whether it has a positive impact on driver speed. Therefore, the critical questions that need to be answered are (1) do drivers slow down when they see a SLOW or STOP warning message on the PDMS and, (2) if so, how much? The hypothesis associated with the second objective of this project is as follows.

*H0: A statistically significant decrease in average speed will occur when the PDMS indicates that the drivers should be prepared to stop because a queue has been detected ahead.*



To analyze these questions, the space mean speeds on the roadway segments upstream of the PDMS were compared to the space mean speeds on the roadway segments downstream of the PDMS. In addition, the speeds of segments upstream and downstream of a PDMS were compared when there is a change in the message on the PDMS. The sample data of the space mean speed from all the four test sites used in this analysis is shown in Table 7.3.

Table 7.3 Sample size of speed data collected at each test site

Test site	Data collection duration	Warning time (accumulated)	Sample sizes (veh) under warning vs. no-warning conditions
Waco	9/2/2020 – 9/11/2020	350 minutes	1229 vs 6473
Big Springs at PDMS 1	9/15/2020 – 10/11/2020	120 minutes	614 vs 11551
Big Springs at PDMS 2	7/3/2021 – 7/6/2021	180 minutes	1088 vs 1708
Ogallala	7/3/2021 – 7/6/2021	420 minutes	1742 vs 912

Figure 7.1 provides a summary box plot of the speed profile changes along with the road segments (i.e., from Segment 12 to Segment 45) for a warning scenario (e.g., PDMS displayed SLOW/STOP warning message) and a non-warning scenario (e.g., PDMS displayed NONE), respectively. The location of PDMS is also marked.

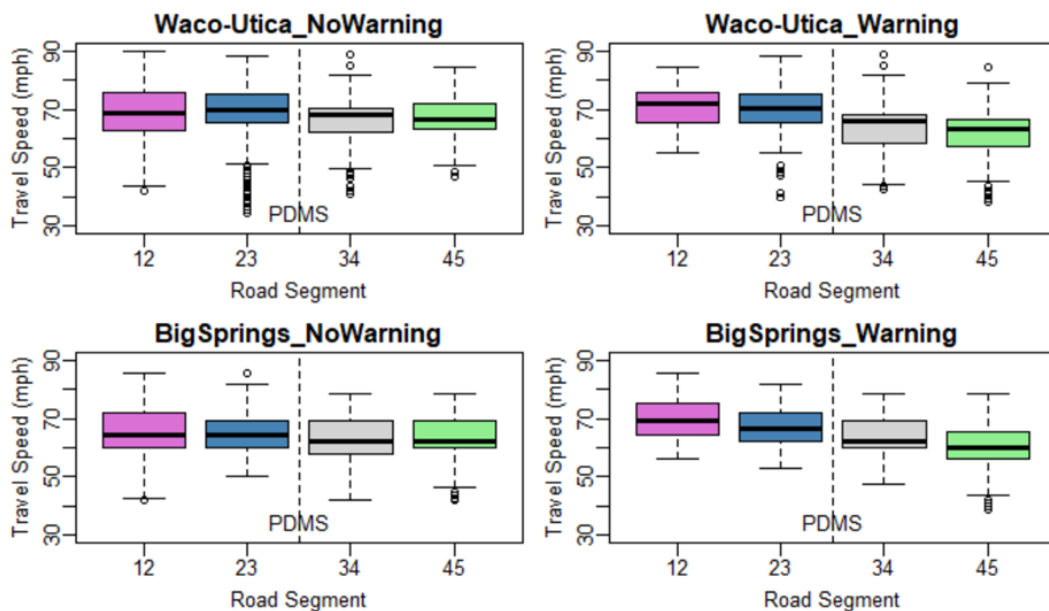


Figure 7.1. Reduction of speeds along with the road segments. Solid lines represent the average and shaded areas represent the 95% confidence intervals.

As shown in Figure 7.1, there is a general pattern that space mean speeds decrease as the vehicles approach the work zone. It should be noted that due to the sight distance at both test sites, drivers cannot

see the work zone ahead when they read the message on the PDMS. However, there is static advisory signage along with the road segments, in addition to the PDMS, indicating that there is a work zone ahead. This may be the key reason for the continuous decrease in speed along with the segments regardless of which message is displayed on the PDMS. It may also be seen that when the PDMS displays a warning message, the reduction in space means is much greater when the PDMS does not display a warning message.

A statistical summary of the speed reduction is listed in Table 7.4, where the significances ( $\alpha = 0.05$ ) of the speed changes are tested using Welch's t-test for the mean equality and F-test for the variance equality between two adjacent road segments.

Table 7.4. Statistics summary of the speed changes

	Welch Two Sample t-test*				Two variances F-test**			
	Avg. Diff. (mph)	Avg. Diff. (%)	t-stat.	p-value	Std. Dev. Diff. (mph)	Std. Dev. Diff. (%)	F-stat.	p-value
Waco-Utica (Warning)								
Seg12-Seg23	0.6	0.8%	-0.893	0.372	-0.1	-1.2%	1.024	0.852
Seg23-Seg34	-7.0	-11.0%	10.72	<2.2e-16	2.5	26.5%	0.54	1.2e-07
Seg34-Seg45	-1.5	-2.4%	2.06	0.039	1.1	10.2%	0.80	0.038
Waco-Utica (NoWarning)								
Seg12-Seg23	-0.3	-0.5%	1.08	0.279	-0.1	-1.2%	1.03	0.626
Seg23-Seg34	-3.6	-5.5%	12.49	<2.2e-16	-1.0	-13.2%	1.28	9.0e-07
Seg34-Seg45	0.7	1.2%	-3.18	0.002	-0.9	-14.3%	1.31	8.8e-08
Big Springs at PDMS 1 (Warning)								
Seg12-Seg23	-2.6	-3.9%	2.31	0.024	-1.6	-28.9%	1.66	0.024
Seg23-Seg34	-3.5	-5.7%	4.87	1.9e-06	1.2	17.3%	0.68	0.025
Seg34-Seg45	-2.2	-3.6%	2.65	0.008	1.5	18.4%	0.67	0.011
Big Springs at PDMS 1 (NoWarning)								
Seg12-Seg23	-1.0	-1.5%	5.08	3.7e-07	-1.2	-17.5%	1.02	< 2.2e-16
Seg23-Seg34	-1.9	-3.0%	10.97	<2.2e-16	-0.2	-5.4%	0.81	0.004
Seg34-Seg45	0.6	0.8%	-3.25	0.001	-0.3	-2.3%	0.54	0.212

\*Alternative hypothesis: true difference in means is not equal to 0.

\*\*Alternative hypothesis: true ratio of variances is not equal to 1.

It may be seen in Table 7.4 under the warning scenario, the speed reductions from segment 23 to segment 34 are 7.0 mph and 3.5 mph at Waco-Utica and Big Springs, respectively. These are, on average, 90% greater than the speed reductions of 3.6 mph and 1.9 mph compared to the same segments under the scenario where the PDMS does not display a warning message. It may also be seen in Table 7.4 that a reduction in space mean speed for both of these scenarios is statistically significant. A summary of the mean speed reduction trend can be found in Figure 7.2 (a).

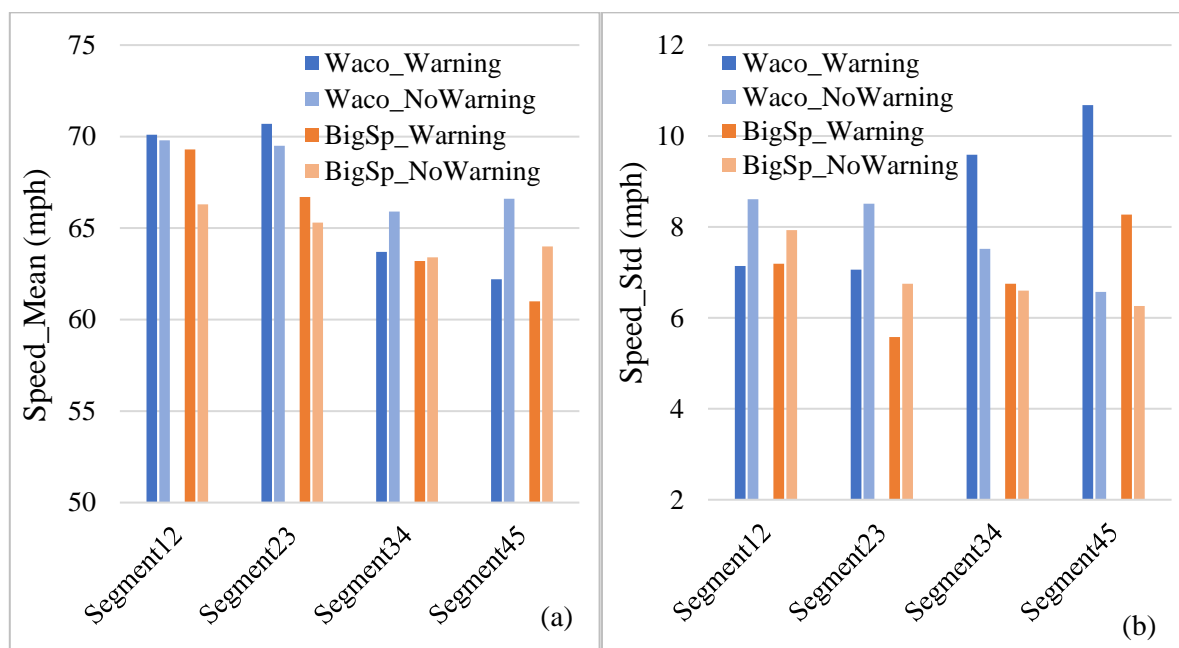


Figure 7.2 comparison of the mean (a) and standard deviation (b) for speeds with and without warning message.

Interestingly, it may be found in Figure 7.2 (b) that the speed reduction standard deviation is greater when the PDMS displays a warning message as compared to when it does not. As also shown in Table 7.4, the difference in the standard deviation is statistically significant between segment 23 and segment 34. It should be noted there are two distinct trends:

- When the PDMS displays a warning message, the space mean speed standard deviation increases by 2.5 mph and 1.2 mph (26.5% and 17.3%), respectively, at the two sites. The increase in variability in speed after the PDMS indicates there is a wide range of driver behavior upstream of the work zone. While the average space mean speed decreases, there is correspondingly more variability in speed indicating some drivers may not be responding to the sign and/or some drivers are reducing their speed below the speed limit.
- In contrast, when the PDMS does not display a warning message, the speed standard deviation decreases by 1.0 mph and 0.2 mph (13.2% and 5.4%) at the two sites, respectively. This indicates the various drivers are much more homogeneous in their speed choices when no warning is given.

Further study on the Phase 2 data supports the above driver behavior with regard to the speed reduction at the PDMS when the warning message was displayed, the comparison results are listed in Table 7.5.

Table 7.5 Speed comparisons upstream and downstream of the PDMS

	Speed (mph)	Big Springs at PDMS 2		Ogallala	
		Segment 12	Segment 23	Segment 12	Segment 23
Star	Sample size	529	559	833	909
	Mean (mph)	61.0	61.9	65.8	66.2
	P-value (t.test)	0.176		0.488	
Slow	Sample size	644	682	414	435
	Mean (mph)	58.8	54.9	63.6	61.7
	P-value (t.test)	<0.001		0.016	
Stop	Sample size	181	201	30	33
	Mean (mph)	56.1	54.0	59.6	56.4
	P-value (t.test)	0.005		0.216*	

\*data due to small sample size

### 7.3. Crash Rates at Work Zones

The number of crashes and crash severity are modeled using data from all work zone on I-80 (including both with and without AQD systems) due to missing information about the time and location of the AQD installation. Model results are shown in Table 7.6 and Table 7.7, respectively. Note that the values are color-coded to indicate their significances. The dark orange indicates significance at 0.05. The light orange indicates marginal significance at 0.1. In the ordered logistic regression model result, the dark pink color indicates the significance of the ordered model.

Table 7.6 Generalized Linear Model - Number of injuries

	Approaching Advance	Transition	Activity	Termination	
(Intercept)	0.183	0.144	0.177	0.291	0.056
RoadCharacterCurved	0.106	-0.07	0.143	0.029	-0.017
RoadSurfaceCondIce/Slush	-0.332	0.44	-0.026	-0.044	-0.003
RoadSurfaceCondWet	0.458	0.159	-0.061	-0.079	-0.041
DirRear-end	0.627	0.685	0.742	0.625	0.076
PopGroupUrban	-0.106	-0.035	-0.142	-0.128	0.014
AlcoholYes	0.459	0.168	0.169	0.094	0.264

Driverless20Yes	-0.157	0.005	0.164	0.037	0.098
HVPercent	-0.181	0.102	-0.101	0.028	-0.064
ContribCir2_RoadYes	0.124	-0.133	0.164	0.058	0.007
WZTypeLaneclosure	0.184	0.056	0.1	0.01	0.094
WZTypeLaneshift	0.346	-0.078	0.019	0.048	0.046
WZTypeOnShoulder	0.366	-0.158	0.117	0.008	0.005
WorkerPresentYes	-0.481	-0.268	-0.48	-0.356	-0.083
AADT (nearest ATR site)	0.26	0.61	0.281	0.17	0.032
PeakhourYes	-0.139	-0.167	-0.025	-0.069	-0.026
DaytimeYes	0.251	0.243	0.099	0.012	-0.013
WeekendYes	-0.082	-0.022	0.005	-0.017	-0.075

Table 7.7 Ordinal Logistic Regression – Crash Severity

	Approaching	Advance	Transition	Activity	Termination
RoadCharacterCurved	-0.102	-0.084	0.41	0.231	0.133
RoadSurfaceTypeConcrete	-0.411	0.294	0.838	0.19	-0.008
AlcoholYes	1.281	0.854	0.715	1.094	1.463
Driverless20Yes	-0.905	-0.103	0.924	0.144	0.298
TotVeh	0.644	0.227	-0.736	0.102	0.314
TotHev	0.148	0.14	-0.191	0.167	0.164
ContribCir1_EnvirNo	-0.6	-0.181	0.891	-0.015	-0.24
ContribCir2_RoadYes	0.825	-0.362	0.9	0.037	0.161
PopGroupUrban	0.267	-0.544	-0.5	-0.487	-0.381
PeakhourYes	-0.509	-0.406	0.201	-0.374	-0.566
WeekendYes	-0.129	-0.063	-0.178	-0.203	-0.306
DaytimeYes	1.393	0.448	-0.193	0.221	-0.526
DirRear-end	1.251	1.619	1.68	1.646	0.911
WorkerPresentYes	-2.08	-0.816	-2.687	-1.372	-0.498
WZTypeLaneclosure	-0.333	0.001	1.001	0.201	-0.224
WZTypeLaneshift	-0.443	-0.572	0.799	-0.397	-0.674
AADT (nearest ATR site)	0.13	0.406	0.829	0.115	-0.493
None Property	-1.078	-1.572	-1.272	-1.505	-1.591
Property Minor	1.514	1.69	2.141	1.702	2.731
Minor Serious	5.534	3.596	4.236	3.756	4.338

As can be seen from Table 7.6, most crashes occurred in the activity area and are rear-ended. In addition, a crash is more likely to occur at: (1) Weekday, (2) Daytime, (3) No worker present, (4) Rural work zone, (5) Off-peak hour.

As can be seen from Table 7.7, a crash is severer when driving drunk, during the daytime, on weekdays, and more vehicles are involved.

- (1) Advance warning/Transition areas need to pay attention to road conditions (e.g., worn, obstruction, debris), AADT, heavy vehicles, rural areas, and driver age younger than 25 years.
- (2) Activity areas need to pay attention to work zone type, heavy vehicle, and curvature.
- (3) Termination areas need to pay attention to nighttime, weekend, driving impaired (alcohol), young driver, and road conditions.

## 8. CONCLUDING REMARKS

The effectiveness of the Nebraska AQD system was examined in two ways. First, the system performance was investigated with respect to whether the PDMS correctly displayed the appropriate warning message for the given traffic conditions (i.e., “NONE”, “SLOW”, and “STOP”). The results indicate that, overall, the AQD system performed well, with an overall error rate of 0.7% – 2.3%.

The types of errors were also analyzed. Intuitively, providing warning messages when they are not required (e.g., category 1 error) would reduce drivers’ trust in the AQD system. In contrast, not providing a warning message or providing the wrong message (e.g., category 2 error) could reduce driver safety. On the surface, category 1 errors that occur in a free-flow condition are, arguably, not as severe as category 2 errors that occur during congested conditions. It was found that the occurrence of the latter was greatest at the Ashland test site ( $1.6 \times 91.3\% = 1.46\%$ ) and was the smallest at the Waco-Utica test site ( $0.7 \times 2.7\% = 0.02\%$ ). More importantly, all four test sites had relatively low error rates which indicated that the AQD system was operating correctly.

To the authors' best knowledge, this was the first study to examine the efficacy of AQD systems using space mean speed rather than instantaneous speed. This approach reduced the probability that any effects found were transitory in nature (e.g., drivers slowing down because of the sign and subsequently speeding up). The space mean speed was analyzed using a measure of central tendency (e.g., mean) and a measure of dispersion (e.g., standard deviation). These were analyzed as a function of the message that was displayed on the PDMS.

It was found that, when drivers pass by a PDMS that does not have a warning message, their space mean speeds were reduced in the range of 1.9 to 3.6 mph. It was found that this reduction is statistically significant at the 0.05 level. More importantly, it was found that when the PDMS displayed a warning message, the space mean speeds were reduced in the range of 3.5 to 7 mph. These reductions were also statistically significant. On average, it was found that the average speed reduction when the PDMS displayed a warning message was 90% higher as compared to the speed reduction when the PDMS did not display a warning message. It was concluded that the AQD systems were very effective at reducing space mean speeds, the reduction in speed was not transitory, and the reductions were statistically significant at the 95% confidence level.

Interestingly, there was no definitive relationship found between the message on the PDMS and the standard deviation of travel time. It was found that the standard deviation increased when there was a warning message on the PDMS. Conversely, when no warning message was displayed, the standard deviation decreased. Given the average speed of all vehicles decreased regardless of a warning message, the reason for the change in speed deviation may be due to the different levels of the vehicles’ response to a warning display on PDMS. Considering the truck percentage (including single unit, single truck trailer, and multiple truck trailer) was up to 62% on the work zones during the data collection, this may indicate that passenger cars and trucks have appreciably different degrees of speed reduction when

confronted with a message on the PDMS. Because the space mean speed measurements were not disaggregated by vehicle type it was impossible to test this hypothesis.

Results from the crash analysis show that most crashes occurred in the activity area and are rear-ended. In addition, a crash is more likely to occur on weekdays, off-peak hour, in the daytime, no worker present at rural work zones. A crash is severer when drivers driving drunk, during the daytime, on weekdays, and more vehicles are involved.

For crash occurred work zone areas, according to the model results, advance warning and transition areas need to pay attention to road conditions (e.g., worn, obstruction, debris), AADT, heavy vehicles, rural areas, and driver age younger than 25 years. Activity areas need to pay attention to work zone type, heavy vehicle, and curvature. Lastly, termination areas need to pay attention to nighttime, weekend, driving impaired (alcohol), young driver, and road conditions.



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# APPENDICES

## A. Algorithm and Codes for Travel Time Collection and Measure

```
library(tidyverse)
library(data.table)

day <- "9-9"
loc <- "WACO_WB_PCMS"
SENSOR <- "RDR02"
PCMS <- "MB10";

Station1<-"SCU6UB_Sta1"; Station2<-"SCU6TZ_Sta2";
Station3<-"SCU6T2_Sta3"; Station4<-"SCU6T1_Sta4";
Station5<-"SCU6VA_Sta5"
dist12 = 2112; dist23 = 3167;
dist34 = 2112;dist45 = 3151;#ft

stp<-as.numeric(as.POSIXct(paste("2020-",day0," 00:00:00",sep="")))
edp<-as.numeric(as.POSIXct(paste("2020-",day0," 23:59:59",sep="")))
bins <- seq(as.numeric(as.POSIXct(paste("2020-",day0," 08:00:00",sep="))),
as.numeric(as.POSIXct(paste("2020-",day0," 20:00:00",sep="))),by=3600)
bin <- data.frame(start.bin=bins[-length(bins)],end.bin=lead(bins)[-length(bins)])
#####
setwd("C:/Users/Liz/Desktop/Data Collection/Waco-Utica/Miovision_Data/")
day <- "09-09"
sta1 <- read.csv(paste(loc,p,"_",day,"_",Station1,".csv",sep=""),sep=",") ## need to change
sta2 <- read.csv(paste(loc,p,"_",day,"_",Station2,".csv",sep=""),sep=",")
sta3 <- read.csv(paste(loc,p,"_",day,"_",Station3,".csv",sep=""),sep=",")
sta4 <- read.csv(paste(loc,p,"_",day,"_",Station4,".csv",sep=""),sep=",")
sta5 <- read.csv(paste(loc,p,"_",day,"_",Station5,".csv",sep=""),sep=",")
sta1$Time <- gsub("[ T ]", " ", sta1$Time, perl=TRUE)
sta2$Time <- gsub("[ T ]", " ", sta2$Time, perl=TRUE)
sta3$Time <- gsub("[ T ]", " ", sta3$Time, perl=TRUE)
sta4$Time <- gsub("[ T ]", " ", sta4$Time, perl=TRUE)
sta5$Time <- gsub("[ T ]", " ", sta5$Time, perl=TRUE)
```

```
sta1 <- sta1 %>% filter(as.numeric(as.POSIXct(Time))>as.numeric(as.POSIXct(paste("2020-",day,"
08:00:00",sep=""))))&
```

```
as.numeric(as.POSIXct(Time))<as.numeric(as.POSIXct(paste("2020-",day," 20:00:00",sep=""))))%>%
```

```
mutate(Uni_time = as.numeric(as.POSIXct(Time))) %>% separate(Time, c("Date",
"Time")," ") %>% separate(Time, c("Time", NA),"-")
```

```
sta2 <- sta2 %>% mutate(Uni_time = as.numeric(as.POSIXct(Time))) %>% separate(Time, c("Date",
"Time")," ") %>% separate(Time, c("Time", NA),"-")
```

```
sta3 <- sta3 %>% mutate(Uni_time = as.numeric(as.POSIXct(Time))) %>% separate(Time, c("Date",
"Time")," ") %>% separate(Time, c("Time", NA),"-")
```

```
sta4 <- sta4 %>% mutate(Uni_time = as.numeric(as.POSIXct(Time))) %>% separate(Time, c("Date",
"Time")," ") %>% separate(Time, c("Time", NA),"-")
```

```
sta5 <- sta5 %>% mutate(Uni_time = as.numeric(as.POSIXct(Time))) %>% separate(Time, c("Date",
"Time")," ") %>% separate(Time, c("Time", NA),"-")
```

```
dt<-ifelse(day=="09-03",1599109200,1599627600)
```

```
sta1$Time0<-(sta1$Uni_time-dt)/86400
```

```
sta2$Time0<-(sta2$Uni_time-dt)/86400
```

```
sta3$Time0<-(sta3$Uni_time-dt)/86400
```

```
sta4$Time0<-(sta4$Uni_time-dt)/86400
```

```
sta5$Time0<-(sta5$Uni_time-dt)/86400
```

```
#####
```

```
##### data when star message is displayed (free traffic) #####
```

```
msg_star <- data.frame(code = msg$Msg_code,begin = msg$Time, end = lead(msg$Time))
```

```
msg_star <- msg_star[-nrow(msg_star),] %>% filter(code == 3|code == 4)
```

```
star_sta1 = star_sta2 = star_sta3 = star_sta4 = star_sta5 <- NULL
```

```
if(nrow(msg_star)!=0){
```

```
for(k in 1:nrow(msg_star)){star_sta1<-rbind(star_sta1,sta1 %>% filter(Time0 %between%
msg_star[k,-1]))}
```

```
for(k in 1:nrow(msg_star)){star_sta2<-rbind(star_sta2,sta2 %>% filter(Time0 %between%
msg_star[k,-1]))}
```

```
for(k in 1:nrow(msg_star)){star_sta3<-rbind(star_sta3,sta3 %>% filter(Time0 %between%
msg_star[k,-1]))}
```

```
for(k in 1:nrow(msg_star)){star_sta4<-rbind(star_sta4,sta4 %>% filter(Time0 %between%
msg_star[k,-1]))}
```

```
for(k in 1:nrow(msg_star)){star_sta5<-rbind(star_sta5,sta5 %>% filter(Time0 %between%
msg_star[k,-1]))}}
```

```
##### data when slow message is displayed (slow traffic) #####
```

```
msg_slow <- data.frame(code=msg$Msg_code,begin=msg$Time,end=lead(msg$Time))
```

```
msg_slow <- msg_slow %>% filter(code==2)
```

```
slow_sta1=slow_sta2=slow_sta3=slow_sta4=slow_sta5<-NULL
```

```
if(nrow(msg_slow)!=0){
```

```
for(k in 1:nrow(msg_slow)){slow_sta1<-rbind(slow_sta1,sta1 %>% filter(Time0 %between%
msg_slow[k,-1]))}
```

```
for(k in 1:nrow(msg_slow)){slow_sta2<-rbind(slow_sta2,sta2 %>% filter(Time0 %between%
msg_slow[k,-1]))}
```

```
for(k in 1:nrow(msg_slow)){slow_sta3<-rbind(slow_sta3,sta3 %>% filter(Time0 %between%
msg_slow[k,-1]))}
```

```
for(k in 1:nrow(msg_slow)){slow_sta4<-rbind(slow_sta4,sta4 %>% filter(Time0 %between%
msg_slow[k,-1]))}
```

```
for(k in 1:nrow(msg_slow)){slow_sta5<-rbind(slow_sta5,sta5 %>% filter(Time0 %between%
msg_slow[k,-1]))}}
```

```
##### data when stop message is displayed (stop traffic) #####
```

```
msg_stop <- data.frame(code = msg$Msg_code,begin = msg$Time, end = lead(msg$Time))
```

```
msg_stop <- msg_stop%>%filter(code == 1)
```

```
stop_sta1 = stop_sta2 = stop_sta3 = stop_sta4 = stop_sta5 <- NULL
```

```
if(nrow(msg_stop)!=0){
```

```
for(k in 1:nrow(msg_stop)){stop_sta1<-rbind(stop_sta1,sta1 %>% filter(Time0 %between%
msg_stop[k,-1]))}
```

```
for(k in 1:nrow(msg_stop)){stop_sta2<-rbind(stop_sta2,sta2 %>% filter(Time0 %between%
msg_stop[k,-1]))}
```

```
for(k in 1:nrow(msg_stop)){stop_sta3<-rbind(stop_sta3,sta3 %>% filter(Time0 %between%
msg_stop[k,-1]))}
```

```
for(k in 1:nrow(msg_stop)){stop_sta4<-rbind(stop_sta4,sta4 %>% filter(Time0 %between%
msg_stop[k,-1]))}
```

```
for(k in 1:nrow(msg_stop)){stop_sta5<-rbind(stop_sta5,sta5 %>% filter(Time0 %between%
msg_stop[k,-1]))}}
```

```
#####
```



```
##### msg_star #####
#####

par(mfrow=c(2,3))
s_lo <- 0
s_hi <- 100
##### from Station 1 to Station 2 #####
star_sta12 <- merge(star_sta1, star_sta2, by = "Object.Identification")
names(star_sta12)[c(5,6,11,12)] <- c("Time.s", "Uni_time.s", "Time.e", "Uni_time.e")
star_sta12 <- star_sta12[!duplicated(star_sta12),c("Object.Identification", "Time.s", "Uni_time.s",
"Time.e", "Uni_time.e")]
star_sta12 <- transform(star_sta12,id=as.numeric(factor(star_sta12$Object.Identification)))

star_t12 <- NULL
for(k in unique(star_sta12$id)){
  star_temp_t12 <- star_sta12[star_sta12$id == k,]
  if(diff(range(star_temp_t12$Uni_time.s)) > 10){star_temp_t12 <- star_temp_t12 %>%
filter(Uni_time.s > min(Uni_time.s) & Uni_time.s < max(Uni_time.s))}
  if(nrow(star_temp_t12) > 0){if(diff(range(star_temp_t12$Uni_time.e)) > 10){star_temp_t12 <-
star_temp_t12 %>% filter(Uni_time.e > min(Uni_time.e) & Uni_time.e < max(Uni_time.e))}}
  if(nrow(star_temp_t12) > 0){star_temp_t12 <- star_temp_t12 %>% mutate(diff = max(Uni_time.e) -
max(Uni_time.s))
  star_t12 <- rbind(star_t12,
star_temp_t12[star_temp_t12$Uni_time.e==max(star_temp_t12$Uni_time.e)&star_temp_t12$Uni_time.s==max(star_temp_t12$Uni_time.s),])
  }}
star_s12 <- data.frame(star_t12,sms=0.681818*dist12/star_t12$diff) ## convert ft/s to mph
star_s12 <- star_s12%>%filter(sms < s_hi & sms> s_lo)

d_star_s12<-hist(star_s12$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 1 - 2")
abline(v = median(star_s12$sms), col= "red", lty="dashed", lwd=2)
text(median(star_s12$sms), max(d_star_s12$density), paste("M=", round(median(star_s12$sms),1),"
N=", nrow(star_s12),sep="" )

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(star_s12$Object.Identification[star_s12$Uni_time.1 >= bin[i,1]
& star_s12$Uni_time.1 <= bin[i,2]])}
```

```

star_sta12_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

##### from Station 2 to Station 3 #####
star_sta23 <- merge(star_sta2, star_sta3, by = "Object.Identification")
names(star_sta23)[c(5,6,11,12)] <- c("Time.s", "Uni_time.s", "Time.e", "Uni_time.e")
star_sta23 <- star_sta23[!duplicated(star_sta23),c("Object.Identification", "Time.s", "Uni_time.s",
"Time.e", "Uni_time.e")]
star_sta23 <- transform(star_sta23,id=as.numeric(factor(star_sta23$Object.Identification)))

star_t23 <- NULL
for(k in unique(star_sta23$id)){
  star_temp_t23 <- star_sta23[star_sta23$id == k,]
  if(diff(range(star_temp_t23$Uni_time.s)) > 10){star_temp_t23 <- star_temp_t23 %>%
filter(Uni_time.s > min(Uni_time.s) & Uni_time.s < max(Uni_time.s))}
  if(nrow(star_temp_t23) > 0){if(diff(range(star_temp_t23$Uni_time.e)) > 10){star_temp_t23 <-
star_temp_t23 %>% filter(Uni_time.e > min(Uni_time.e) & Uni_time.e < max(Uni_time.e))}}
  if(nrow(star_temp_t23) > 0){star_temp_t23 <- star_temp_t23 %>% mutate(diff = max(Uni_time.e) -
max(Uni_time.s))
  star_t23 <- rbind(star_t23,
star_temp_t23[star_temp_t23$Uni_time.e==max(star_temp_t23$Uni_time.e)&star_temp_t23$Uni_time.s==max(star_temp_t23$Uni_time.s),])
}}
star_s23 <- data.frame(star_t23,sms=0.681818*dist23/star_t23$diff) ## convert ft/s to mph
star_s23 <- star_s23%>%filter(sms < s_hi & sms> s_lo)

d_star_s23<-hist(star_s23$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 2 - 3")
abline(v = median(star_s23$sms), col= "red", lty="dashed", lwd=2)
text(median(star_s23$sms), max(d_star_s23$density), paste("M=", round(median(star_s23$sms),1),"
N=", nrow(star_s23),sep="" )

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(star_s23$Object.Identification[star_s23$Uni_time.2 >= bin[i,1]
& star_s23$Uni_time.2 <= bin[i,2]])}
star_sta23_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

```

```

##### from Station 3 to Station 4 #####
star_sta34 <- merge(star_sta3, star_sta4, by = "Object.Identification")
names(star_sta34)[c(5,6,11,12)] <- c("Time.s", "Uni_time.s", "Time.e", "Uni_time.e")
star_sta34 <- star_sta34[!duplicated(star_sta34),c("Object.Identification", "Time.s", "Uni_time.s",
"Time.e", "Uni_time.e")]
star_sta34 <- transform(star_sta34,id=as.numeric(factor(star_sta34$Object.Identification)))

star_t34 <- NULL
for(k in unique(star_sta34$id)){
  star_temp_t34 <- star_sta34[star_sta34$id == k,]
  if(diff(range(star_temp_t34$Uni_time.s)) > 10){star_temp_t34 <- star_temp_t34 %>%
filter(Uni_time.s > min(Uni_time.s) & Uni_time.s < max(Uni_time.s))}
  if(nrow(star_temp_t34) > 0){if(diff(range(star_temp_t34$Uni_time.e)) > 10){star_temp_t34 <-
star_temp_t34 %>% filter(Uni_time.e > min(Uni_time.e) & Uni_time.e < max(Uni_time.e))}}
  if(nrow(star_temp_t34) > 0){star_temp_t34 <- star_temp_t34 %>% mutate(diff = max(Uni_time.e) -
max(Uni_time.s))
  star_t34 <- rbind(star_t34,
star_temp_t34[star_temp_t34$Uni_time.e==max(star_temp_t34$Uni_time.e)&star_temp_t34$Uni_time.s==max(star_temp_t34$Uni_time.s),])
}}
star_s34 <- data.frame(star_t34,sms=0.681818*dist34/star_t34$diff) ## convert ft/s to mph
star_s34 <- star_s34%>%filter(sms < s_hi & sms > s_lo)

d_star_s34<-hist(star_s34$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 3 - 4")
abline(v = median(star_s34$sms), col= "red", lty="dashed", lwd=2)
text(median(star_s34$sms), max(d_star_s34$density), paste("M=", round(median(star_s34$sms),1),",
N=", nrow(star_s34),sep="" )

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(star_s34$Object.Identification[star_s34$Uni_time.3 >= bin[i,1]
& star_s34$Uni_time.3 <= bin[i,2]])}
star_sta34_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

##### from Station 4 to Station 5 #####
star_sta45 <- merge(star_sta4, star_sta5, by = "Object.Identification")
names(star_sta45)[c(5,6,11,12)] <- c("Time.4", "Uni_time.4", "Time.5", "Uni_time.5")

```

```

star_sta45 <- star_sta45[!duplicated(star_sta45),c("Object.Identification", "Time.4", "Uni_time.4",
"Time.5", "Uni_time.5")]
star_sta45 <- transform(star_sta45,id45=as.numeric(factor(star_sta45$Object.Identification)))

star_t45 <- NULL
for(k in unique(star_sta45$id)){
  star_temp_t45 <- star_sta45[star_sta45$id == k,]
  if(diff(range(star_temp_t45$Uni_time.4)) > 10){star_temp_t45 <- star_temp_t45 %>%
filter(Uni_time.4 > min(Uni_time.4) & Uni_time.4 < max(Uni_time.4))}
  if(nrow(star_temp_t45) > 0){if(diff(range(star_temp_t45$Uni_time.5)) > 10){star_temp_t45 <-
star_temp_t45 %>% filter(Uni_time.5 > min(Uni_time.5) & Uni_time.5 < max(Uni_time.5))} }
  if(nrow(star_temp_t45) > 0){ star_temp_t45 <- star_temp_t45 %>% mutate(diff = max(Uni_time.5) -
max(Uni_time.4))
  star_t45 <- rbind(star_t45,
star_temp_t45[star_temp_t45$Uni_time.5==max(star_temp_t45$Uni_time.5)&star_temp_t45$Uni_time.4==max(star_temp_t45$Uni_time.4),])
} }
star_s45 <- data.frame(star_t45,sms=0.681818*dist45/star_t45$diff) ## convert ft/s to mph
star_s45 <- star_s45%>%filter(sms < s_hi & sms> s_lo)

d_star_s45<-hist(star_s45$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 4 - 5")
abline(v = median(star_s45$sms), col= "red", lty="dashed", lwd=2)
text(median(star_s45$sms), max(d_star_s45$density), paste("M=", round(median(star_s45$sms),1),"
N=", nrow(star_s45),sep=""))

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(star_s45$Object.Identification[star_s45$Uni_time.4 >= bin[i,1]
& star_s45$Uni_time.4 <= bin[i,2]])}
star_sta45_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

#####
##### msg_slow #####
#####

##### from Station 1 to Station 2 #####
slow_sta12 <- merge(slow_sta1, slow_sta2, by = "Object.Identification")

```

```

names(slow_sta12)[c(5,6,11,12)] <- c("Time.s", "Uni_time.s", "Time.e", "Uni_time.e")
slow_sta12 <- slow_sta12[!duplicated(slow_sta12),c("Object.Identification", "Time.s", "Uni_time.s",
"Time.e", "Uni_time.e")]
slow_sta12 <- transform(slow_sta12,id=as.numeric(factor(slow_sta12$Object.Identification)))

slow_t12 <- NULL
for(k in unique(slow_sta12$id)){
  slow_temp_t12 <- slow_sta12[slow_sta12$id == k,]
  if(diff(range(slow_temp_t12$Uni_time.s)) > 10){slow_temp_t12 <- slow_temp_t12 %>%
filter(Uni_time.s > min(Uni_time.s) & Uni_time.s < max(Uni_time.s))}
  if(nrow(slow_temp_t12) > 0){if(diff(range(slow_temp_t12$Uni_time.e)) > 10){slow_temp_t12 <-
slow_temp_t12 %>% filter(Uni_time.e > min(Uni_time.e) & Uni_time.e < max(Uni_time.e))}}
  if(nrow(slow_temp_t12) > 0){slow_temp_t12 <- slow_temp_t12 %>% mutate(diff = max(Uni_time.e)
- max(Uni_time.s))
  slow_t12 <- rbind(slow_t12,
slow_temp_t12[slow_temp_t12$Uni_time.e==max(slow_temp_t12$Uni_time.e)&slow_temp_t12$Un
i_time.s==max(slow_temp_t12$Uni_time.s),])
  }}
slow_s12 <- data.frame(slow_t12,sms=0.681818*dist12/slow_t12$diff) ## convert ft/s to mph
slow_s12 <- slow_s12%>%filter(sms < s_hi & sms > s_lo)

d_slow_s12<-hist(slow_s12$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 2 - 3")
abline(v = median(slow_s12$sms), col= "red", lty="dashed", lwd=2)
text(median(slow_s12$sms),
max(d_slow_s12$density),
paste("M=",
round(median(slow_s12$sms),1),", N=", nrow(slow_s12),sep="" )

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(slow_s12$Object.Identification[slow_s12$Uni_time.1 >=
bin[i,1] & slow_s12$Uni_time.1 <= bin[i,2]])}
slow_sta12_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

##### from Station 2 to Station 3 #####
slow_sta23 <- merge(slow_sta2, slow_sta3, by = "Object.Identification")
names(slow_sta23)[c(5,6,11,12)] <- c("Time.s", "Uni_time.s", "Time.e", "Uni_time.e")
slow_sta23 <- slow_sta23[!duplicated(slow_sta23),c("Object.Identification", "Time.s", "Uni_time.s",
"Time.e", "Uni_time.e")]

```

```

slow_sta23 <- transform(slow_sta23,id=as.numeric(factor(slow_sta23$Object.Identification)))

slow_t23 <- NULL
for(k in unique(slow_sta23$id)){
  slow_temp_t23 <- slow_sta23[slow_sta23$id == k,]
  if(diff(range(slow_temp_t23$Uni_time.s)) > 10){slow_temp_t23 <- slow_temp_t23 %>%
filter(Uni_time.s > min(Uni_time.s) & Uni_time.s < max(Uni_time.s))}
  if(nrow(slow_temp_t23) > 0){if(diff(range(slow_temp_t23$Uni_time.e)) > 10){slow_temp_t23 <-
slow_temp_t23 %>% filter(Uni_time.e > min(Uni_time.e) & Uni_time.e < max(Uni_time.e))}}
  if(nrow(slow_temp_t23) > 0){slow_temp_t23 <- slow_temp_t23 %>% mutate(diff = max(Uni_time.e)
- max(Uni_time.s))
  slow_t23 <- rbind(slow_t23,
slow_temp_t23[slow_temp_t23$Uni_time.e==max(slow_temp_t23$Uni_time.e)&slow_temp_t23$Un
i_time.s==max(slow_temp_t23$Uni_time.s),])
  }}
slow_s23 <- data.frame(slow_t23,sms=0.681818*dist23/slow_t23$diff) ## convert ft/s to mph
slow_s23 <- slow_s23%>%filter(sms < s_hi & sms> s_lo)

d_slow_s23<-hist(slow_s23$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 2 - 3")
abline(v = median(slow_s23$sms), col= "red", lty="dashed", lwd=2)
text(median(slow_s23$sms), max(d_slow_s23$density), paste("M=",
round(median(slow_s23$sms),1),"", N=", nrow(slow_s23),sep="" )

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(slow_s23$Object.Identification[slow_s23$Uni_time.1 >=
bin[i,1] & slow_s23$Uni_time.1 <= bin[i,2]])}
slow_sta23_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

##### from Station 3 to Station 4 #####
slow_sta34 <- merge(slow_sta3, slow_sta4, by = "Object.Identification")
names(slow_sta34)[c(5,6,11,12)] <- c("Time.s", "Uni_time.s", "Time.e", "Uni_time.e")
slow_sta34 <- slow_sta34[!duplicated(slow_sta34),c("Object.Identification", "Time.s", "Uni_time.s",
"Time.e", "Uni_time.e")]
slow_sta34 <- transform(slow_sta34,id=as.numeric(factor(slow_sta34$Object.Identification)))

slow_t34 <- NULL

```

```

for(k in unique(slow_sta34$id)){
  slow_temp_t34 <- slow_sta34[slow_sta34$id == k,]
  if(diff(range(slow_temp_t34$Uni_time.s)) > 10){slow_temp_t34 <- slow_temp_t34 %>%
filter(Uni_time.s > min(Uni_time.s) & Uni_time.s < max(Uni_time.s))}
  if(nrow(slow_temp_t34) > 0){if(diff(range(slow_temp_t34$Uni_time.e)) > 10){temp_t34 <-
slow_temp_t34 %>% filter(Uni_time.e > min(Uni_time.e) & Uni_time.e < max(Uni_time.e))}}
  if(nrow(slow_temp_t34) > 0){slow_temp_t34 <- slow_temp_t34 %>% mutate(diff = max(Uni_time.e)
- max(Uni_time.s))
  slow_t34 <- rbind(slow_t34,
slow_temp_t34[slow_temp_t34$Uni_time.e==max(slow_temp_t34$Uni_time.e)&slow_temp_t34$Un
i_time.s==max(slow_temp_t34$Uni_time.s),])
  }}
slow_s34 <- data.frame(slow_t34,sms=0.681818*dist34/slow_t34$diff) ## convert ft/s to mph
slow_s34 <- slow_s34%>%filter(sms < s_hi & sms> s_lo)

d_slow_s34<-hist(slow_s34$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 2 - 3")
abline(v = median(slow_s34$sms), col= "red", lty="dashed", lwd=2)
text(median(slow_s34$sms), max(d_slow_s34$density), paste("M=",
round(median(slow_s34$sms),1)," N=", nrow(slow_s34),sep=""))

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(slow_s34$Object.Identification[slow_s34$Uni_time.3 >=
bin[i,1] & slow_s34$Uni_time.3 <= bin[i,2]])}
slow_sta34_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

##### from Station 4 to Station 5 #####
slow_sta45 <- merge(slow_sta4, slow_sta5, by = "Object.Identification")
names(slow_sta45)[c(5,6,11,12)] <- c("Time.4", "Uni_time.4", "Time.5", "Uni_time.5")
slow_sta45 <- slow_sta45[!duplicated(slow_sta45),c("Object.Identification", "Time.4", "Uni_time.4",
"Time.5", "Uni_time.5")]
slow_sta45 <- transform(slow_sta45,id45=as.numeric(factor(slow_sta45$Object.Identification)))

slow_t45 <- NULL
for(k in unique(slow_sta45$id)){
  slow_temp_t45 <- slow_sta45[slow_sta45$id == k,]

```

```

if(diff(range(slow_temp_t45$Uni_time.4)) > 10){slow_temp_t45 <- slow_temp_t45 %>%
filter(Uni_time.4 > min(Uni_time.4) & Uni_time.4 < max(Uni_time.4))}
if(nrow(slow_temp_t45) > 0){if(diff(range(slow_temp_t45$Uni_time.5)) > 10){slow_temp_t45 <-
slow_temp_t45 %>% filter(Uni_time.5 > min(Uni_time.5) & Uni_time.5 < max(Uni_time.5))}}
if(nrow(slow_temp_t45) > 0){ slow_temp_t45 <- slow_temp_t45 %>% mutate(diff = max(Uni_time.5)
- max(Uni_time.4))
slow_t45 <- rbind(slow_t45,
slow_temp_t45[slow_temp_t45$Uni_time.5==max(slow_temp_t45$Uni_time.5)&slow_temp_t45$U
ni_time.4==max(slow_temp_t45$Uni_time.4),])
}}
slow_s45 <- data.frame(slow_t45,sms=0.681818*dist45/slow_t45$diff) ## convert ft/s to mph
slow_s45 <- slow_s45%>%filter(sms < s_hi & sms> s_lo)

d_slow_s45<-hist(slow_s45$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 2 - 3")
abline(v = median(slow_s45$sms), col= "red", lty="dashed", lwd=2)
text(median(slow_s45$sms), max(d_slow_s45$density), paste("M=",
round(median(slow_s45$sms),1)," N=", nrow(slow_s45),sep="" )

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(slow_s45$Object.Identification[slow_s45$Uni_time.4 >=
bin[i,1] & slow_s45$Uni_time.4 <= bin[i,2]])}
slow_sta45_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

#####
##### msg_stop #####
#####

##### from Station 1 to Station 2 #####
stop_sta12 <- merge(stop_sta1, stop_sta2, by = "Object.Identification")
names(stop_sta12)[c(5,6,10,11)] <- c( "Time.1", "Uni_time.1", "Time.2", "Uni_time.2")
stop_sta12 <- stop_sta12[!duplicated(stop_sta12),c("Object.Identification", "Time.1", "Uni_time.1",
"Time.2", "Uni_time.2")]
stop_sta12 <- transform(stop_sta12,id12=as.numeric(factor(stop_sta12$Object.Identification)))

stop_t12 <- NULL
for(k in unique(stop_sta12$id)){

```



```

stop_temp_t12 <- stop_sta12[stop_sta12$id == k,]
if(diff(range(stop_temp_t12$Uni_time.1)) > 10){stop_temp_t12 <- stop_temp_t12 %>%
filter(Uni_time.1 > min(Uni_time.1) & Uni_time.1 < max(Uni_time.1))}
if(nrow(stop_temp_t12) > 0){if(diff(range(stop_temp_t12$Uni_time.2)) > 10){stop_temp_t12 <-
stop_temp_t12 %>% filter(Uni_time.2 > min(Uni_time.2) & Uni_time.2 < max(Uni_time.2))}}
if(nrow(stop_temp_t12) > 0){stop_temp_t12 <- stop_temp_t12 %>% mutate(diff = max(Uni_time.2)
- max(Uni_time.1))
stop_t12 <- rbind(stop_t12,
stop_temp_t12[stop_temp_t12$Uni_time.2==max(stop_temp_t12$Uni_time.2)&stop_temp_t12$Uni_
time.1==max(stop_temp_t12$Uni_time.1),])
}}
stop_s12 <- data.frame(stop_t12,sms=0.681818*dist12/stop_t12$diff) ## convert ft/s to mph
stop_s12 <- stop_s12%>%filter(sms < s_hi & sms> s_lo)

d_stop_s12<-hist(stop_s12$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 2 - 3")
abline(v = median(stop_s12$sms), col= "red", lty="dashed", lwd=2)
text(median(stop_s12$sms), max(d_stop_s12$density), paste("M=", round(median(stop_s12$sms),1),"
N=", nrow(stop_s12),sep=""))

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(stop_s12$Object.Identification[stop_s12$Uni_time.1 >= bin[i,1]
& stop_s12$Uni_time.1 <= bin[i,2]])}
stop_sta12_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

##### from Station 2 to Station 3 #####
stop_sta23 <- merge(stop_sta2, stop_sta3, by = "Object.Identification")
names(stop_sta23)[c(5,6,10,11)] <- c( "Time.2", "Uni_time.2", "Time.3", "Uni_time.3")
stop_sta23 <- stop_sta23[!duplicated(stop_sta23),c("Object.Identification", "Time.2", "Uni_time.2",
"Time.3", "Uni_time.3")]
stop_sta23 <- transform(stop_sta23,id23=as.numeric(factor(stop_sta23$Object.Identification)))

stop_t23 <- NULL
for(k in unique(stop_sta23$id)){
stop_temp_t23 <- stop_sta23[stop_sta23$id == k,]
if(diff(range(stop_temp_t23$Uni_time.2)) > 10){stop_temp_t23 <- stop_temp_t23 %>%
filter(Uni_time.2 > min(Uni_time.2) & Uni_time.2 < max(Uni_time.2))}

```

```

if(nrow(stop_temp_t23) > 0){if(diff(range(stop_temp_t23$Uni_time.3)) > 10){stop_temp_t23 <-
stop_temp_t23 %>% filter(Uni_time.3 > min(Uni_time.3) & Uni_time.3 < max(Uni_time.3))}}
if(nrow(stop_temp_t23) > 0){stop_temp_t23 <- stop_temp_t23 %>% mutate(diff = max(Uni_time.3)
- max(Uni_time.2))
stop_t23 <- rbind(stop_t23,
stop_temp_t23[stop_temp_t23$Uni_time.3==max(stop_temp_t23$Uni_time.3)&stop_temp_t23$Uni_
time.2==max(stop_temp_t23$Uni_time.2),])
}}
stop_s23 <- data.frame(stop_t23,sms=0.681818*dist23/stop_t23$diff) ## convert ft/s to mph
stop_s23 <- stop_s23%>%filter(sms < s_hi & sms> s_lo)

d_stop_s23<-hist(stop_s23$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 2 - 3")
abline(v = median(stop_s23$sms), col= "red", lty="dashed", lwd=2)
text(median(stop_s23$sms), max(d_stop_s23$density), paste("M=", round(median(stop_s23$sms),1),"
N=", nrow(stop_s23),sep="" )

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(stop_s23$Object.Identification[stop_s23$Uni_time.2 >= bin[i,1]
& stop_s23$Uni_time.2 <= bin[i,2]])}
stop_sta23_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

##### from Station 3 to Station 4 #####
stop_sta34 <- merge(stop_sta3, stop_sta4, by = "Object.Identification")
names(stop_sta34)[c(5,6,10,11)] <- c( "Time.3", "Uni_time.3", "Time.4", "Uni_time.4")
stop_sta34 <- stop_sta34[!duplicated(stop_sta34),c("Object.Identification", "Time.3", "Uni_time.3",
"Time.4", "Uni_time.4")]
stop_sta34 <- transform(stop_sta34,id34=as.numeric(factor(stop_sta34$Object.Identification)))

stop_t34 <- NULL
for(k in unique(stop_sta34$id)){
stop_temp_t34 <- stop_sta34[stop_sta34$id == k,]
if(diff(range(stop_temp_t34$Uni_time.3)) > 10){stop_temp_t34 <- stop_temp_t34 %>%
filter(Uni_time.3 > min(Uni_time.3) & Uni_time.3 < max(Uni_time.3))}
if(nrow(stop_temp_t34) > 0){if(diff(range(stop_temp_t34$Uni_time.4)) > 10){stop_temp_t34 <-
stop_temp_t34 %>% filter(Uni_time.4 > min(Uni_time.4) & Uni_time.4 < max(Uni_time.4))}}

```

```

if(nrow(stop_temp_t34) > 0){stop_temp_t34 <- stop_temp_t34 %>% mutate(diff = max(Uni_time.4)
- max(Uni_time.3))
stop_t34 <- rbind(stop_t34,
stop_temp_t34[stop_temp_t34$Uni_time.4==max(stop_temp_t34$Uni_time.4)&stop_temp_t34$Uni_
time.3==max(stop_temp_t34$Uni_time.3),])
}}
stop_s34 <- data.frame(stop_t34,sms=0.681818*dist34/stop_t34$diff) ## convert ft/s to mph
stop_s34 <- stop_s34%>%filter(sms < s_hi & sms> s_lo)

d_stop_s34<-hist(stop_s34$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 2 - 3")
abline(v = median(stop_s34$sms), col= "red", lty="dashed", lwd=2)
text(median(stop_s34$sms), max(d_stop_s34$density), paste("M=", round(median(stop_s34$sms),1),"
N=", nrow(stop_s34),sep="" )

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(stop_s34$Object.Identification[stop_s34$Uni_time.3 >= bin[i,1]
& stop_s34$Uni_time.3 <= bin[i,2]])}
stop_sta34_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

##### from Station 4 to Station 5 #####
stop_sta45 <- merge(stop_sta4, stop_sta5, by = "Object.Identification")
names(stop_sta45)[c(5,6,10,11)] <- c( "Time.4", "Uni_time.4", "Time.5", "Uni_time.5")
stop_sta45 <- stop_sta45[!duplicated(stop_sta45),c("Object.Identification", "Time.4", "Uni_time.4",
"Time.5", "Uni_time.5")]
stop_sta45 <- transform(stop_sta45,id45=as.numeric(factor(stop_sta45$Object.Identification)))

stop_t45 <- NULL
for(k in unique(stop_sta45$id)){
stop_temp_t45 <- stop_sta45[stop_sta45$id == k,]
if(diff(range(stop_temp_t45$Uni_time.4)) > 10){stop_temp_t45 <- stop_temp_t45 %>%
filter(Uni_time.4 > min(Uni_time.4) & Uni_time.4 < max(Uni_time.4))}
if(nrow(stop_temp_t45) > 0){if(diff(range(stop_temp_t45$Uni_time.5)) > 10){stop_temp_t45 <-
stop_temp_t45 %>% filter(Uni_time.5 > min(Uni_time.5) & Uni_time.5 < max(Uni_time.5))}}
if(nrow(stop_temp_t45) > 0){ stop_temp_t45 <- stop_temp_t45 %>% mutate(diff = max(Uni_time.5)
- max(Uni_time.4))

```

```

stop_t45 <- rbind(stop_t45,
stop_temp_t45[stop_temp_t45$Uni_time.5==max(stop_temp_t45$Uni_time.5)&stop_temp_t45$Uni_
time.4==max(stop_temp_t45$Uni_time.4),])
})
stop_s45 <- data.frame(stop_t45,sms=0.681818*dist45/stop_t45$diff) ## convert ft/s to mph
stop_s45 <- stop_s45%>%filter(sms < s_hi & sms> s_lo)

d_stop_s45<-hist(stop_s45$sms, freq = FALSE, xlab = "Average Speed (mph)", main =
"Freeflow_Stations 2 - 3")
abline(v = median(stop_s45$sms), col= "red", lty="dashed", lwd=2)
text(median(stop_s45$sms), max(d_stop_s45$density), paste("M=", round(median(stop_s45$sms),1),"
N=", nrow(stop_s45),sep="" ) )

count<-NULL
for(i in 1:nrow(bin)) {count[i]<-length(stop_s45$Object.Identification[stop_s45$Uni_time.4 >= bin[i,1]
& stop_s45$Uni_time.4 <= bin[i,2]])}
stop_sta45_count<-data.frame(from_hour=seq(8,19,1),to_hour=seq(9,20,1),count=count)

```

## B. Distributions of the Travel Speed

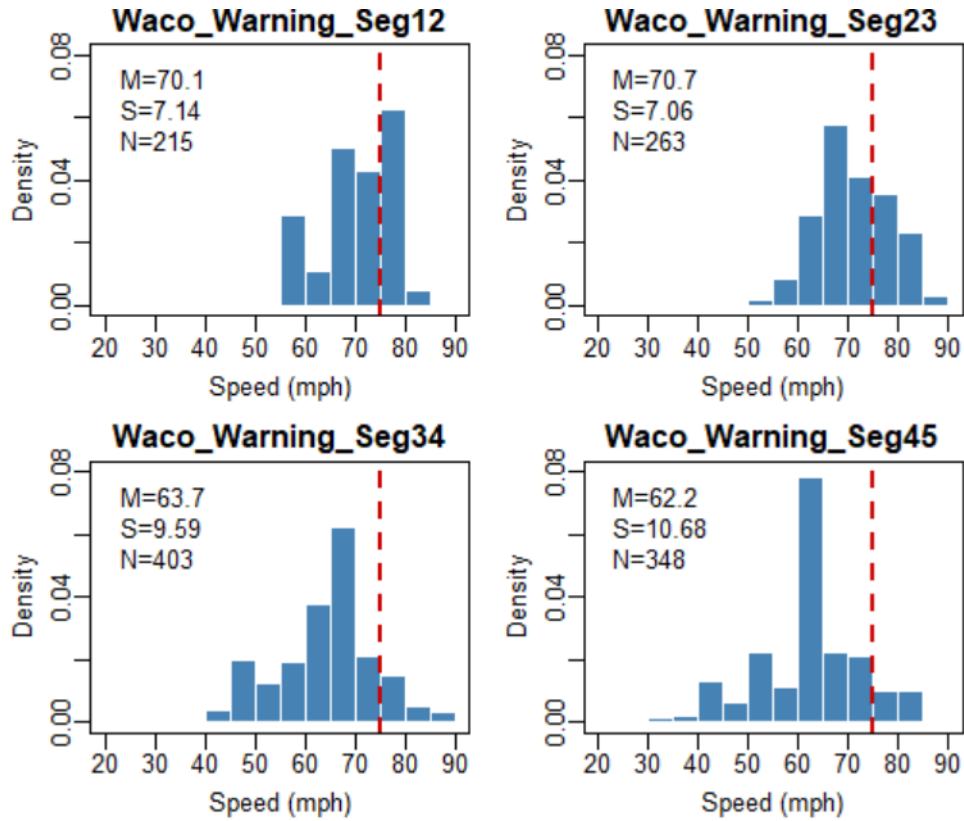


Figure B.1. Travel speed during warning message at Waco-Utica test site

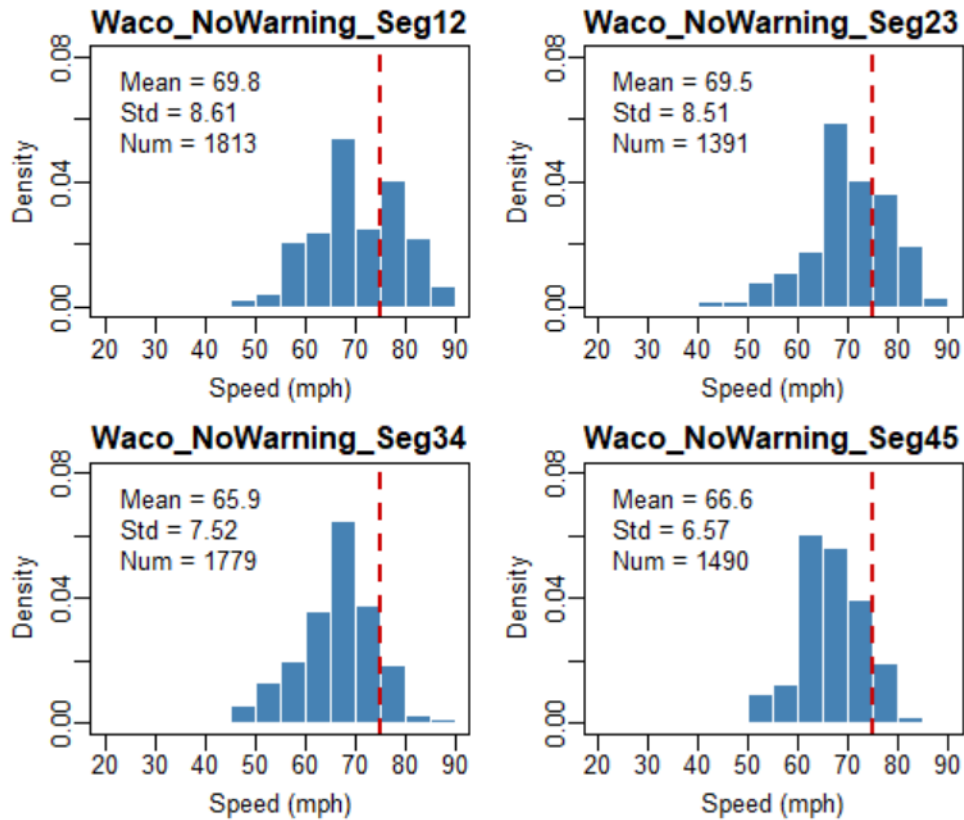


Figure B.2. Travel speed during non-warning at Waco-Utica test site

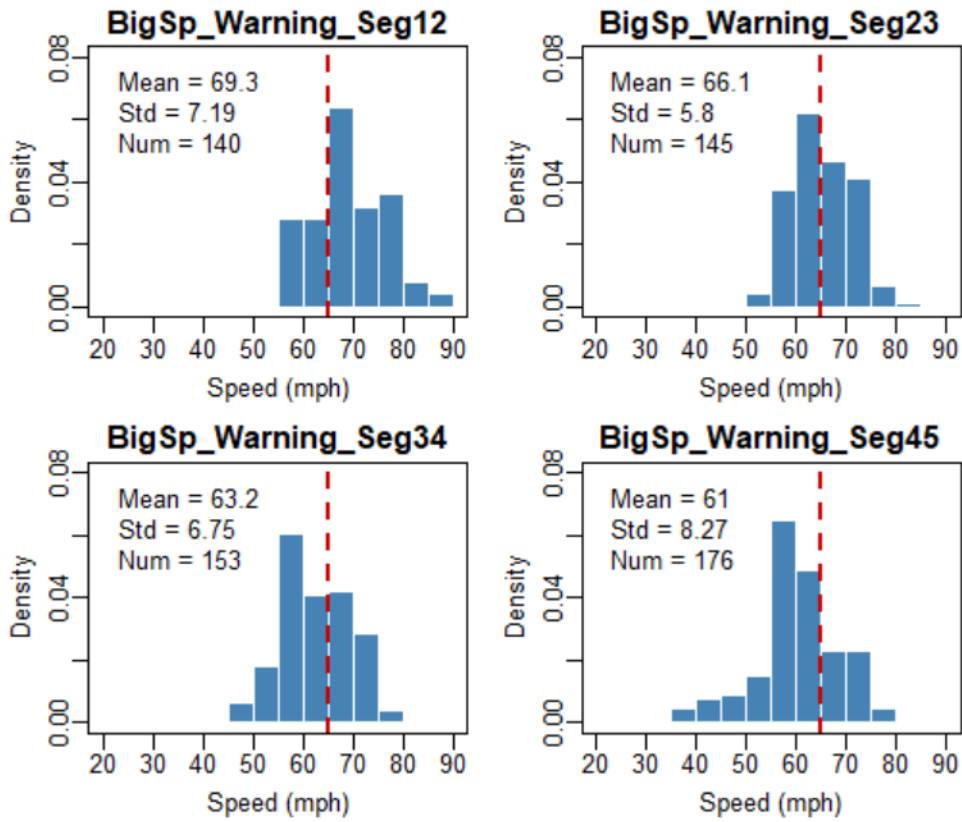


Figure B\_3. Travel speed during warning message at Big Springs test site

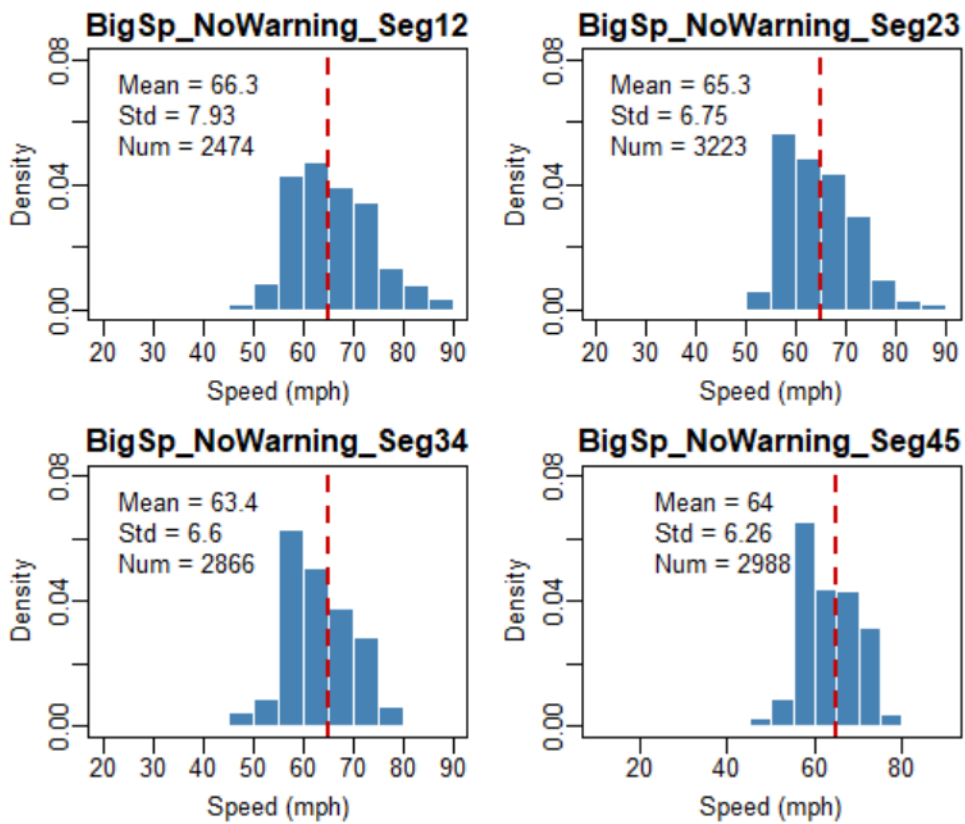


Figure B\_4. Travel speed during no warning message at Big Springs test site

## C. Technical Memorandum

### Technical Memorandum 1

#### Intelligent Work Zone Using Automatic Queue Detection Systems (FY21 (007))

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To	Matt Neemann, Lead TAC Member - NDOT Traffic Matt BakerLead TAC Member - NDOT Operations
From	L.R. Rilett, Ph.D., P.E. Li Zhao, Ph.D. Ernest Tufuor
Date:	July 15, 2020
Re:	Proposed Data Collection Plan

---

### 1. Background

The research team analyzed data from three potential candidate sites and seven total locations:

1. Waco-Utica (WB I-80 / EB I-80)
2. Mahoney (WB I-80 / EB I-80)
3. Big Springs (WB I-80 / EB I-80 / EB I-76)

A synopsis of each site, including map and a speed – day of week graph, is provided in Appendix A. Note that the Goehner-Milford (WB I-80 / EB I-80) site has yet been activated and therefore was not considered in this document. When it becomes activated it will also be considered for data collection.

### 2. Recommendation

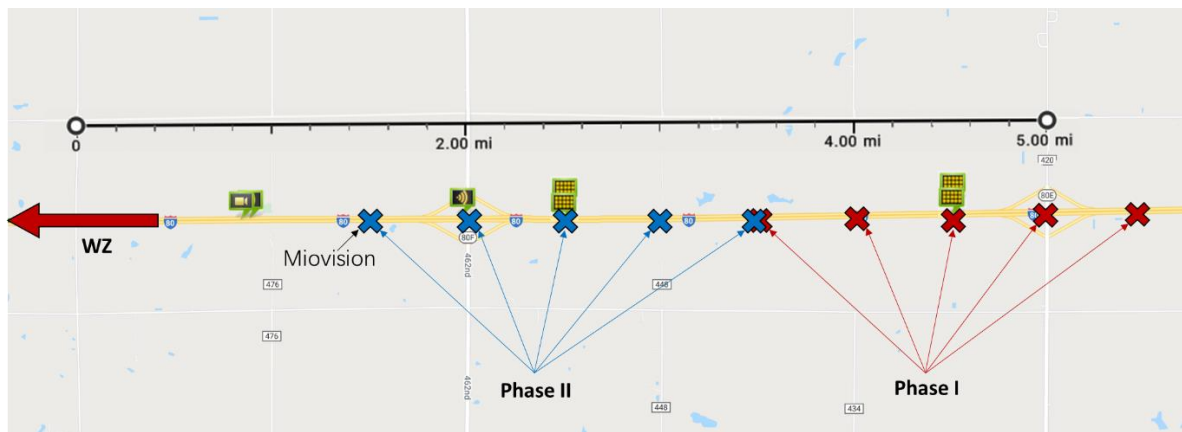
Because Waco-Utica has the most congestion, the research team recommends that this site be used for the first data collection. This was based on the data analysis described in Appendix A.

The team proposes collecting data on the westbound location first. Once this is complete, it is proposed that data on the eastbound location be collected next.

### 3. Waco-Utica Data Collection Plan

#### 3.1 Waco-Utica: Westbound I-80

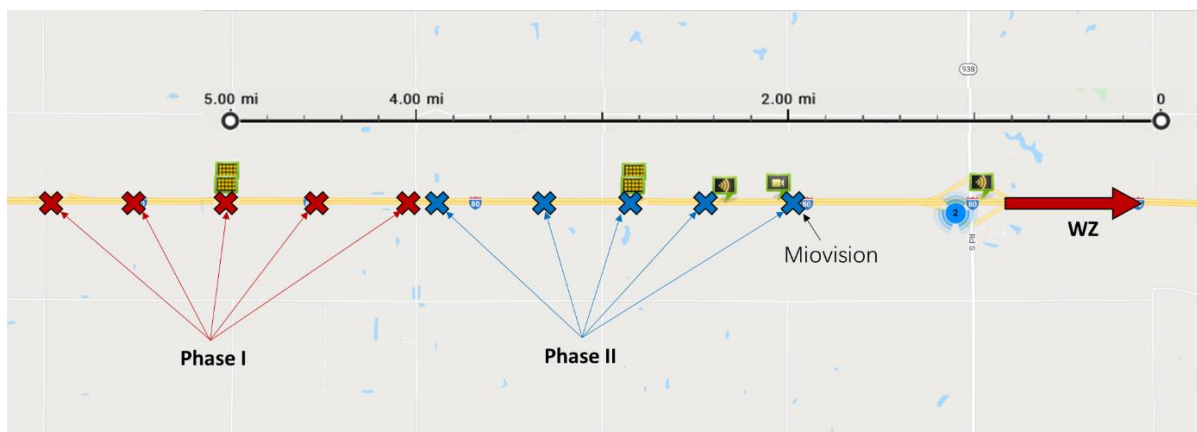
The data collection will be conducted in two phases in order to capture behavior at both of the PDMSs. Both phase 1 and phase 2 will consist of data collection over 10 weekdays (e.g. 20 days in total). Five (5) Miovision sensors will be placed upstream and downstream of the target PDMS at 0.5-mile intervals as shown in Figure C1\_1 below. The data will be monitored to see if the Miovision spacing plan should be modified.



**Figure C1\_1. Data Collection Plan: Westbound 1-80 Waco-Utica**

### 3.2 Waco-Utica: Eastbound I-80 location

The eastbound I-80 data collection will be conducted in two phases in order to capture behavior at both of the PDMS signs. Both phase 1 and phase 2 will consist of data collection over 10 weekdays (e.g. 20 days in total). Five (5) Miovision sensors will be placed upstream and downstream of the target PDMS at 0.5-mile intervals as shown in Figure C1\_2 below. The data will be monitored to see if the Miovision spacing plan should be modified.



**Figure C1\_2. Data Collection Plan: Eastbound 1-80 Waco-Utica**

In addition to the Miovision data, the video data, if available, will be collected from the subcontractor. The travel data from the Regional Integrated Transportation Information System (RITIS) will also be collected. Note that research team is still working with the RITIS team to obtain the relevant data. The HCM/WZQ-Pro tool will also be used, prior to the data collection, to estimate the max queue length accumulated upstream of WZ.

### 4. Questions for NDOT Technical Advisory Committee

- The research team would like to know 1) the start date and 2) the tentative end date for of every SWZ project listed in Appendix A.



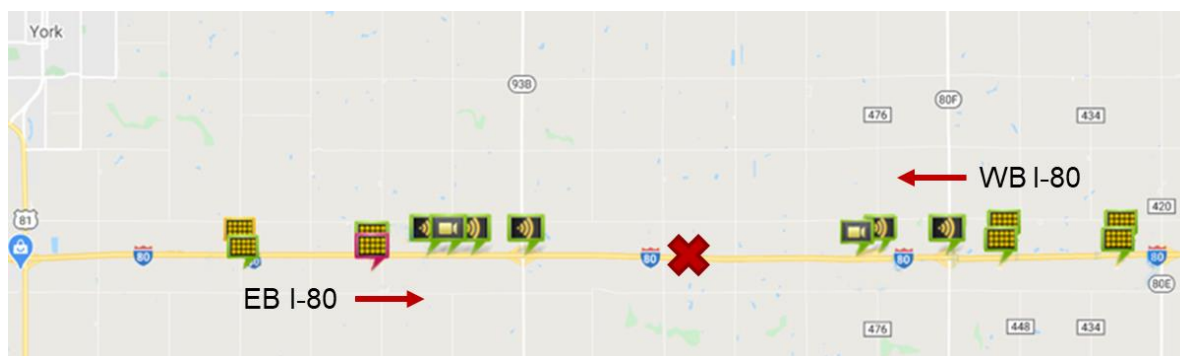
- If possible, the research team would like to know the work schedule (Weekdays/weekends? 8 am – 5 pm?) for each smart work zone listed in Appendix A so that we can better plan the data collection.
- The research team would like to record the video from the field cameras in each of the SWZ systems. Is it possible for the contractors to provide this data? At a minimum the research team would like the video records for the days the team is collecting data. Ideally, we would like all video data when the work zone is active.
- Is the recommended data collection plan acceptable? If so, we will contact the NDOT contact for the site and begin to coordinate the data collection process.

## 5. Concluding Remarks

The research team will continue to monitor the sites remotely. If traffic increases such that queues begin to form on a regular basis the team will revisit their data collection plan. This will be particularly true for the Mahoney site as it is scheduled to end in August, and it is the only three-lane SWZ active in 2020 (to the team’s best knowledge).

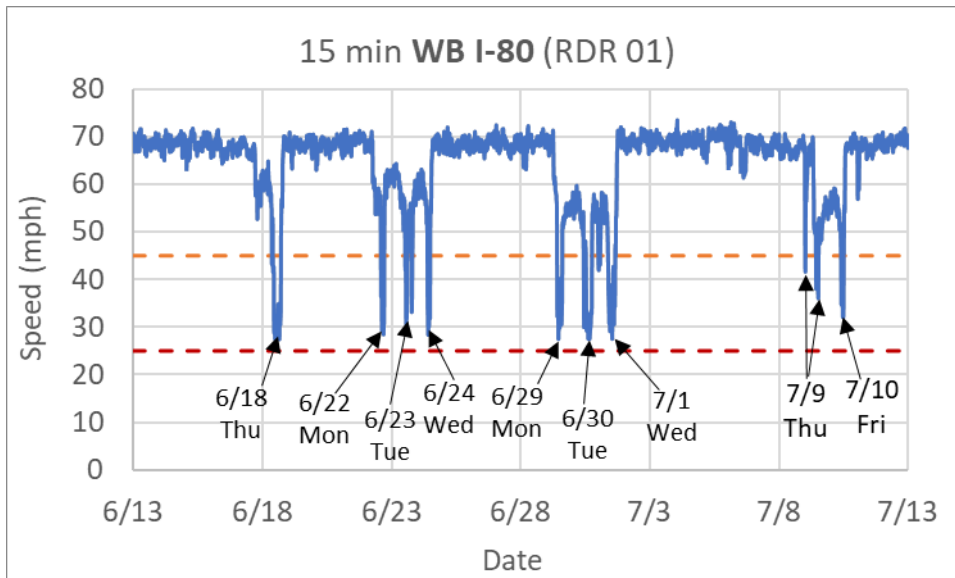
## 6. Potential Data Collection Sites

### (1) Waco-Utica (2 locations: Westbound I-80 and Eastbound I-80)



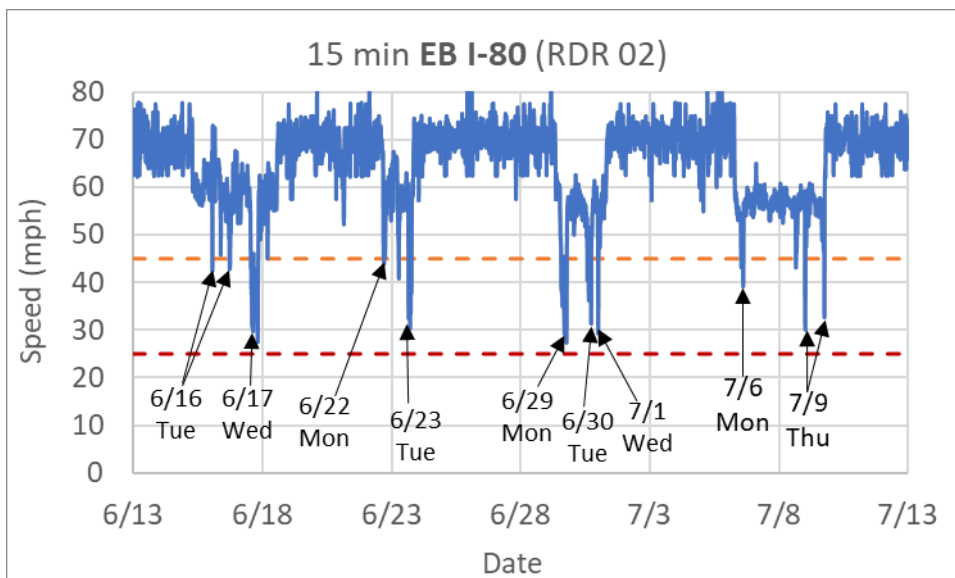
**Figure C1\_3. Site Map at Waco-Utica**

- **Data Sources:** Salander - Total traffic counts (at 1-min interval), Average speed (at 1-min interval), Vehicle count by type (at 1-min interval), PDMS posted messages, Camera
- **NDOT Contact:** District 4 Construction Engineer: Eric Klein [eric.klein@nebraska.gov](mailto:eric.klein@nebraska.gov)



**Figure C1\_4. Westbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020**

- **WB Synopsis:** Speeds have dropped below 45 mi/h on a number of days during the past month. These mainly occur on weekdays. Good candidate for collecting data.



**Figure C1\_5. Eastbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020**

- **EB Synopsis:** Speeds have dropped below 45 mi/h on a number of days during the past month. These mainly occur on weekdays. Good candidate for collecting data.

## (2) Mahoney (Two locations: Westbound I-80 and Eastbound I-80) Site Map

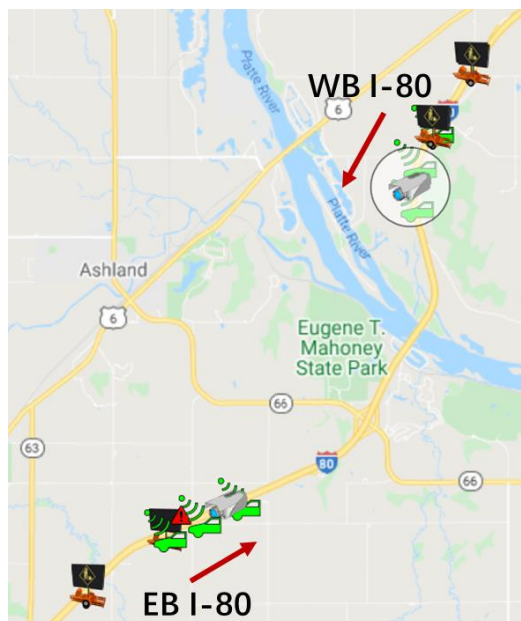


Figure C1\_6. Site Map at Mahoney

- **Data Sources:** Ver-Mac, Total traffic counts (at 1-min interval), Average speed (at 1-min interval), Occupancy (at 1-min interval), Gap/Headway (at 1-min interval), Vehicle count by type (at 1-min interval), PDMS posted messages, Camera
- **NDOT Contact:** District 1 Construction Engineer: Curt Mueting [curt.mueting@nebraska.gov](mailto:curt.mueting@nebraska.gov)

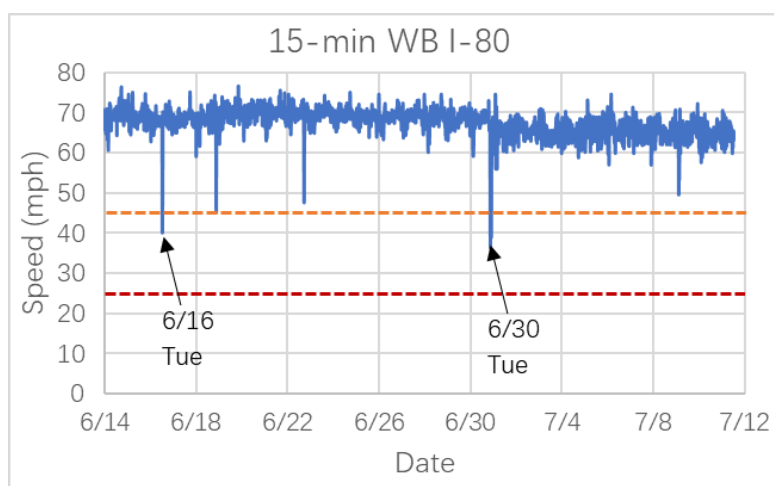
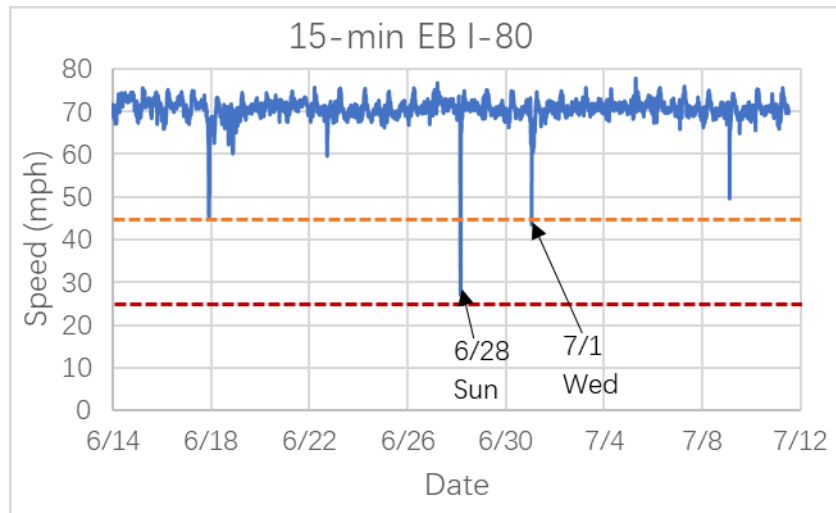


Figure C1\_7. Westbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020

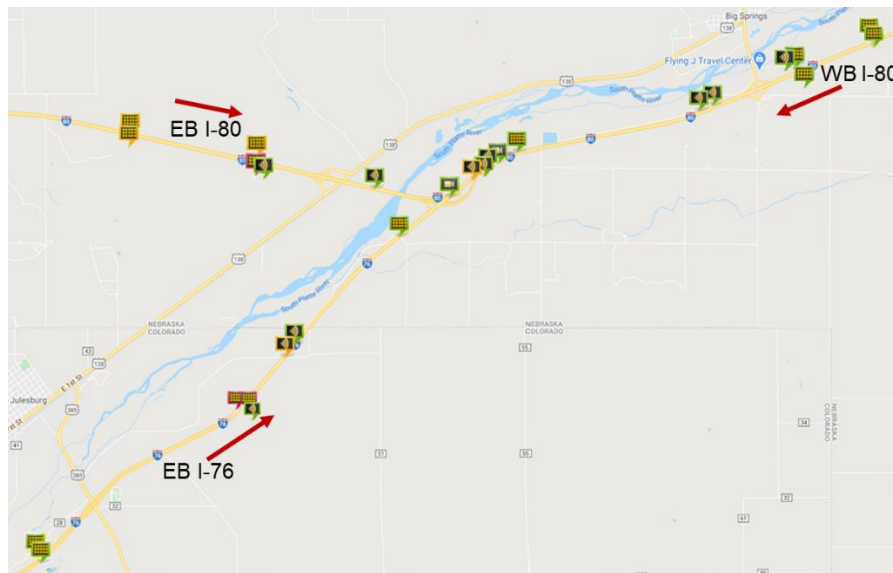
- **Synopsis:** Speeds have dropped below 45 mi/h on only two days during the past month. Both times were for less than one hour. Currently not a very good candidate for collecting data. Will continue to monitor site as the Mahoney WZ is the only three lane work zone that is currently active.



**Figure C1\_8. Eastbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020**

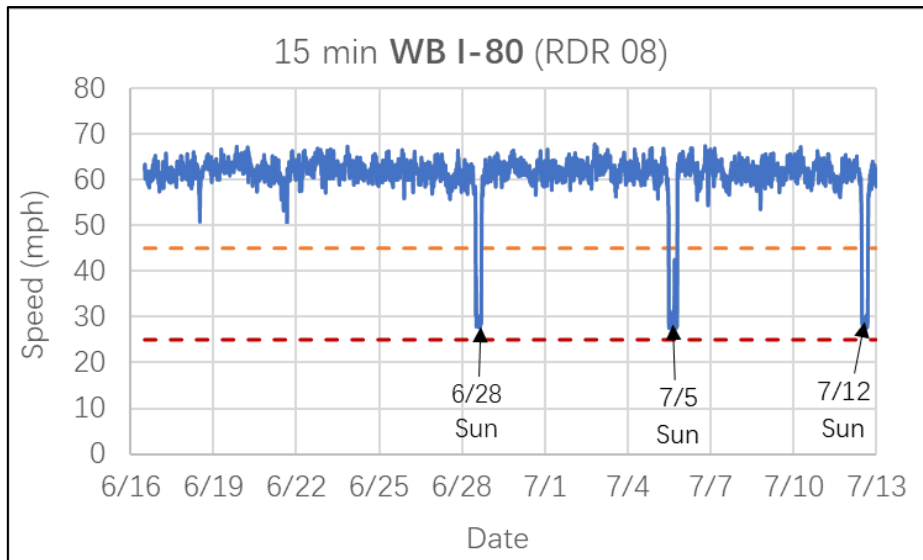
- **Synopsis:** Speeds have dropped below 45 mi/h on only two days during the past month. Both times were for less than one hour. The occurrences appeared to be random over the month. At no time were the speeds less than 25 mi/h. Currently not a very good candidate for collecting data. Will continue to monitor site as the Mahoney WZ is the only three lane work zone that is currently active.

**(3) Big Springs (Three locations: Eastbound I-80, Westbound I-80, Eastbound I-76)**



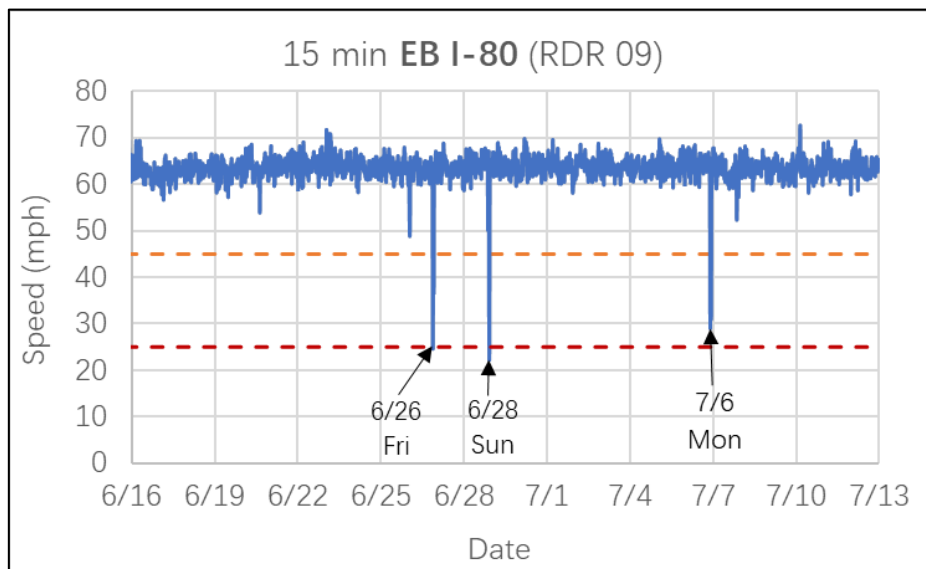
**Figure C1\_9. Site Map at Big Springs**

- **Data Sources:** Salander, Total traffic counts (at 1-min interval), Average speed (at 1-min interval), Vehicle count by type (at 1-min interval), PDMS posted messages, Camera
- **NDOT Contact:** District 6 Construction Engineer: Cameron  
Craig Cameron.craig@nebraska.gov



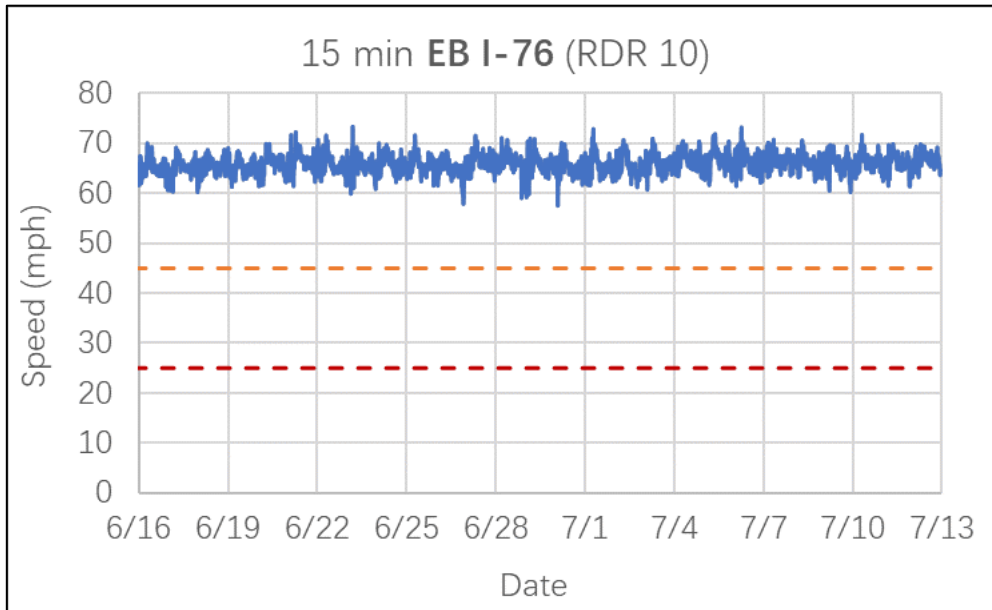
**Figure C1\_10. Westbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020**

- **Synopsis:** Speeds have dropped below 45 mi/h on only three days during the past month. All three days were Sundays and the queues lasted for several hours. It is unsure if this patten will continue in the future. Currently not a very good candidate for collecting data as the congestion only appears to occur 1 day per week. Will continue to monitor site.



**Figure C1\_11. Eastbound I-80: Travel speed versus Day – June 14, 2020 - July 12, 2020**

- **Synopsis:** Speeds have dropped below 45 mi/h on only three days during the past month. Both times were for less than one hour. Occurrences were random over the month. On only two occasions was the speed less than 25 mi/h. Each time the speed drop was only for 30 minutes or less (15 min aggregate data). Currently not a very good candidate for collecting data. Will continue to monitor site.



**Figure C1\_12. Eastbound I-76: Travel speed versus Day – June 14, 2020 - July 12, 2020**

- **Synopsis:** Speeds have not dropped below 45 mi/h during the past month. Currently not a very good candidate for collecting data. Will continue to monitor site.

## 7. Data Collection System Contact

**Table C1\_1. Technical Consultation Contact**

Contractor	Project	Online data operated by subcontractor	Contact
SmartStreets	Grand Island	Transnomis	Tim Jackson <a href="mailto:tjackson@streetsmartrental.com">tjackson@streetsmartrental.com</a>
SmartStreets	Mahoney	JamLogic	Tim Jackson <a href="mailto:tjackson@streetsmartrental.com">tjackson@streetsmartrental.com</a>
Salander	Big Springs, Waco-Utica	Salander	JP Story <a href="mailto:jp@slndrtech.com">jp@slndrtech.com</a>

## Technical Memorandum 2

### Intelligent Work Zone Using Automatic Queue Detection Systems (FY21 (007))

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To Matt Neemann, Lead TAC Member - NDOT Traffic  
Matt Baker Lead TAC Member - NDOT Operations  
Josh R. Willard, Highway Project Manager, NDOT District 6, North Platte  
Cameron Craig, Construction Engineer, NDOT District 6, North Platte  
Kurt Snider, Inspector, NDOT District 6, North Platte

From L.R. Rilett, Ph.D., P.E.  
Li Zhao, Ph.D.  
Ernest Tufuor, Ph.D.

Date: September 16, 2020

Re: Data Collection at Big Springs Work Zone – Miovision Battery Replacement

---

#### 1. Background

The research team has installed five Miovision detectors on the westbound section of I-80 at the NDOT work zone at Big Springs, Nebraska. A map showing the approximate locations is shown below in Figure C2\_1.

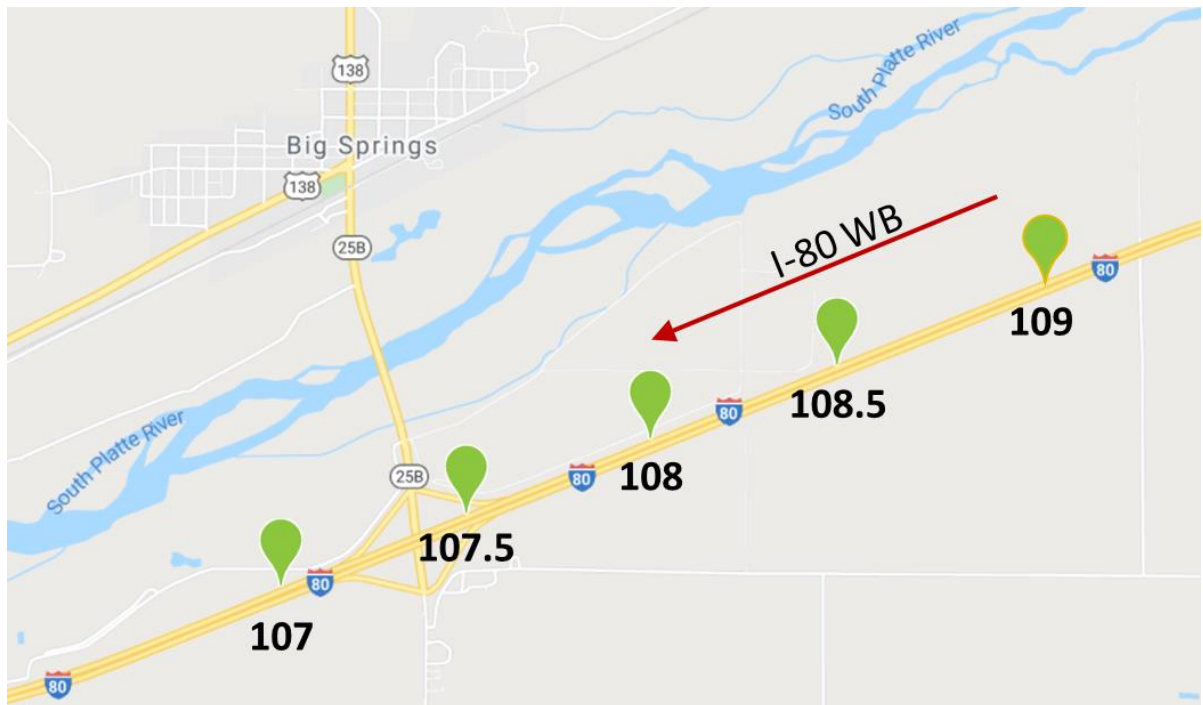


Figure C2\_1. Map showing approximate Miovision locations.

The Miovision units are attached to mile marker signs at five locations. These mile markers are: 109, 108.5, 108, 107.5 and 107 on the westbound section of I-80. Figure C2\_2 shows a typical setup of the Miovision unit at Big Springs.

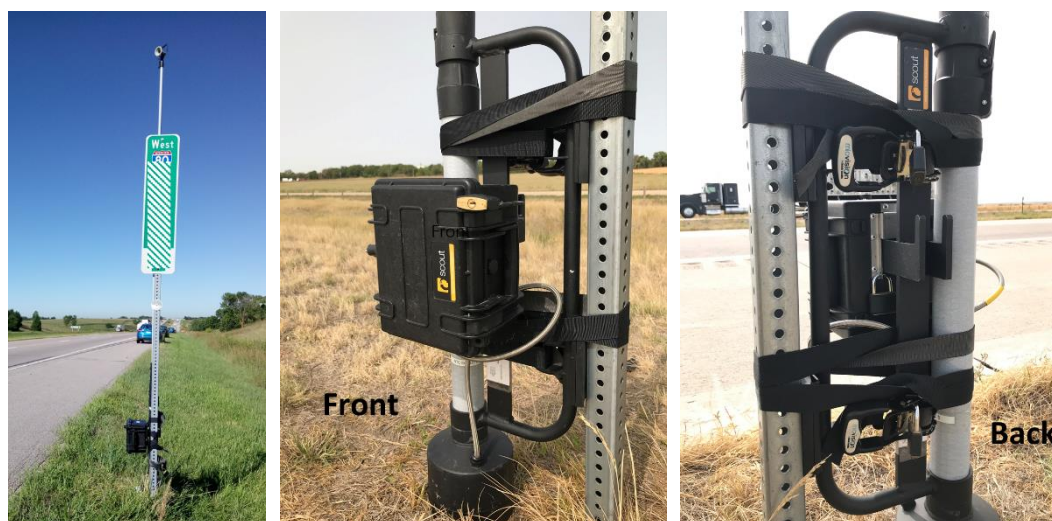


Figure C2\_2. Miovision set up

## 2. Battery Replacement Plan

NDOT has agreed to help with the recharging of the Miovision batteries. This will be done every seven days. Over the next two weeks the plan would be to charge the batteries twice. The required charging days and periods are as follows:

- **On September 22:** Batteries are removed in the afternoon of September 22, charged overnight (>12hrs), and placed back in the morning of September 23.
- **On September 29:** Batteries are removed in the afternoon of September 29, charged overnight (>12hrs), and placed back in the morning of September 23.

## 3. Battery Removal and Replacement Process

On the side of the Miovision unit, there are Video portal and Battery portal, see Figure 3. They will be used in the following process.

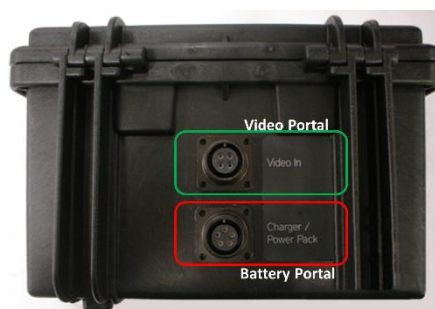


Figure C2\_3. Miovision Unit with Video Portal and Battery Portal



### 3.1. Battery Replace Procedure

- *Disconnect the Video Portal*

The Video cable needs to be disconnected first, as seen in Figure C2\_4. The video portal is indicated in Figure C2\_3. Note: Each Miovision unit should be marked with the location so that when they can be replaced to the same location next time.



**Figure C2\_4. Disconnect the video cable**

- *Battery Removal*

The battery removal consists of two steps as shown in Figure C2\_5. The first step is to unlock the battery box as shown in Figure C2\_5a. The key was provided to Kurt Snider. The second step is to remove the battery. This is done by sliding the unit upwards and out as shown in Figure C2\_5b.



**Figure C2\_5a. Unlock the unit**



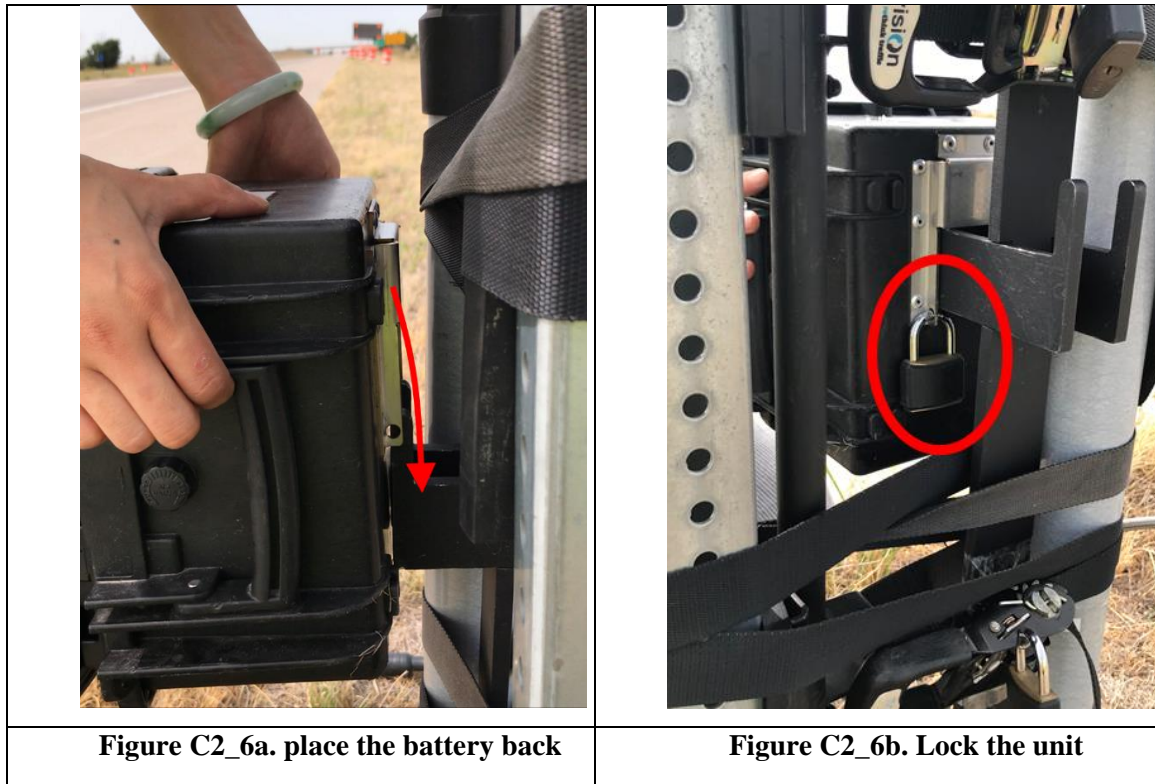
**Figure C2\_5b. Remove the battery**

- *Battery Charging*

Once all five batteries have been removed, they can then be charged. The battery charger is connected directly to the battery portal (as indicated in Figure C2\_3). The five battery chargers were provided to Kurt Snider.

- *Battery Replacement*

The charged battery is placed back in the reverse order that they were removed. See Figure C2\_6.



- *Connect the Video Portal*

Put back the video cable to the video portal as shown in Figure C2\_7. The video portal is indicated in Figure C2\_3. Note: Make sure the Miovision unit is the same one that was been replaced.



**Figure C2\_7. Connect the video cable**

### Technical Memorandum 3

#### Intelligent Work Zone Using Automatic Queue Detection Systems (FY21 (007))

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To Matt Neemann, Lead TAC Member - NDOT Traffic  
Matt Baker, Lead TAC Member - NDOT Operations

From L.R. Rilett, Ph.D., P.E.  
Li Zhao, Ph.D.  
Ernest Tufuor, Ph.D.

Date: February 19, 2021

Re: NDOT AQD System

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#### Overview

The research team studied the AQD data from two test sites:

4. Waco-Utica, WB I-80
5. Big Springs, WB I-80

A synopsis of each site, including the layout of the AQD system and the speed-warning message data on selected congestion days, and the analysis work is provided below followed by a number of questions to the TAC.

#### AQD System at Waco-Utica WB I-80

As can be seen in Figure C3\_1, the AQD system at the Waco-Utica WB I-80 consists of a sensor (i.e., RDR02) at the beginning of the work zone, and two sets of PCMSs at 1 mile (i.e., MB07 and MB08) and 3 miles (i.e., MB09 and MB10) upstream. The RDR02 detects speed to feed the PCMS with corresponding messages.

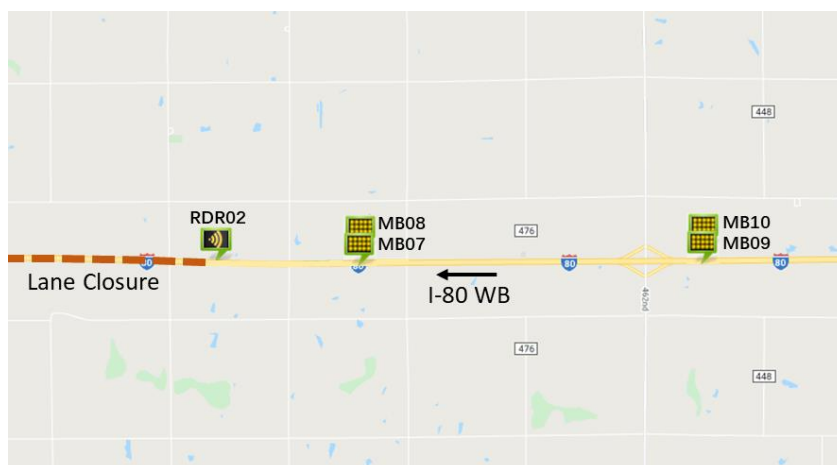
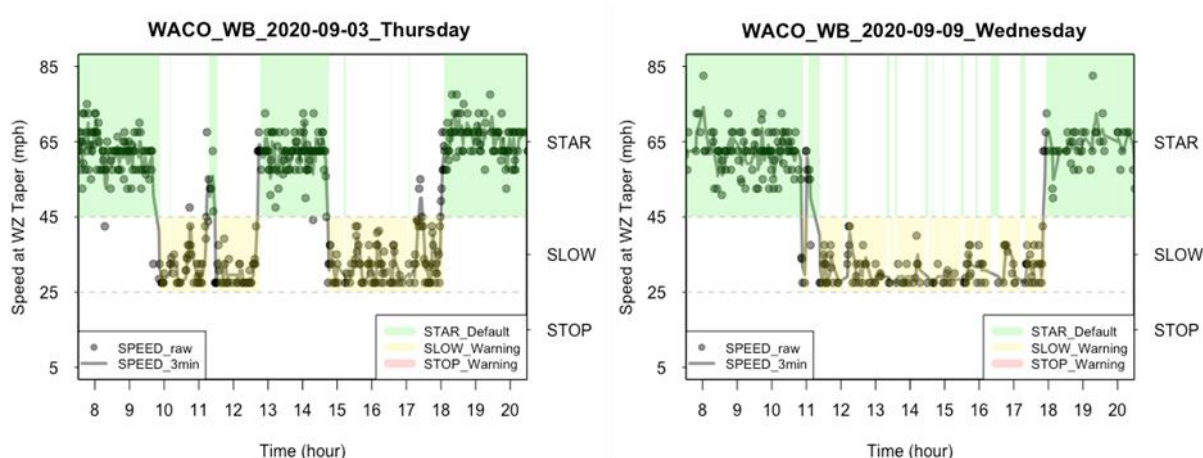


Figure C3\_1. AQD System installed at Waco-Utica WB I-80

The speed raw data and its 3-min average are shown in Figure C3\_2 (black dots and line corresponding to the left y axis). The PCMS message durations are also shown in Figure C3\_2 (red, yellow, and green shades corresponding to the right y axis).

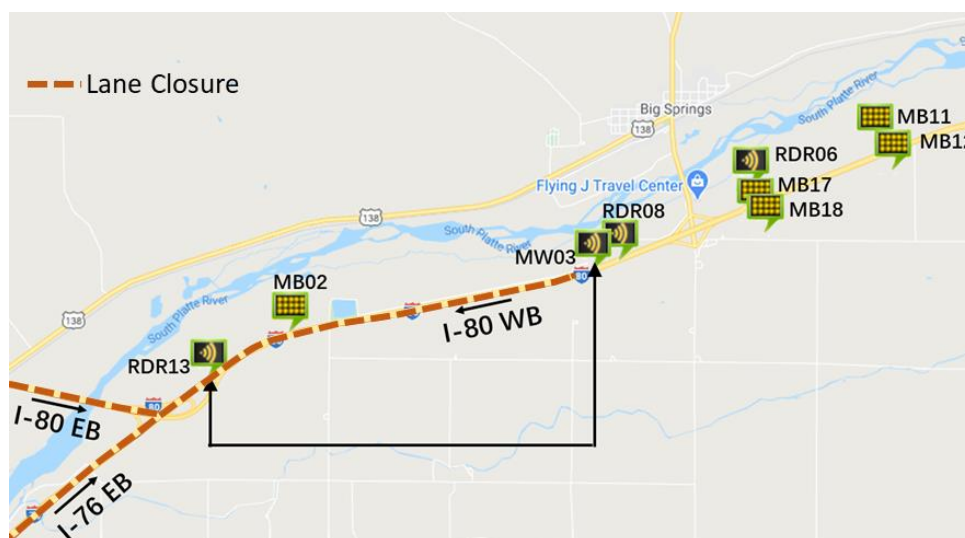


**Figure C3\_2. AQD speed detected from sensor RDR02 and message released on PCMSs 07-10.**

It can be seen from Figure C3\_2 that, when the average speed dropped below 45 mph, the PCMSs displayed warning message for “Slow Traffic”. This verifies the functionality of the AQD system according to its algorithm. There was no warning message for “Stop Traffic” as no speed below 25 mph was detected.

### AQD System at Big Springs WB I-80

As can be seen in Figure C3\_3, the AQD system at the Big Springs WB I-80 consists of two sensors (i.e., RDR13 and MW03), and three sets of PCMSs (i.e., MB02, MB17&18, and MB11&12). Both the RDR13 and the MW03 detect speeds to feed the PCMS with corresponding messages together.



**Figure C3\_3. AQD System installed at Big Springs WB I-80**

Due to the complexity of this test site, the algorithm of the AQD system is slightly different from the previous settings. For example, the jam speed threshold is 20 mph instead of 25 mph, and the average speed is calculated using a three (3) minute window instead of a five (5) minute window. However, the most notable difference is that information from two speed sensors (e.g., RDR13 located in the work zone and MW03 located at the beginning of work zone) are both used in deciding the activation of the warning message. The sensors are approximately 3.5 miles apart. The data collection components used in the algorithm of the AQD system at this test site are listed in Figure C3\_4.

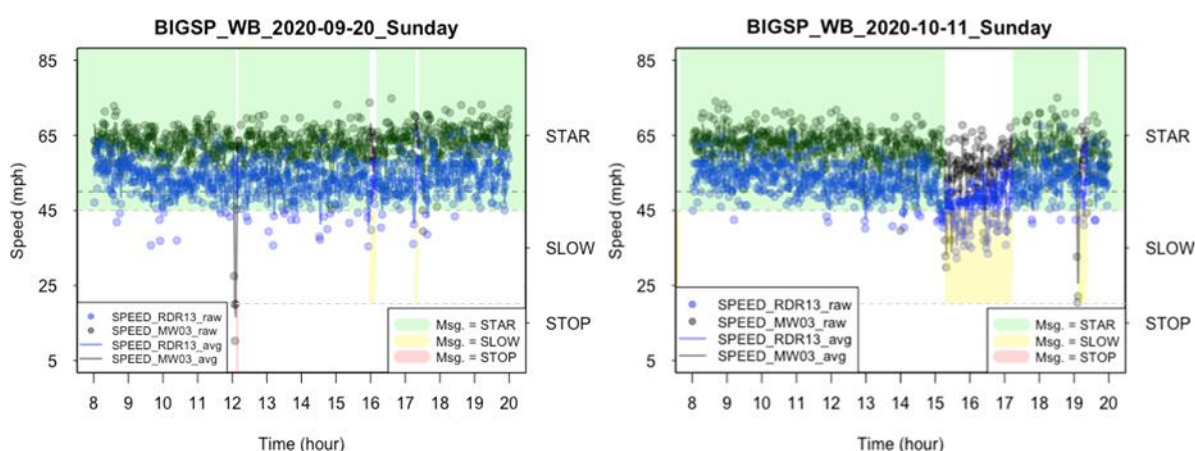
WB80 1 - Sensor List						
Order	Sensor	Current Speed	Free Flow Speed	Cong. Speed	Jam Speed	Avg Min
1	<a href="#">RDR 13</a>	55.95	50.0	45.0	20.0	3
2	<a href="#">MW 03</a>	63.0577	50.0	45.0	20.0	3

WB80 1 - Sign List	
Order	Sign
1	<a href="#">MB11</a>
2	<a href="#">MB12</a>
3	<a href="#">MB17</a>
4	<a href="#">MB18</a>
5	<a href="#">MB02</a>

**Figure C3\_4. The list of the AQD system devices at WB I-80 test site, Big Springs.**

To illustrate, the speeds and the posted message collected from the AQD system, and data from two example days are shown in Figure C3\_5. Note the speeds collected from RDR13 in the work zone are indicated using a blue circle, and the speeds collected from MW03 at the beginning of the work zone are indicated using a black circle. In general, the latter speed value are lower than the former. This makes sense because the speed limits at the two sections are 65 mph and 55 mph, respectively. The latter is the merge location.



**Figure C3\_5. AQD speed detected from sensors MW03 & RDR13 and message released on PCMSs 02, 11, 12, 17, and 18.**

On 2020-09-20, sensor MW03 at the beginning of work zone (black color) detected a 4-min speed drop below 20 mph after 12 pm. At this point, a “stop traffic” warning message was posted on the PCMSs. Similarly, there were a sporadic time that the RDR13 (blue color) detected slow speeds and activated the “slow traffic” warning message in the afternoon.

On 2020-10-11, the sensor RDR13 in the work zone (blue color) detected a 2-hour speed reduction below 45 mph during 3 – 5 pm. Sensor MW03 (black color) also detected slow speeds at 7 pm for a couple of minutes. They also activated the corresponding “slow traffic” warning message as expected.

In summary, it was concluded that the algorithm works as designed, in that either one of the speed sensors, i.e., RDR13 in work zone or MW03 at beginning of work zone, will activate the PCMS with the predefined warning messages corresponding to speed thresholds.

### Questions for NDOT Technical Advisory Committee

- (1) As shown in Figure C3\_3 at the Waco-Utica test site, there seems a cut-off speed of 26.3 mph. It seems problematic as the lowest detected speed is always 26.3 mph during the entire data collection period at this test site.

In fact, the data collected by NTC research team at the same time, as can be seen in Figure C3\_6, showed a significant queue accumulated most of the day and the average speeds was as low as 7 mph. A queue accumulated longer than 2 miles and lasted longer than 6 hours was observed in both speed data and from video.

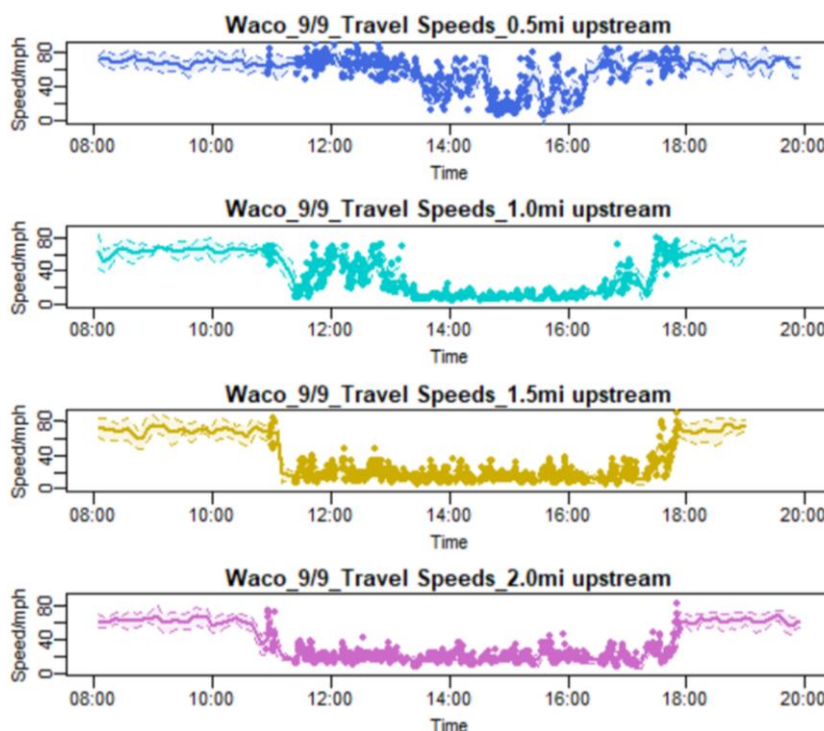


Figure C3\_6. Data collected by the research team in 2 miles upstream of the work zone.

It confirms that, therefore, “stop traffic” (instead of “slow traffic”) warning messages should be released on the PCMSs upstream. We would like to know if there were any changes to the algorithm during this time period because the results disagree with the validation of the AQD system functionality using our data.

- (2) At Big Springs test site, the algorithm using two sensors a few miles apart. One of these is in the work zone and one is not. Is this a concern to NDOT?

For example, when the sensor MW03 at the beginning of work zone detected a slow/stop speed and posted warning message on all the PCMSs. Note the PCMS-MB02 in the work zone displayed the warning message as well. However, drivers traveled around PCMS-02 in the work zone may not experience any slow traffic.

Alternatively, when the sensor in the work zone detected a slow/stop speed and posted warning message at all PCMSs, whilst the traffic at the beginning of the work zone was free flow, it may also cause confusion and driver’s decreased trust in the AQD warning system.

- (3) To conduct the crash analysis at the work zone, we need NDOT to help to identify at least 10 locations of AQD system and their activation dates. This data should be from the past few years.

### Concluding Remarks

The research team will continue to monitor the construction activities remotely through the Salander portal in the Spring and Summer in hoping to find two more new test sites for data collection. Any assistance from NDOT on identifying collection sites will be appreciated.

The research team will also keep working with StreetSmarts contractors (see Table C3\_1) to find out the exact algorithms that was used at the different test sites. Any assistance from NDOT on identifying the logic of the algorithms will be appreciated.

**Table C3\_1. Project contractor contact**

Contractor	Project	Online data operated by subcontractor	Contact
SmartStreets	Waco-Utica, Big Springs	Transnomis	Tim Jackson <a href="mailto:tjackson@streetSMARTrental.com">tjackson@streetSMARTrental.com</a>
Salander		Salander	JP Story <a href="mailto:jp@slndrtech.com">jp@slndrtech.com</a>

**Technical Memorandum 4**  
**Intelligent Work Zone Using Automatic Queue Detection Systems (FY21 (007))**

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To	Matt Neemann, Lead TAC Member - NDOT Traffic Matt Baker, Lead TAC Member - NDOT Operations
From	L.R. Rilett, Ph.D., P.E. Li Zhao, Ph.D. Ernest Tufuor, Ph.D.
Date:	May 2, 2022
Re:	NDOT AQD System

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**Overview**

This tech memo intended to conduct a brief cost-benefit analysis. The cost would be the payment for the service of the AQD systems. The benefit would be the number of vehicles exposed to the AQD systems, which provide warning information of the work zone traffic conditions when needed.

The traffic volume data are obtained using the AQD count data at each test site. The device cost breakdown information is provided by NDOT. With these data, the unit price of the system (dollar per vehicle) is used as a measure of the cost-benefit analysis. Sensitivity analysis is also conducted in the end to examine the changes of the unit price as a function of traffic volumes, totally system costs, and the service time periods.

**Traffic Volume**

Daily traffic volumes at seven (7) I-80 work zone test sites are listed in Table C4\_1. To compare among different test sites, the traffic volume is converted into passenger car unit (pcu) using a PCE = 2 for trucks. Given a six-month period, the total traffic counts in pcu are also given in Table C4\_1.

**Table C4\_1. Traffic volume at all test sites**

Site	Location	Direction	Truck	Daily Traffic (pcu*/24 h)	6-month Traffic (pcu*)
1	Waco	WB	35.2%	13838	2490840
2	Ogallala	WB	31.7%	19205	3456900
3	Ashland	WB	18.4%	39671	7140780
4	Big Springs	WB	31.6%	18878	3398040
5	Henderson	EB	44.2%	19610	3529800
6	Shelton	EB	44.6%	19448	3500640
7	Wood River	EB	33.0%	23432	4217760





















































\* PCE = 2



## System Cost

- AQD System at one test site**

As can be seen in Figure C4\_1, take test site at Westbound I-80 in Ogallala for example, a typical AQD system includes one (1) CCTV camera, three (3) non-intrusive detection, and two pairs (4) of PDMS.

MB06 (Sign)		I-80 WB mile 128.30 at right side		Signal Warning  		
MB10 (Sign)		I-80 WB mile 128.30 at left side		Ok  		
MB05 (Sign)		I-80 WB mile 127.00 at right side		Ok  		
MB07 (Sign)		I-80 WB mile 127.00 at left side		Ok  		
RDR 22 (Sensor)		I-80 WB mile 127.00		Ok  		 70 mph 
CCTV 06 (Camera)		I-80 WB mile 125.00		Ok  		 
MW 08 (Sensor)		I-80 WB mile 125.00		Ok  		 62 mph 
RDR 21 (Sensor)		I-80 WB mile 124.50 at taper		Ok  		 59 mph 

**Figure C4\_1. AQD system at one test site**

When the construction work became complicated, the AQD system may also be adjusted to fit the traffic at work zone. For example, to accommodate the long queue traffic in Westbound I-80 work zone in Big Springs, two additional pairs of PDMS were added to upstream to cover longer distances.

- System cost at one test site**

Based on an estimation of 6 months, the cost of a typical AQD system, take Ogallala as example, is calculated in Table C4\_2.

**Table C4\_2. System cost at one test site**

Device	Unit	Price\$	Count	Month	Sum\$
Portable Queue Detection System	Lump sum	15000	1	-	15000
Central Computer	Lump sum	18250	1	-	18250
Closed Circuit Television Camera	Each	13000	1	-	13000
Portable Dynamic Message Signs	Each/day	156.62	4	6	112766
Portable Non-intrusive Traffic Sensors	Each/day	13.35	3	6	7209
Total\$					166225

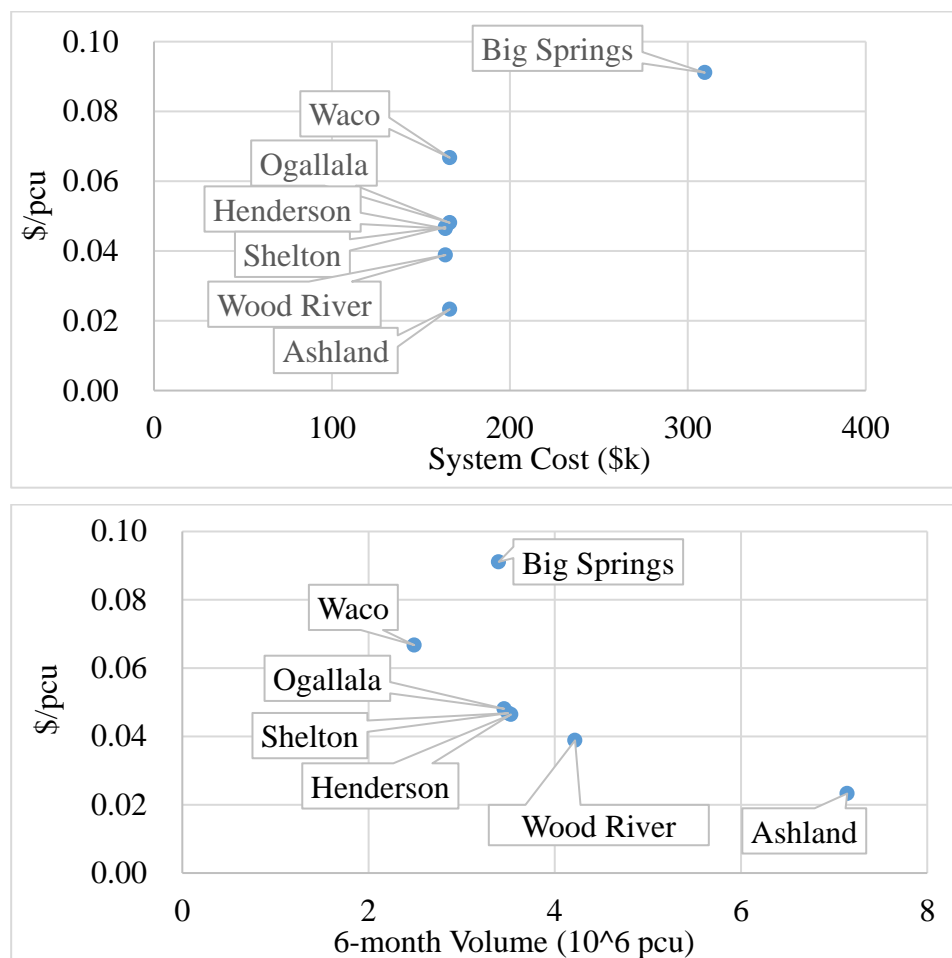
- **Cost benefit analysis**

The system costs for seven test sites are calculated, together with the traffic volumes (pcu), the unit price per vehicle (pcu) is estimated as shown in Table C4\_3.

**Table C4\_3. System costs for all test sites**

Site	Location	System Cost for 6-month period (\$)	6-month Volume (pcu)	\$/pcu
1	Waco	166225	2490840	0.067
2	Ogallala	166225	3456900	0.048
3	Ashland	166225	7140780	0.023
4	Big Springs	309586	3398040	0.091
5	Henderson	163822	3529800	0.046
6	Shelton	163822	3500640	0.047
7	Wood River	163822	4217760	0.039

Figure C4\_2 show the plot of unit price of the system cost per vehicle (pcu) at different test sites using data from Table C4\_3.

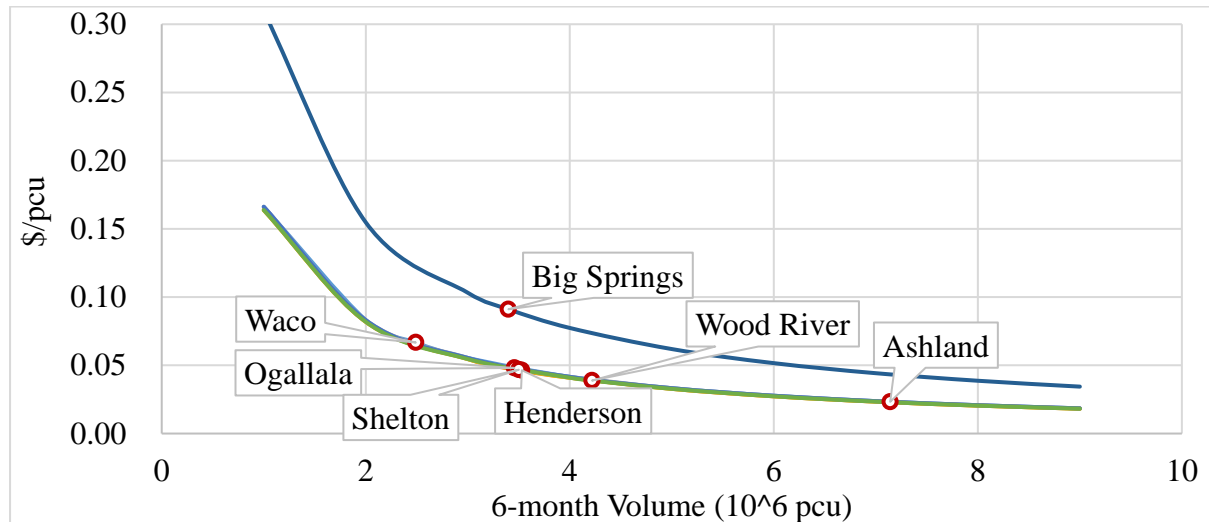


**Figure C4\_2. Unit price of the system cost**

## Sensitivity Analysis

- **Volume**

Given a 6-month period, assume traffic volumes varies from 1 million pcu to 9 million pcu at the locations where the AQD systems could be applied, the sensitivity of the unit price of the system as a function of traffic volume can be found in Figure C4\_3. The dots on the curves represent the actual unit price given the field traffic volume at the corresponding test sites.

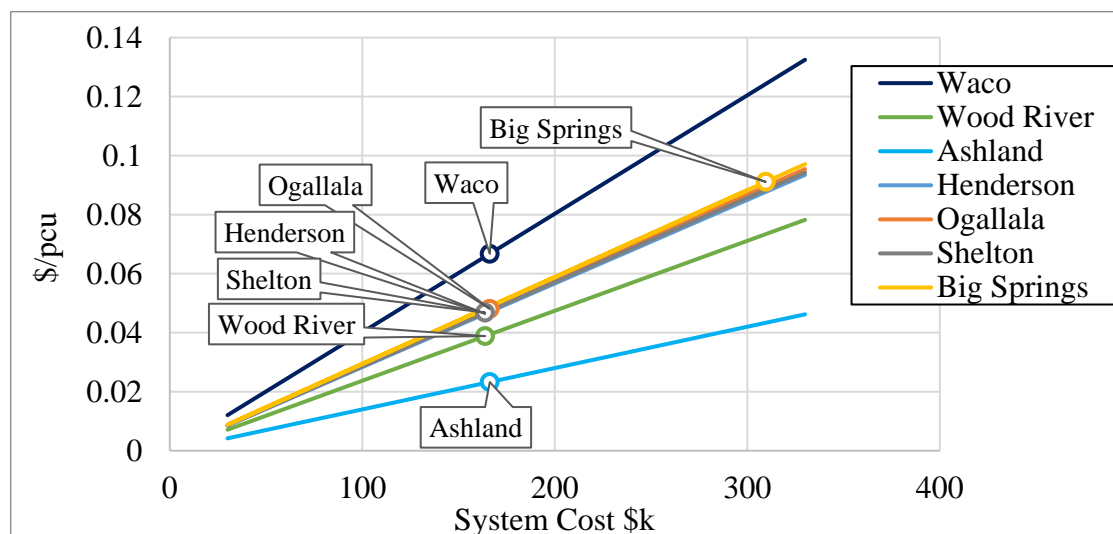


**Figure C4\_3. Unit cost as a function of volume**

It is intuitive that the system is more cost-effective when it serves at the location where the traffic volume is higher.

- **Cost**

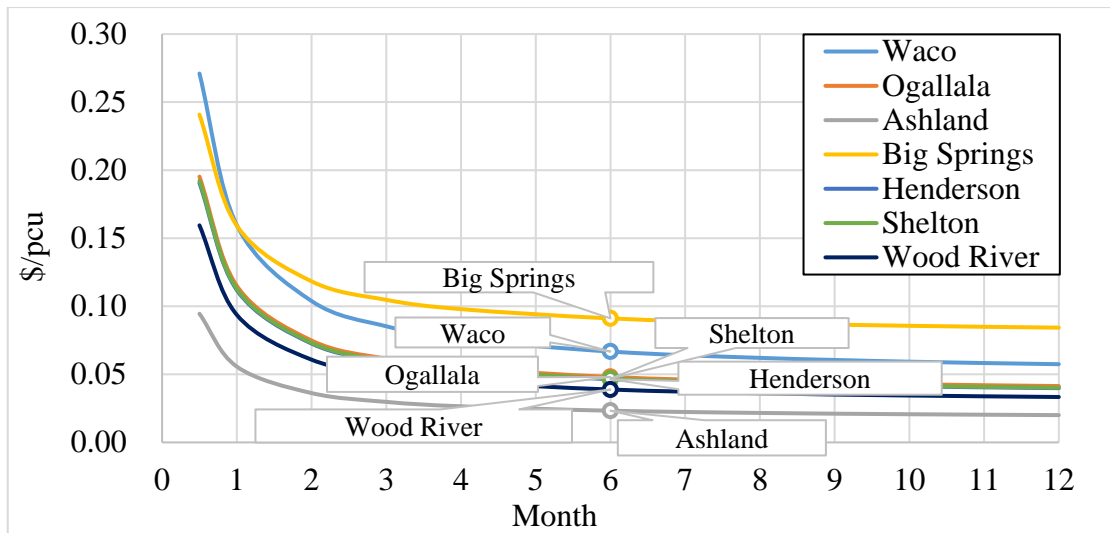
The sensitivity of the unit price as a function of the total system cost can be found in Figure C4\_4. Assume the cost of the AQD systems in a 6-month period varies from \$30k to \$300k (the cost may vary depending on the complexity of the AQD system). The dots on the curves in Figure C4\_4 represent the actual unit price given the total system cost at the corresponding test sites.



**Figure C4\_4. Unit cost as a function of system cost**

- **Service Time**

The unit price is also sensitive to the service time that the AQD systems in operation. This is because as time passes, the system costs increase due to some of the devices are paid at a daily rate (e.g., cameras, detectors, PDMS). At the same time, the traffic volume is also accumulated. The resulting relationship at each test site is shown in Figure C4\_5. The dots on the curves in Figure C4\_5 represent the actual unit price estimated based on a six-month service time period at the corresponding test sites.



**Figure C4\_5. Unit cost as a function of time (months)**

As time passes by, the increase of the system cost and the increase of the traffic volume that the system served will reach to a balance. In other words, the unit price goes down to a steady level after a certain service time of the AQD systems.

### Concluding Remarks

In the analysis, several assumptions were made:

1. One-day (24 hours) traffic volume was collected at each test site and was projected to 6-month (180 days), assume that traffic volume does not change over time.
2. The lump sum of the Portable Queue Detection Systems and the Centre Computer are given as \$15k and \$18.25k (in Table C4\_2). It was assumed that this price works for all the test sites, regardless of the complexity of the AQD systems that was actually in operation.