Usefulness and Reliability of Probe Data When Alerting Work Zone Message Signs

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SWZDI
Smart Work Zone Deployment Initiative

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16. Abstract

This study investigated the viability of using crowdsourced data sets, specifically segment speed data (SSD) and connected vehicle data (CVD), for providing real-time traffic information to the public. After a literature review and interviews with state department of transportation personnel were conducted, the study focused on work zone queue warning systems (QWS). Data from six work zones in Iowa were analyzed and compared in terms of data completeness, accuracy, and latency between SSD, CVD, and sensor data. The SSD showed high data completeness but poor performance in terms of missed and false calls, latency, and queue warning display. CVD, despite having challenges with overnight data coverage, achieved low missed calls and better latency than SSD. A virtual QWS approach was developed to evaluate the effectiveness of combining SSD and CVD. This involved using the archived data as a data feed to determine whether a queue warning would have been displayed. The SSD and CVD were compared against when the sensor data would have supplied a warning. In addition, an option combining both the SSD and CVD was tested. For this test, CVD performed better than SSD. The option combining both CVD and SSD was incrementally better than CVD alone. The study suggests that CVD has some potential for QWS applications, although low data coverage during overnight hours may be challenging. While SSD has good data coverage, it is less effective at identifying congestion. Further refinement in data processing and integration methods may be able to reduce false calls and improve overall performance.

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USEFULNESS AND RELIABILITY OF PROBE DATA WHEN ALERTING WORK ZONE MESSAGE SIGNS

Final Report
October 2024

Principal Investigator
Christopher M. Day, Associate Professor
Department of Civil, Construction, and Environmental Engineering, Iowa State University

Co-Principal Investigator
Skylar Knickerbocker, Research Scientist
Center for Transportation Research and Education, Iowa State University

Research Assistant
Dorcas Okaidjah

Authors
Christopher Day, Dorcas Okaidjah, Skylar Knickerbocker

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A report from
Smart Work Zone Deployment Initiative
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
https://swzdi.intrans.iastate.edu/

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EXECUTIVE SUMMARY

An effective strategy to improve work zone safety and provide better service to the public is the provision of public information on changeable message signs (CMS), as illustrated in Figure ES1. Previous studies have found that queue warning systems (QWS) can reduce the number and severity of rear-end crashes on freeways. QWS are now widely used and rely on the use of field sensors (most often radar sensors) to measure traffic speeds in the field. The deployment and management of these devices incurs costs, and there can be challenges when the extents of work zones change.

Figure ES1. Example queue warning display on portable CMS

With recent advances in data collection, it is now possible to obtain real-time traffic data from a variety of sources without any field infrastructure. Such options include average speeds for defined road segments, which we will call segment speed data (SSD), and vehicle trajectories, including geographic waypoints and instantaneous speed measurements, from connected vehicle data (CVD). Such data have been used for a variety of applications. SSD, being the older of the two, has been widely used by agencies for congestion monitoring at a high level, such as identifying the total amount of congestion on a road or where congestion has tended to occur over time, with a few exploratory studies into the use of the data for real-time monitoring. CVD are much newer and are still being tested. The purpose of the present study was to determine whether these data sets are capable of filling the role of physical radar sensor data in providing public information about work zones. A further question investigated in this study was whether SSD and CVD can be combined for this purpose. This research focused on these data sources for QWS applications.

This study included a series of interviews with state department of transportation (DOT) personnel to better understand their practices with respect to public information about work zones. All of the DOTs use QWS, and this application is considered a much higher priority use case for public information compared to the provision of travel time or other information. Some states provide additional information using 511 systems or smartphone applications and other services. The use of radar sensor data to determine whether to present a queue warning was reported by all of the DOT interviewees, with a few having tested the use of SSD for this application with mixed results. Latency, or the delay between the start of congestion in the field and the time it is reported by the data, was a concern for the use of SSD. Another concern was the size of the segments. Because the segments are typically 0.5 miles or longer, and an average speed is reported, it tends to be less sensitive to changes in speed. Congestion must be severe, or slow traffic must be present on the greater portion of a segment, for it to be observable with SSD. Small changes at the start of congestion are harder to detect.

Tests of Crowdsourced Data Sets (SSD and CVD)

To supply sufficient data for QWS, it is necessary for a crowdsourced data set to be complete (i.e., covering all times of day and days of the week), be accurate, and have low latency. This research focused on these basic requirements to determine whether SSD and CVD would be able to supply a data feed for a QWS. To do so, data were obtained from six work zones in Iowa. The SSD included average speed readings obtained from INRIX, using the company’s proprietary XD segmentation scheme, while the CVD were sourced from Wejo. During the intended time period for data collection, the CVD vendor ceased data delivery, necessitating the use of archived data from June 2022. Fortunately, work zone data from SSD, CVD, and field sensors were available for the study period.

Data were acquired from the three sources along with information on the geographic extent of work zones. Spatial relationships between SSD segments, CVD waypoints, Global Positioning System (GPS) locations of sensors, and work zone extent information were used to select and filter the data. After checking that the selected data reflected the correct location and direction of travel in the work zones, four tests were carried out to examine data completeness, accuracy, and latency. In these tests, the sensor data were considered to be the ground truth record of congestion in the work zones. This assumption was necessary because the use of archived data precluded the deployment of alternative means to independently verify the presence of congestion. When selecting work zone locations, sites where the data showed evidence of sensor data errors such as the reporting of a low speed for extended periods of time were excluded.

The first test looked at data completeness. The amounts of available SSD and CVD for the six work zones were compared to assess how many 1-minute intervals during the study period had data. The SSD were largely complete, with over 95% of minutes having real-time data during the study period, and almost no minutes with completely missing data. The CVD, on the other hand, exhibited low sample rates during overnight hours, as illustrated in Figure ES2.

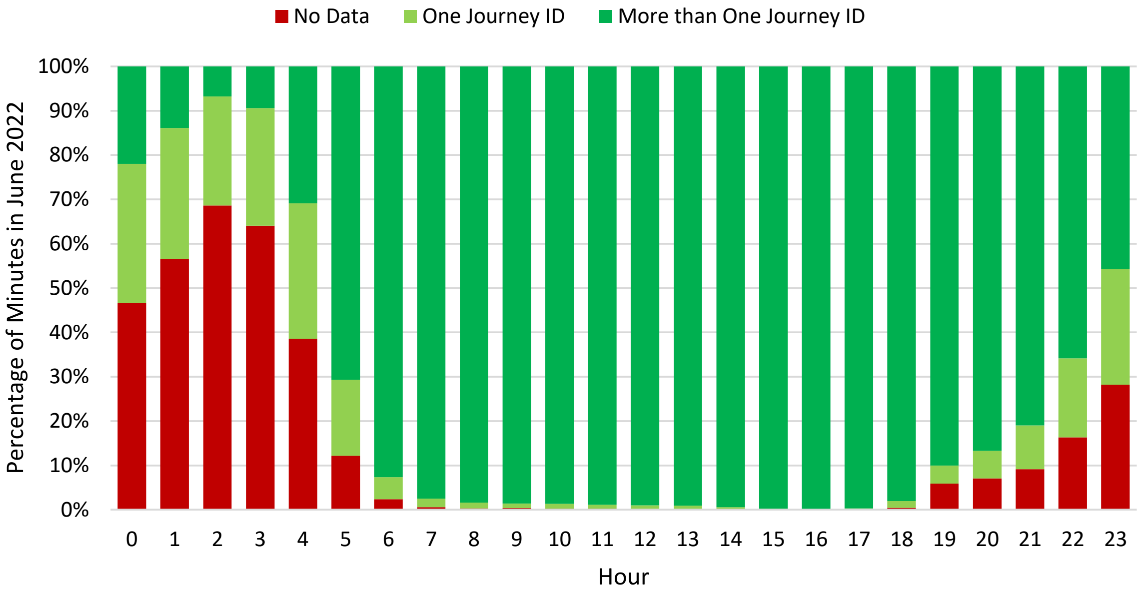


Figure ES2. Results of data completeness test for CVD on weekdays

The second test examined whether the crowdsourced data sets were able to provide high-quality information about congestion by comparing whether the SSD or CVD were able to capture the congestion reported by the sensors and whether the congestion reported by the SSD or CVD was also seen by the sensors. A failure to detect congestion resulted in a missed call, whereas a false call was a report of congestion not verified by the sensors. For this test, several different options for aggregating the SSD and CVD were considered. For the CVD, several different statistical measures were applied to the individual speed observations, along with options for aggregating across individual vehicles and variations in whether data were used for the most recent minute or for the most recent 3-minute period (to mitigate the problem of low sample counts during certain times of day). The results are shown in Figure ES3.

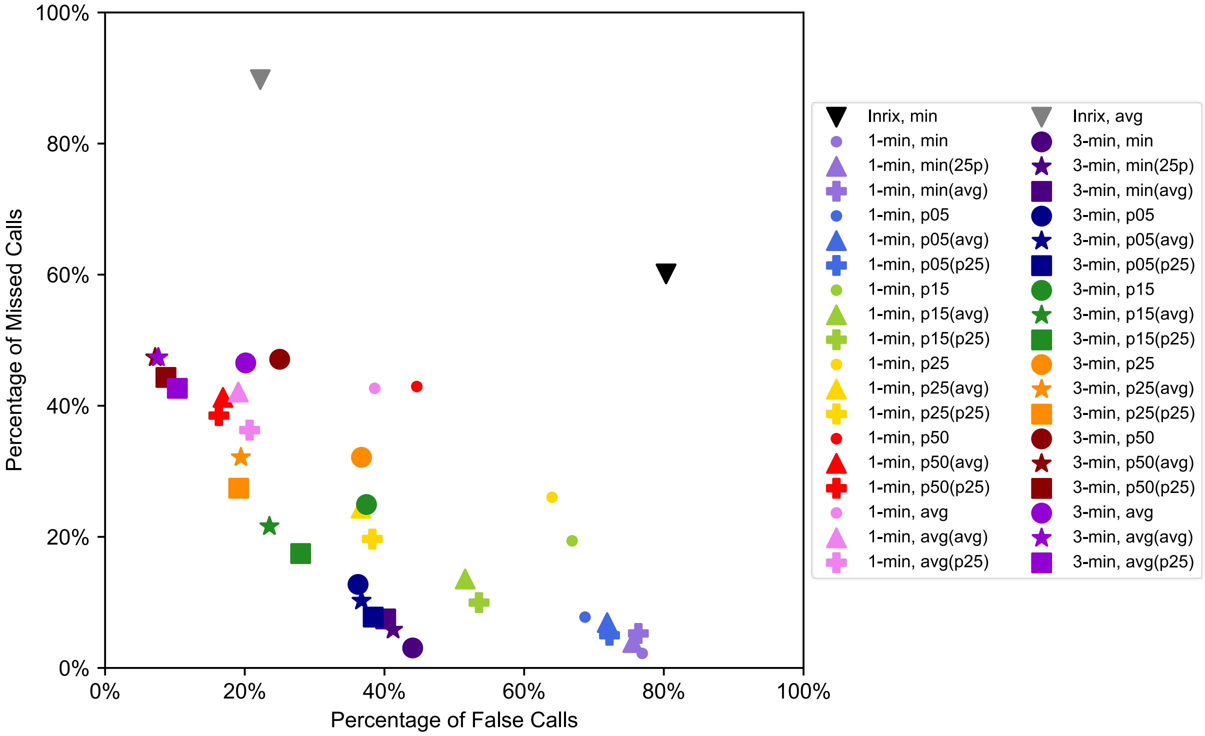


Figure ES3. Results of missed call-false call analysis for various performance measures derived from crowdsourced data

This diagram includes two aggregations for the SSD (labeled “Inrix” in Figure ES3) and several options for aggregating the CVD. The details of the aggregation options are presented in further detail in the report; for this summary, we can observe that the two SSD options (inverted triangle symbols) have high numbers of missed calls and false calls, while the various CVD options (all other symbols) have lower numbers of missed calls and a wide distribution of false calls. There is clearly a tradeoff between missed and false calls depending on the type of summary statistics derived from the data. The minimal value for either missed or false calls appears to be approximately 45%. There is one option (labeled “3-min, min” in Figure ES3, indicating the minimum speed reported within the most recent three minutes) that achieved a low value of missed calls (about 3%) while also achieving a relatively low percent of false calls compared to other options with about the same number of missed calls.

The third test examined latency. For this test, the best-performing metrics for the SSD and CVD identified in the previous test were used to compare these data sets against the sensor data. Occurrences of congestion (i.e., speeds below 45 mph) lasting 5 minutes or longer were identified from the sensor data in the work zones. These were compared against the SSD and CVD for the same location during the same time period. To estimate latency, these were filtered to exclude incidents where the SSD or CVD failed to detect the congestion. Latency in detection of the onset of congestion as well as recovery from congestion were tested. The results showed that the CVD has lower latency than the SSD for detecting the onset of congestion. The SSD had an average latency of 5.1 minutes, compared to the CVD latency of -1.3 minutes. The negative value indicates that, on average, the CVD actually reported congestion about a minute earlier than the sensor data. For congestion recovery, the results were different. The average SSD latency was 4.6 minutes, while the average CVD latency was 5.5 minutes. The CVD exhibited more variation in CVD recovery, and the distribution of latency times indicated that the CVD would detect recovery from congestion early or late with roughly equal likelihood.

The fourth test utilized a virtual QWS approach to simulate when a QWS would display a slow traffic warning based on selected data. This involved analyzing all of the minutes in June 2022 for five work zones. The sensor data and the top-performing performance measure from the second test for the SSD and CVD were used to determine when each would trigger a queue warning. Additionally, a fusion option was tested that combined both the SSD and CVD. To evaluate the effectiveness of the test data, the amount of agreement with the sensor data was calculated by counting the minutes when the CVD, SSD, or fusion data would also trigger a warning. The results, as shown in Figure ES4, indicated that the SSD had low agreement for most work zones, with less than 50% agreement in most work zone-direction pairs. In contrast, the CVD and fusion options had significantly higher agreement, usually above 50%, although two work zone-direction pairs had values below 50%. The fusion option performed slightly better than the CVD by a few percentage points.

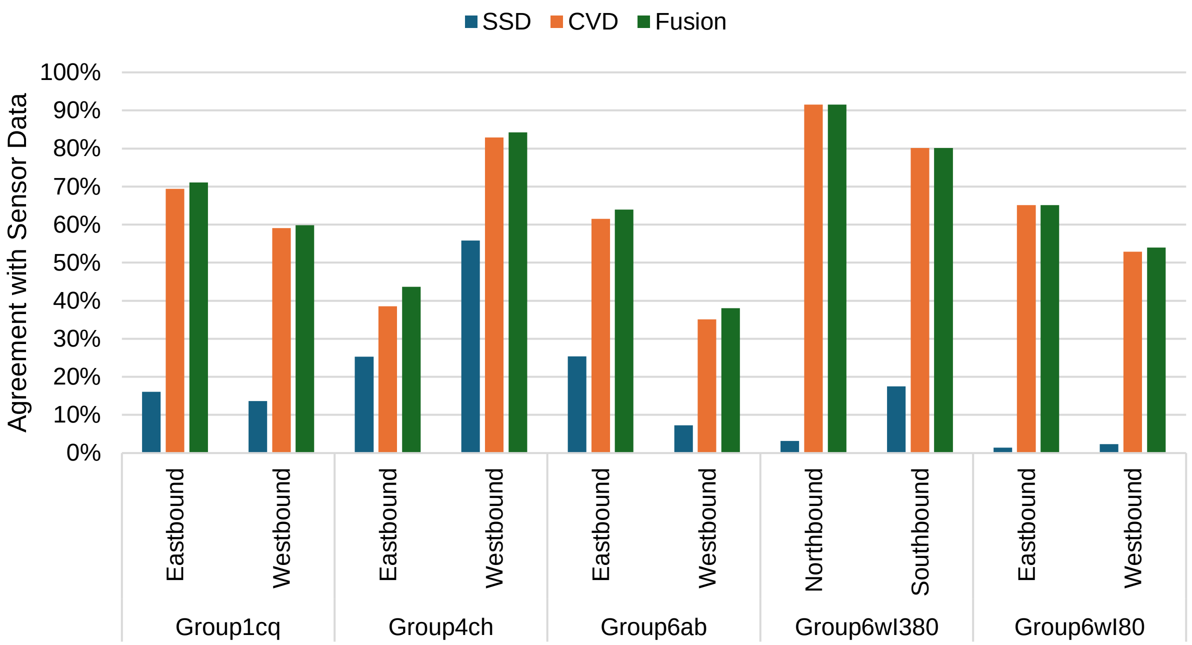


Figure ES4. Results of virtual QWS testing of crowdsourced data

Conclusions

Overall, the results for the crowdsourced data sets (SSD and CVD) varied depending on the test results. The SSD exhibited good completeness but performed poorly in terms of missed and false calls, onset latency, and display of a queue warning compared to the sensor data. On the other hand, the CVD had problems with coverage during overnight hours but was able to achieve low missed calls and had better latency than the SSD, even reporting congestion onset earlier than the sensor data on average (although it had more mixed results with congestion recovery), and with more agreement with the sensors regarding display of a queue warning.

The study's most promising results for the CVD showed that certain options achieved very low numbers of missed calls, ranging from 2% to 3% compared to the sensor data, despite low overnight data completeness. However, these options had high numbers of false calls, with the lowest being about 45%. Using a 3-minute rolling window instead of just the most recent minute significantly reduced false calls, suggesting that the CVD could be used to drive a QWS. Missed calls might be reduced by refining geographic data definitions, performing more data cleaning, exploring additional performance measures, and implementing other refinements.

Data coverage was a challenge for the CVD, particularly during overnight hours, but certain CVD options still achieved low missed calls despite this. As more connected vehicles join the vehicle fleet, increasing data coverage is likely to mitigate these issues. In comparison, the SSD had excellent data coverage at all hours but did not perform as well in QWS applications. The SSD missed many congestion incidents in the second and fourth tests, likely due to the reliance on average speed over relatively long segments, making the data less sensitive to localized slowdowns. Cooperation with data vendors to use other existing or new products, such as smaller segments, which are being used by some agencies, or perhaps to add other statistical measures besides the average speed might be able to improve SSD performance. Given the value of queue warnings for preventing rear-end crashes, it seems likely that there would be demand for such a crowdsourced data product.

There are several opportunities for further research to make QWS driven by infrastructure-free data sources viable. While the CVD avoids missed calls, the high number of false calls could be reduced by refining data processing methods or considering additional performance measures. Exploring other SSD offerings could also be beneficial, especially if a new data product specifically for QWS is requested by transportation agencies. Finally, further investigation of the combination of CVD and SSD for QWS applications would also be worthwhile.

1. INTRODUCTION

1.1. Data to Support Operation of Work Zone Queue Warning Systems

Slow or stopped traffic can present a hazard for road facilities, especially on freeways and other roads where drivers are less likely to expect to encounter such conditions. In work zones, the likelihood of slow or stopped traffic increases because of various changes to the road geometry that may be unexpected to drivers. Although speed limits are lowered and ample visual cues are usually provided to indicate the presence of a work zone, slow or stopped traffic remains a hazardous situation that can lead to severe rear-end crashes if drivers unexpectedly encounter the back of a queue without sufficient time to stop.

Transportation agencies use queue warning systems (QWS) to inform drivers of the presence of slow or stopped traffic in work zones. These systems require some means of measuring speeds in the work zone. When the speeds fall below a certain threshold, a warning is presented to drivers approaching the work zone using a changeable message sign (CMS). In some locations, additional means of communication might be used, but the use of CMS is the most direct means of conveying the information to the largest number of drivers moments before they actually enter the work zone where the slowdown is occurring.

QWS for work zones have mostly used temporary speed sensors deployed in the field to directly measure vehicle speeds. While such sensors are able to observe a high percentage of traffic and consequently provide good measurements of the actual speeds where the sensors are located, they are limited in that they are only able to measure speeds on limited sections of the road. To reduce the likelihood that sensors will fail to observe congestion, it is possible to use multiple sensors to cover a work zone, but each additional sensor comes with additional cost.

In recent years, several means of obtaining data from the vehicle fleet have emerged, enabling agencies to measure speeds by using crowdsourced vehicle probes representing a sample of the vehicles actually using the road system. Since the turn of the century, a few sources of data have seen widespread use:

- Automated vehicle identification (AVI) data use timestamped vehicle identifiers collected at various points in the system. Matched identifiers can be used to identify travel time. License plate numbers, Bluetooth and other wireless network identifiers for transported mobile devices, and automated tolling system transponders have been used for this purpose.
- Automated vehicle location (AVL) data use timestamped location information obtained from mobile devices equipped with Global Positioning System (GPS) connectivity moving on the road network. The raw waypoint data are available at several different reporting intervals ranging on the order of seconds up to one minute or so. Although data aggregators possess the raw position data, agencies more commonly purchase the data in the form of average speeds per minute for predefined road segments.
- Connected vehicle (CV) data are similar to raw AVL data in that they also consist of crowdsourced timestamped locations. However, they are obtained from onboard units

(OBUs) installed on vehicles rather than through a transported mobile device. In the past few years, raw CV waypoints have become available for purchase by data vendors, and some transportation agencies have begun to explore the uses of such data.

At present, two data sets that offer extensive coverage of the road network without any field infrastructure by agencies include what this report will refer to as segment speed data (SSD) and connected vehicle data (CVD).

- SSD consist of a reading of the average speed for a given time interval for predefined road segments. The National Performance Measures Research Data Set (NPMRDS) provides an average speed every five minutes, while commercial data sets are available for every minute.
- CVD include the entire vehicle trajectory, consisting of waypoints with a time resolution on the order of seconds.

Since these data sets are currently available for all public roads in the United States and can be obtained in real time, the question arises whether such data could be used to drive a QWS, which would alleviate the need for the deployment of sensors in work zones. That is the purpose of the present study.

1.2. Study Overview

This study examines whether SSD and CVD can be used to provide public information about work zones. Based on the information gathered from practitioner interviews (Chapter 3), which revealed that reporting slow or stopped traffic is a more critical application than providing travel time information, this study focused on the application of SSD and CVD for QWS. To do so, four tests were carried out to examine data completeness, ability to detect congestion, latency, and a virtual QWS application. The data sets were compared against physical radar sensor data from the same work zone locations for this purpose. The results of these tests identified strengths and weaknesses in the data sets and opportunities for using the data for QWS, as summarized in Chapter 5.

1.3. Organization of the Report

The second chapter of the report presents the results of the literature review. The review focuses on QWS applications but also covers SSD, CVD, and applications that incorporate both types of data. The third chapter summarizes findings from interviews with practitioners that were conducted as part of the research. The fourth chapter presents the methodology for data collection and processing, site selection, and the results of four tests to examine the performance of SSD and CVD for QWS applications. Finally, the fifth chapter summarizes the findings of the research and presents overall conclusions.

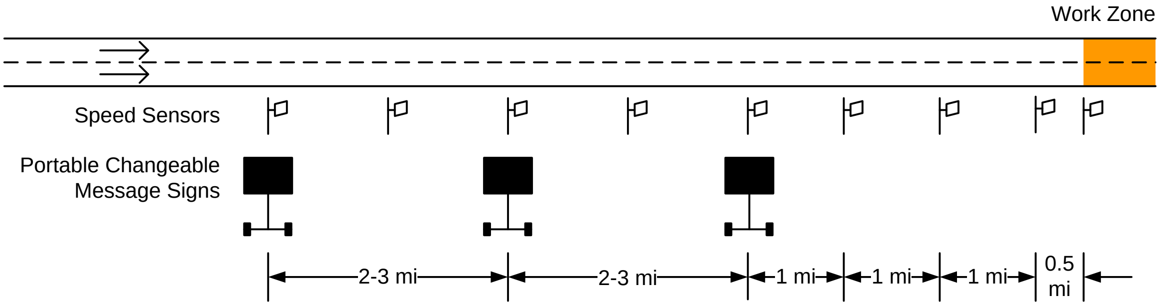
2. LITERATURE REVIEW

This chapter presents a review of relevant literature on QWS applications for work zones, the data used to support the operation of such systems, and sources of SSD and CVD, which are potential data sources for QWS that the present study investigates. This literature search was conducted using the Transportation Research Board's Transportation Research Information Services (TRIS) database, Elsevier's Engineering Village database, the U.S. Department of Transportation's (DOT's) Intelligent Transportation Systems (ITS) Deployment Evaluation website, and a general web search.

2.1. Work Zone QWS with Field Devices

The problem of drivers encountering unexpected slow or stopped traffic on freeways has long been recognized as a serious potential hazard. Work zones are a particularly challenging situation because they often induce changes to normal traffic patterns, reductions in capacity, and other conditions that may lead to congestion, and it has historically been challenging to deploy technology to automatically detect these conditions and to provide a warning to drivers approaching a queue.

QWS have been deployed since the 1990s, but their use in work zones by state DOTs has increased in recent years. Today, many such systems are in use. At present, such systems rely on sensors to measure traffic in the field. An example configuration is shown in Figure 1. This particular arrangement, based on an illustration from Federal Highway Administration (FHWA) guidance, uses an array of three CMS and nine speed sensors, with approximate distances. Agencies have used various configurations for QWS, often with fewer sensors and CMS.



After Schroeder et al. 2021

Figure 1. Queue warning system layout with CMS and sensors

Several studies have examined QWS driven by sensor measurements of vehicle speeds. One of the earliest descriptions of such a system dates to the early 1990s. This application used an ultrasonic detector that would have been positioned 700 ft upstream from the work zone. The intent was to inform road workers of the growth of a queue (Stout et al. 1993). The alert would be activated whenever a vehicle was detected for longer than 15 seconds. It was intended that workers would adjust warning devices to inform drivers of the queue situation. A Minnesota DOT (MnDOT) study evaluated the use of a portable traffic management system for work zones, which included real-time measurement and the provision of public information (SRF Consulting Group 1997). This system used a portable video detector that could identify stopped traffic and transmit the information to a traffic management center, which could then display a warning message on a CMS. Approaching traffic speeds reportedly decreased by 9 mph. To our knowledge, this is the first field study on the response of traffic to a QWS with quantitative results. In Pennsylvania, a system including eight portable infrared detectors was used to identify work zone congestion and provide a warning to drivers using CMS (FHWA 1998).

A study by Iowa State University (Maze et al. 1999) included a measurement of back-of-queue propagation, which found that queues may grow at speeds up to 30 to 40 mph, as measured by driving a roadside vehicle at the same speed as the back of the queue and tracking distance with mileposts. This motion at the back of the queue creates a speed differential of approximately 100 mph when compared to ordinary traffic speeds.

In the early 2000s, researchers at the University of Michigan developed a “smart barrel” system wherein traffic control barrels equipped with speed sensors could be deployed to measure traffic speeds (Sullivan et al. 2005). Several different types of speed sensors were tested, and the researchers found passive infrared detection to be superior to active infrared and magnetic sensors.

An FHWA study on ITS applications for work zones (Luttrell et al. 2008) included the investigation of a several systems for the provision of public information. Most of these focused on diverting traffic from the work zone during periods of congestion. Volume measurements showed reductions in volume from systems deployed in Texas and the District of Columbia, and a driver survey showed that 82% of respondents stated that the ITS systems “improved their ability to react to stopped or slow traffic.”

FHWA produced an implementation guide for work zone ITS applications in 2014 (Ullman et al. 2014). The guide includes a discussion of QWS, including a report of a 14% reduction in crashes for a deployment in Illinois. A contemporaneous report from pooled fund study TPF-5(231) includes a synthesis of several reports from numerous QWS deployments and other informational resources (Roelofs and Brookes 2014). In addition to the Illinois results, a 66% reduction in “incidents” was reported in San Diego, California, and a “notable reduction” (although no quantitative data are provided) in rear-end crashes in Ontario, Canada (Browne and Byrne 2008).

A study evaluating the deployment of a QWS on I-35 in central Texas found that there was a 44% reduction in crashes due to deployment of the QWS, while the crashes that were not prevented tended to be less severe than those that occurred when the QWS was not deployed (Ullman et al. 2016). More specifically, the percentage of crashes considered “severe” was reduced from 58% to 41%. The QWS included different types of portable speed sensors and portable rumble strips. A more comprehensive study found that the use of portable rumble strips with a QWS led to a 60% reduction in crashes, while a QWS alone led to a 53% reduction (Hsieh et al. 2017).

An evaluation of a QWS deployment in Colorado (Walderman et al. 2020) compared one month of QWS operation against one month with the system inactive. Average speeds and “abrupt speed drops” were measured at the test location. An abrupt speed drop was defined as a reduction in speed greater than 10 to 15 mph. A warning message reporting slow traffic was displayed when speeds fell under 45 mph, and the message changed to a warning of stopped traffic when speeds fell below 20 mph. Doppler radar sensors were used. The data showed that average speeds were higher when the QWS was visible, but the number of abrupt speed drops was lower.

A previous Smart Work Zone Deployment Initiative (SWZDI) study on driver behavior at back-of-queue locations (Hallmark et al. 2020) examined two data sets: (1) video recordings of locations in Iowa where work zone queues were expected and (2) data from the SHRP Naturalistic Driving Study (NDS), including “safety-critical events” (SCEs) associated with the back of a queue. The video data showed that 54% and 40% of SCEs were associated with drivers traveling at the prevailing speed or faster than the prevailing speed, respectively, while 54% of SCEs were associated with drivers following too closely. The NDS data included several variables on driver behavior, enabling a statistical model to be evaluated to estimate the probability of a near-crash. This model found that the probability of a near-crash correlated with driver distraction measures (“glances away over 1 second”) and close following. The results showed that drivers were about four times more likely to be involved in an SCE if they were engaged in an activity that diverted their attention away from the driving task for longer than 1 second and that drivers were about three times more likely to be involved in an SCE if they were following more closely than 2 seconds.

A supplement to FHWA’s work zone ITS guide (Schroeder et al. 2021) includes updated information about QWS deployments. The information includes a cost estimate for deployment of a QWS that features three CMS in advance of the work zone along with nine sensor deployments. A total cost of $102,045 (2020 dollars) was reported for this configuration. Of this cost, $22,500, or roughly 22%, is required for sensors.

A Nebraska study (Zhao et al. 2022, Zhao and Rilett 2023) examined the effectiveness of automated QWS at four test sites. The QWS used speed sensors, varying by work zone. Instantaneous speeds were obtained, and a three-minute rolling average was taken. If speeds fell below 45 mph, a message warning of slow traffic was displayed, and if speeds fell below 25 mph, a warning of stopped traffic was displayed. The types of speed sensors varied by location. To evaluate the effect on traffic, portable data collection units were used that could collect digital identifiers from electronic devices being carried on traveling vehicles. This permitted the speeds of individual vehicles to be measured as drivers approached the work zone. The results showed that the QWS had low rates of error (0.7% to 2.3%), meaning times when a queue warning message was displayed in error or when the system failed to display the message despite the presence of slow or stopped traffic. The data showed that drivers reduced their speed by 1.9 to 3.6 mph when passing by the portable CMS when it was not displaying a message. The speed reduction was between 3.5 and 7 mph when a warning message was displayed.

In summary, QWS using roadside sensors have been used in work zones for nearly 30 years and have been the subject of several field evaluations that have demonstrated their effectiveness at reducing rear-end crashes at the ends of queues.

2.2. Segment Speed Data

The purpose of the present study was not to evaluate the impact of QWS but rather to investigate whether alternative data sources could be used to drive a QWS in lieu of sensor data. This could prove advantageous in the event that the sensor data become unavailable due to an equipment malfunction, or it may enable QWS to be deployed with fewer sensors or without sensors, if the data are effective. Two data sets were targeted for this purpose: SSD and CVD. This section covers SSD, while the next section examines CVD.

In the 2010s, mobile cellular electronic devices with the ability to obtain location data from GPS data had proliferated to the point where such data could be readily obtained for the purposes of observing traffic movement. While SSD in their raw form consist of GPS waypoints from mobile devices, the data are usually provided to agencies in the form of an average speed for a predefined interval (such as 1 minute) for predefined road segments. This type of data is used by many transportation agencies for traffic monitoring and evaluation and is available in real time from some data providers. The advantage of SSD (and of CVD) is that no field infrastructure is needed to obtain the data.

The application of SSD for work zone monitoring was investigated in several studies from the 2010s, which demonstrated the viability of this relatively new data set. Edwards and Fontaine (2012) presented one of the earliest studies on work zone performance measurement with SSD. They used 2010 INRIX data from 15 freeway and arterial work zones in Virginia to assess travel time reliability characteristics, with a focus on changes in travel time reliability. The researchers quantified the increase in variability induced by work zones, finding that the average buffer index increased by 48%, the average planning time index increased by 18%, and the average 95th percentile travel time increased by 16% compared to non-work zone conditions. Lane closures had particularly detrimental effects. Higher volumes and a higher concentration of access points also contributed to greater variability (less reliability). While such impacts are well understood, this research demonstrated the capability of SSD to quantify them.

Fontaine et al. (2014) further investigated the use of SSD for work zone management in a subsequent study that included an estimation of queue length. The method assumed that queuing would be indicated by the speeds on the corridor falling below 60% of the historical average speed. Ultimately, it was found that the success of measuring queue length depended heavily on the segment length. At the time, traffic message channel (TMC) segments were used, which are sometimes very long. Queues were more easily estimated for shorter segments than for longer segments.

An FHWA report produced around the same time (Mudge et al. 2013) investigated the use of SSD for work zone performance measures. SSD from several different sources were compared, including Bluetooth and toll tag vehicle identification data, cell phone data, floating car data, and commercial SSD. The report highlighted the lower cost and ease of deployment of such data sources compared to the use of sensors but also noted a lack of consistency between different data sources, difficulties in estimating traffic volumes, and issues with data sharing and licensing.

As real-time SSD became more commonly used, applications for real-time work zone monitoring became apparent. The first algorithm for the use of SSD for queue-end detection was presented by Dinh et al. (2014). The algorithm assumed that individual vehicle traces are available in real time. The problem of low penetration rate was mitigated with the use of “ghost traces,” which interpolated between consecutive real traces, and a concept of “memory,” wherein the last known position of a queue was retained until new real-time data showed that the back of the queue had moved. An assumption that vehicles travel at a constant speed between waypoints was used. This analysis was developed and tested for a European data source that included speed data for individual probe vehicles, and good agreement was found between the estimated and actual back of the queue.

Li et al. (2015) proposed a method for identifying shockwaves on freeway segments by calculating the difference between the speeds of neighboring segments, called the “delta speed.” Large values of delta speed correspond to a segment with high speeds sending traffic into another segment with low speeds. Data from freeways in Indiana showed that visualizations of delta speed enable the movement of shockwaves to be tracked in real time. The limitation of the approach is that measurements can only be taken at the interface between neighboring segments. This study used INRIX XD segments, which have average lengths of approximately 0.5 miles. As the shockwave traverses a segment, the speed of the segment decreases, and the delta speed compared to the next segment upstream grows from a lower value to a higher value when the shockwave reaches the boundary between segments. As the next section will show, a technique similar to this has been employed in some studies for back-of-queue location using CVD.

The use of SSD for an alert system was presented by Mekker et al. (2017). In this study, an alert was triggered when traffic speeds fell under 45 mph for at least four out of five of the most recent 5-minute windows (e.g., 80% of recent observations). The results were compared against a ground truth comparison with camera images and other data for two case studies involving incidents on I-69 in Indianapolis. The findings demonstrated the ability of the system to track the position of the end of the queue from the inception of the queue to the time that it dispersed.

The Virginia DOT (VDOT) has used SSD for work zone performance measures for several years (FHWA 2019). Recently, this has included the use of “sub-XD” segments. The sub-XD segments have an average length of 0.16 miles, compared to 0.42 miles for XD segments and 1.16 miles for TMC segments. A comparison of the sub-XD segment data with radar detection data showed that the two data sets agreed for 97.7% of the time periods considered, but this level of agreement decreased to 86.7% when speeds were under 55 mph.

2.3. Connected Vehicle Data

This section covers studies relevant to uses of CVD for QWS. CVs are equipped with devices that are meant to permit communication with other CVs, infrastructure, and potentially other road users. The vision for CV technology led by FHWA in the 2010s used dedicated short-range communication (DSRC) via radio communication as the medium to transmit messages. Today, some vehicles are equipped with DSRC, and some roadside infrastructure has been deployed with compatible roadside units (RSUs). However, the technology currently in more widespread use among the vehicle fleet is cellular communication, referred to as cellular vehicle-to-everything (CV2X), sometimes also called 5G. Several auto manufacturers have included CV2X communication in some vehicle models and have been using the cellular communication features of the equipment to track vehicle movements. In the past few years, data vendors have emerged that purchase these data from auto manufacturers and resell them to customers, including transportation agencies. These commercially available CV data are sold with a reporting interval of 3 seconds, whereas DSRC-based CV data should be available on a 0.1-second basis.

Dowling et al. (2015a, 2015b) presented an evaluation of the potential impacts of several CV-enabled applications, including a queue warning application called Q-WARN. The QWS algorithm was developed by researchers at the Texas Transportation Institute (Balke et al. 2014). Testing was done in a simulation environment. The algorithm was intended to provide an advisory speed to CVs with the goal of reducing the likelihood of back-of-queue crashes as well as enabling speed harmonization. The Q-WARN prototype gathers average speeds for segments (in Balke et al. [2014], the segments are 0.5 miles in length) using a combination of infrastructure sensors and CVs. A CV is considered to be in a queued state when its current speed and separation distance are below preset thresholds. Each segment is determined to be in a queued or non-queued state by such an analysis of CV states, along with available measurements from field sensors. From this, it is possible to determine the back of the queue by finding the furthest upstream segment with a queue. Overall, the simulation results showed that the prototype system was able to reduce speed differences between vehicles, reducing shockwave speeds and thus potentially reducing the risk of crashes, at the cost of spreading out congestion over a broader area. Benefits were observed at CV penetration rates as low as 10%.

Khazraeian et al. (2017) estimated the potential safety effects of QWS with CVs. This study also used simulation to assess results. The QWS application relied on the division of the road into short subsegments of 100 ft. Average speeds were calculated for each minute. The subsegments were considered to be in a queued state if the average speed fell below 35 mph; the back of the queue was identified as the location of the first subsegment without a queue. The front of the queue was identified when the difference between neighboring subsegment speeds exceeded 30 mph. The simulation results found that there was about a 6.5% error in the back-of-queue location at 3% CV market penetration, with the error falling to 2.4% at 15% market penetration.

Sakhare et al. (2021) used CV data to assess the impacts of providing a queue warning. The CV data were obtained from a commercial vendor that provided a data feed consisting of “hard-braking” events, which occurred when a deceleration in excess of 8.76 ft/s^2 was observed. The presence of a queue warning for trucks was found to reduce hard-braking events by approximately 80%.

2.4. Multiple Data Sets: Comparisons and Data Fusion

SSD has been the subject of many validations and comparisons against data sets such as Bluetooth automatic vehicle identification travel times. The present review focuses on recent comparisons with sensor data for real-time queue detection.

Sharma et al. (2017) compared SSD from INRIX against fixed-location sensor data in a study for the Nebraska DOT (NDOT). The INRIX data were compared against data from 65 automatic traffic recorders in Nebraska. Performance comparisons were made for several performance measures derived from the data sets. The results showed that the SSD often reported lower speeds compared to the sensor data. The SSD were found to be effective at detecting recurring congestion but less reliable at identifying congestion related to incidents. The authors observed that the average latency was about 5 minutes but that it ranged from 3 to 12 minutes on freeways and 7 to 20 minutes on non-freeway roads.

Liu et al. (2019) examined the use of SSD from Waze to determine the location of the back of a queue. A model was developed that used "jam reports" from Waze. The data were clustered using the Spatiotemporal Density-Based Spatial Clustering of Applications with Noise (ST-DBSCAN) algorithm. This method permitted greater flexibility in cluster formation than static clustering methods. The cluster locations were then used to identify the location of the back of a queue, which could be updated as new data were received.

In Virginia, a "queue management team" was used to provide a warning of downstream queues (Cottrell and Lan 2019). This team included two pickup trucks with vehicle-mounted CMS and a communication system for the providers. A study examining the effectiveness of this team also included a pilot of an automated QWS. The system displayed a warning of slowed traffic when speeds fell to 45 mph or lower and a stopped traffic warning when speeds fell below 25 mph. The cost of the QWS was reported at $110,495. The QWS evaluation included a comparison of the speeds captured by the radar detectors used in the system to SSD from INRIX. The comparison showed that the radar speeds tended to be lower and have greater variability, while the traffic counts from the radar detectors on site were similar to those obtained at a nearby continuous count station. In comparing radar versus INRIX data, "false calls" were defined as cases where radar sensors reported speeds under 45 mph but the INRIX data did not show this speed, while "missed calls" were defined as cases where INRIX reported speeds under 45 mph but the radar sensors did not. The comparison was done on a minute-by-minute basis. Less than 1% of the minutes had false detections, while around 12% to 17% of the minutes had missed calls.

Sakhare et al. (2022) presented a scalable methodology for using both SSD and CVD for monitoring work zone operations. The methodology used real-time data updated at 1-minute intervals. The data were spatially mapped to a common linear referencing scheme, enabling the preparation of various types of informational views for decision-makers, including weekly reports and real-time monitoring. Performance measures included speeds and the prevalence of hard-braking events. While this study did not focus on QWS specifically, it combined both SSD and CVD into an algorithm for adjusting lane closures.

2.5. Conclusion

This chapter reviewed the literature on QWS in work zones and the data used to support such systems, including sensor data, SSD, and CVD. Some studies from prior field evaluations were presented.

The effectiveness of QWS has been well documented. For instance, a deployment in Illinois reported a 14% reduction in crashes (Ullman et al. 2014), while a study in Texas found a 44% reduction in crashes, and greater reductions were found when these systems were combined with portable rumble strips (Ullman et al. 2016, Hsieh et al. 2017). Similarly, a QWS deployment in Colorado demonstrated improved traffic flow and reduced abrupt speed drops (Walderman et al. 2020).

The introduction of SSD and CVD show promise for QWS applications. Several studies were presented that showed good accuracy of the tools for monitoring real-time traffic conditions, including those for the estimation of the presence of queues and the location of the back of the queue. Multiple methodologies have been tested that had good performance. Some previous work also showed that the integration of SSD and CVD (in conjunction with traditional sensors in some cases) can provide fuller insights into traffic conditions. Thus, the concept explored in this study, driving a QWS entirely from commercially available data sets without the use of field sensors, is suggested to be feasible based on previous results.

However, in interpreting these results, we must note that the possibility of using probe data hinges on the accuracy of the results over 24-hour conditions. Many previous studies selected data from incidents to evaluate various methodologies for congestion measurement, which was necessary for the methodologies' development. Vesal et al. (2018) compared SSD against sensor data and found that the data were highly reliable for most Interstate routes during the daytime. However, the data were less reliable for non-Interstate routes and during nighttime. Although it has been several years since this study, and the market penetration of emerging data sets is expected to continually increase, it is not clear whether the data are currently ready for this application at all hours of the day and whether they can perform comparably to sensors at supplying an alert. The present study seeks to help answer these questions.

3. PRACTITIONER INTERVIEWS

To develop a better understanding of practitioner experiences with the provision of queue warnings, the research team conducted a series of interviews with state DOT practitioners. Invitations for interviews were sent to several participants in May 2023, with five groups of interviewees representing the states of Iowa, Michigan, Virginia, Wisconsin, and Minnesota ultimately participating. This chapter presents the findings from these interviews.

3.1. QWS for Work Zones: Public and Internal Information

Interviewees were asked about the sorts of public information they use for work zones on state highways in their area and whether such data are also used for additional internal purposes other than the provision of public information.

The Iowa DOT uses QWS for work zones, with alerts generated by data collected from side-fire radar sensors. In addition to displays on portable CMS, alerts via text/email are generated and are also visible on the video wall at the traffic management center. The Iowa DOT also has travel time messaging on permanent CMS in larger cities, which use sensor data and SSD and are only used during the morning and evening commute periods, along with congestion delay information displayed using the 511 system. Bottleneck locations are identified using SSD at the traffic management center. The travel times and bottleneck locations are not specific to work zones.

The Michigan DOT (MDOT) also provides QWS in work zones using radar sensors. The sensors have sometimes had issues during overnight or low-volume operation, sometimes triggering a queue warning when there was no queue. Other public information includes travel time data using SSD, although MDOT has found that this sometimes yields questionable results when historical data are used or when roads are completely closed.

The Wisconsin DOT (WisDOT) provides queue warnings, which are currently used in most work zones on high-speed roads. Warnings may be displayed on CMS that alert drivers to slow or stopped conditions and, optionally, provide the distance to the disruption, or warnings may be communicated through static signs with flashers. Guidelines are in place to decide on the type of sign to be deployed. The DOT additionally uses SSD for travel time applications in select areas. At present, the DOT is not purchasing the data statewide but is planning on doing so in the near future. The QWS alerts are standalone and are not integrated with the advanced traffic management system (ATMS). The ATMS is able to provide alerts to permanent CMS installations throughout the state but not to portable CMS in work zones.

QWS have been used in Minnesota for about 5 to 10 years. Travel time displays have been in place for more than 16 years. MnDOT has been using SSD for 4 years. In addition to QWS, sensor data are used to provide travel times in many locations in the state. More recently, SSD have been used for travel time information.

VDOT has deployed smart work zones, including sensors that generate messages on portable CMS. VDOT has provided travel times on Interstate routes since 2010 using SSD. Travel time messages are only displayed when there is a sufficient amount of real-time SSD. The system is able to capture work zone congestion, but VDOT has found that sensor data are more reliable than SSD because of the large sizes of the segments.

3.2. Communication to the Public

In Iowa, CMS and the 511 system are used for public communication. Work zone queue alerting has been in use since 2013. Communication of queue warnings to the public is a high priority, whereas the provision of travel time data is a lower priority.

High numbers and severities of rear-end crashes led MDOT to begin using QWS around 2012–2013. The third round of the FHWA Every Day Counts program, which included QWS as a focus technology, helped initiate this effort. QWS is now a common application in Michigan, although it is not feasible to implement in every work zone. Queue warnings are primarily communicated to the public through CMS. MDOT is currently engaged in two projects related to queue warnings in work zones: Safety Alerts for Work Zones (SAFEZONE 2021) and Partnering Automated Work Zones (PAWZ 2022). These projects aim to improve safety for commercial motor vehicle (CMV) operators by integrating smart work zone applications, including video detection scene recognition, vehicle-to-everything (V2X) communication, smart digital signage, and traffic management safety alerts for both static (SAFEZONE) and mobile (PAWZ) work zones. MDOT's goal is to reduce CMV and bus crashes, enhance work zone navigation, and improve the accuracy of work zone messages, with an overall anticipated crash reduction of 30%. MDOT is also exploring ways to provide work zone data directly to vehicles and has previously tested work zone data exchange feeds. Contractors' paint trucks are currently equipped with emergency vehicle warning systems (HAAS Alert, developed by HAAS, Inc.), which notify the public about the presence of emergency vehicles. Concerns remain about the potential for the display of incorrect information to cause public skepticism of the system's reliability.

In Wisconsin, queue warnings are provided with the use of portable CMS and signs with flashing beacons. Messages related to lane closures and work zones are provided by the 511 system, and some may include travel time information where SSD are available, but the QWS are not integrated with this system. WisDOT generates a daily email that includes information about road work activities over the next two weeks. WisDOT administrators have been increasingly focused on work zone safety and have been adding other features to work zones, including portable rumble strips, speed feedback signs, and dynamic zipper merge systems. Radar sensor data are used for QWS and zipper merge applications. Wisconsin deployed one QWS in 2011, followed by a few additional systems in 2016–2017, followed by more extensive use after 2018. Smart work zones have been required for some projects.

MnDOT similarly uses portable CMS for QWS. The 511 system is also used to communicate with the public. Queue warnings are considered very important. On permanent CMS, MnDOT's system is able to prioritize messaging, and queue warning messages take priority over other messages such as travel time information. Smart work zones are supported throughout the agency, and the state is increasing their use. It is felt that the public appreciates the information based on informal feedback. MnDOT receives complaints when public information systems are not working well, which indicates that the systems are used by the public.

VDOT uses portable CMS and the 511 system, as well as DriveWyze, an app for freight drivers. VDOT is partnered with INRIX to push real-time in-cab alerts to drivers through the app. These include queue warnings identified by SSD across the state. It is possible to geofence work zones to specifically monitor them, but VDOT has not done that yet. Dealing with nonrecurring congestion is a high priority for VDOT leadership and the communications group. Public affairs personnel are included in larger projects.

3.3. Alert Automation

Alerts in Iowa are fully automated, using both in-house and vendor solutions. Work zone queue warnings, traffic management center operator notifications, and travel time information are integrated with the ATMS. Text and email alerts for work zone queue warnings use in-house systems. With respect to automated alerts, some false alerting is considered acceptable given that identifying slowdowns quickly is principally important (rather than waiting until the slowdowns are significant). Any time that the messaging is activated, a notification is sent to traffic management center operators, who can verify that the message is correct, although it is not required for operators to confirm the message. Traffic management center operators can also blank out the CMS if a message is incorrect.

In Michigan, equipment from several vendors is able to send work zone alerts automatically. Efforts are currently underway to integrate these into MiDrive, MDOT’s public information website. Queue alerting is primarily done by contractors that use vendor software. MDOT has previously tried to use its ATMS, but it has been challenging to integrate CMS into the ATMS while continuing to use the signs with other systems used by construction staff. Previous integration projects had difficulties with integrating field control of display devices.

In Wisconsin, the QWS are standalone and are handled by vendors and not integrated with the ATMS or other systems. Travel time data are integrated with the ATMS but currently only cover a portion of the road system.

MnDOT’s QWS and travel time data are all automated through the ATMS. MnDOT previously experimented with the use of probe data to generate an alert for internal use when the delay exceeded 15 minutes. This would be used to notify district personnel of a potential issue. A previous pilot test for one work zone project had promising results, so MnDOT is considering trying it again.

Virginia’s travel time messages are fully automated and integrated through the ATMS.

3.4. Supporting Data

The Iowa DOT employs a variety of data sources for applications related to traffic operations. Radar speed sensors are used for queue warning systems. The Iowa DOT also makes use of INRIX data, connected vehicle data, and traffic data from Google. Connected vehicle data were being tested for use in queue warning systems, but development was delayed because the data provider ceased operations. A consultant monitors the work zone queue alert messages and determines whether the sensors are valid. Through this process, recent problems with the Iowa DOT's QWS were identified, leading to a change in vendor products to address them.

In Michigan, QWS employ radar speed sensors. Previous attempts at using SSD for queue detection did not work well. Because SSD calculate an average speed over long segments, these data do not seem to always accurately capture queuing and congestion. SSD have been explored for a variety of other uses. Road closures can be a problem for SSD because this data source uses historical data when no real-time measurements can be made in the field because the road is empty during a closure. The latency and accuracy of the data are also uncertain. MDOT is not currently using CVD. Speed feedback signs are able to store speed measurement data, but MDOT is not currently using the data. Evaluation of QWS accuracy is mostly anecdotal at this point. For example, DOT staff might drive through a work zone during congestion and observe the absence of a warning on the CMS.

Radar speed sensors are used for QWS in Wisconsin. Other data include SSD for select locations. Bluetooth (AVI) data are still used in some areas. WisDOT is part of a Pooled Fund Study with Purdue University to explore uses of CVD. The early QWS were evaluated after deployment, and periodic spot checking has been done since then to ensure that slowdowns are captured. No major issues have been seen so far.

MnDOT's primary source of information for detecting congestion is speed sensors. Radar sensors are used for QWS applications. The state buys SSD from one vendor but is not currently using these data for QWS because of latency issues. So far, spot checks of the data have not revealed major issues. In places where MnDOT has made comparisons, the SSD and sensor data seem to agree most of the time.

VDOT uses SSD and sensor data and is beginning to explore CVD. For SSD, VDOT has recently been starting to use sub-XD segment data, which use smaller segment lengths. This type of data has been tested for a few projects, but the data format is not as convenient as that of other probe data tools that are more typically used. VDOT is also providing HAAS Alerts. VDOT has used SSD very extensively and has been heavily involved in validation of the data through the I-95 Corridor Coalition.

3.5. Challenges

For the Iowa DOT, recognizing when the system is not working well has been a challenge. This usually requires human observation to first recognize that there is a problem, followed by investigation to determine the cause of the problem. It is hard to differentiate between missed calls and nonevents. Providing data access to project partners is sometimes an issue.

For MDOT, one of the most significant current issues is the ability to quickly process and extract actionable information. It is not always clear whether a new data feed has good potential for actually being put to use. It would be helpful to have tools for what-if decisions, such as estimating the impact of lane closures at different times of day or scheduling work to take place at night. It is difficult to differentiate between causes of congestion, such as special events, work zone activities, etc. Liability is also a concern; for example, it is unclear whether data could be used in court even if the DOT did not have the information at the time. Guidance on data retention and dealing with public information requests would be helpful.

WisDOT personnel noted that challenges arise when work zone boundaries move. Contractors dislike having to move sensors and CMS as the boundaries of the project change. One possible solution is to set up a closure farther out from the construction activities, but this may require more barrels and cones. Some issues with sensors have arisen because of weather and other environmental interference. Sometimes issues have occurred due to the detection of construction vehicles; these issues were addressed by changing the threshold on the minimum number of observed vehicles needed to generate a queue warning.

MnDOT had problems with temporary detection before probe data were introduced. The use of probe data for some applications has greatly reduced the cost and labor involved in moving temporary detectors around. The implementation and integration of QWS was found to be smooth, but validation was considered challenging.

3.6. Summary

A few commonalities are evident in the information obtained through the interviews. All five DOTs employ QWS. Safety remains a central focus, with all DOTs aiming to reduce rear-end collisions and improve work zone safety through better traffic management and public information systems. The signs are believed to deliver a benefit to road safety. All DOTs noted that QWS are considered a higher priority application than travel time messaging. One state also provides dynamic zipper merge signs based on traffic speeds.

All five DOTs use radar speed sensors to display queue warnings on portable CMS. Some states also provide real-time information on traffic conditions using SSD. A few states have tested the use of SSD for QWS with varying success. Latency in the SSD was noted as an issue, as well as the sensitivity of the data to segmentation. One SSD application that identifies significant slowdowns (with 15 minutes of delay) was considered to work well. A few agencies are exploring CVD but are not yet using that data source for QWS or similar applications.

Most DOTs mentioned efforts to integrate QWS with their ATMS. Iowa, Minnesota, and Virginia have had success at integration, whereas Michigan and Wisconsin have faced challenges integrating these systems fully. All DOTs reported using portable CMS and the 511 system to communicate traffic conditions and queue warnings to the public. Several states are using additional methods of public communication, like text/emails and apps (e.g., Virginia’s use of the DriveWyze app).

Common challenges include the integration of technology with existing systems, the reliability of data feeds, and operational issues like the need to relocate sensors as work zones change. Environmental factors and the need for human oversight to confirm automated systems were also noted as challenges. Most DOTs have not formally evaluated the accuracy of QWS, although most noted ways that they try to detect problems, and a few have done limited validations.

4. COMPARISON OF DATA SETS FOR PUBLIC INFORMATION ABOUT WORK ZONES

This chapter presents the results of a comparison of different data sets for providing public information about work zones. Based on the results of practitioner interviews, this analysis focuses on the use case of queue warning: the use of CMS to display a message that warns drivers that slowed or stopped traffic is ahead. First, the data preparation methodology is discussed. This is followed by an analysis of data completeness, as assessment of the data sets' effectiveness at providing alerts in terms of missed calls and false calls, an assessment of latency in the detection of congestion onset and recovery, and finally a comparison of queue warning performance among the data sets.

4.1. Data Preparation

Three data sets were used for this study: sensor data, SSD, and CVD. The study compared SSD and CVD against sensor data. Sensor data served as the ground truth in this case. Although sensor data are not completely free of error, the use of a fourth data set was not possible during the study period, and the sensor data represent the primary method agencies currently use. The CVD provider became unable to supply the data as of May 2023, coinciding with the data collection period for this study. This situation necessitated the use of archived data for the comparison. Data from the month of June 2022 were used. To facilitate queue warning, several performance measures were developed from the data sources and compared against each other. This section describes how these were developed from the three data sets.

4.1.1. Sensor Data

Sensors are capable of measuring vehicle speeds at specific locations with a measuring range typically restricted to a few hundred feet. The Iowa DOT uses side-fire radar sensors (i.e., Wavetronix HD, Houston Radar Speedlane) to provide queue warnings and uses Open Transportation Management System (OpenTMS) for its ATMS, along with additional external mapping tools to track the location of ITS devices such as sensors. The sampling rate for radar sensor data is either 20 seconds or 60 seconds, varying by work zone installation. The sensor data set includes several columns, as described in Table 1. For this study, the date, start time, end time, lane count, lane speed, direction, and device ID were the most important columns. A sample of raw sensor data is shown in Table 2. The date and time data, initially in Coordinated Universal Time (UTC), were adjusted to Central Standard Time (CST). This was necessary for consistency across the three data sets

Table 1. Description of columns in sensor data

Column	Description
Date	The date provided for the data time period in UTC
Time	The time of the data provided in UTC
Start time	The start time of the data provided in UTC
End time	The end time of the data provided in UTC
Device ID	The sensor name using the OpenTMS naming convention
Lane count	The total vehicles in the time period for the given lane
Lane speed	The average speed of the vehicles detected for the time period, lane, and direction
Link direction	The direction of the link for the sensor

Table 2. Example sensor data

Date	Time	Start Time	End Time	Lane Count	Lane Speed	Direction	Device ID
20220620	51100	51040	51100	0	65	Eastbound	OpenTMS-Detector47833
20220620	51100	51040	51100	0	67	Eastbound	OpenTMS-Detector47833
20220620	51100	51040	51100	0	55	Eastbound	OpenTMS-Detector17622185
20220620	51100	51040	51100	0	70	Eastbound	OpenTMS-Detector17622185
20220610	50700	50600	50700	0	75	Eastbound	OpenTMS-Detector47900
20220610	50700	50600	50700	3	71	Eastbound	OpenTMS-Detector47900
20220610	50700	50600	50700	2	69	Eastbound	OpenTMS-Detector47900

For the sensor data, several different performance measures were calculated for each 1-minute interval, which are listed below. The number of performance measures was limited based on the available data, which only provide the average speed of vehicles by lane. For most QWS, multiple sensors are placed along the approach to the work zone, which can allow for a comparison of speeds across the sensors.

- **Minimum simple average speed**. The average speed is taken across all lanes for each sensor. The minimum average speed is taken from the sensors associated with each work zone.
- **Average simple average speed.** The average speed is taken across all lanes. The average speed is then taken across all sensors associated with each work zone.
- **Minimum vehicle-weighted average speed.** For each sensor, the vehicle-weighted average speed is calculated by accounting for the average speed and vehicle count in each lane (i.e., a lane with a higher vehicle count would be weighted more). The minimum speed across all of the sensors associated each work zone is then used.
- **Average vehicle-weighted average.** The same process used to calculate the minimum vehicle-weighted average speed is used to calculate the speed for each sensor. The speed is then average across all of the sensors associated with each work zone.

Contextual information such as the work zone name and direction were also included in the final data table. An example of the processed data containing the sensor-based metrics is shown in Table 3.

Table 3. Example sensor data joined to work zone information.

Start Time (CST)	Minimum Simple Average Speed	Minimum Vehicle-Weighted Average Speed	Average Simple Average Speed	Average Vehicle-Weighted Average Speed	WZ Name	Direction
5/31/2022 23:58	70.0	67.0	70.0	67.0	Group6wI80	Eastbound
5/31/2022 23:59	56.5	58.0	62.3	60.5	Group6wI80	Eastbound
6/1/2022 0:00	58.9	55.0	62.2	63.0	Group6wI80	Eastbound
6/1/2022 0:01	62.3	64.5	68.1	67.8	Group6wI80	Eastbound
6/1/2022 0:02	67.2	65.2	70.7	68.2	Group6wI80	Eastbound
6/1/2022 0:03	71.3	64.0	71.8	68.4	Group6wI80	Eastbound
6/1/2022 0:04	65.3	54.0	68.6	62.0	Group6wI80	Eastbound

To select a sensor performance measure that captures the greatest amount of congestion, we compared the results of the count of speed observations less than 45 mph. This definition was applied because of its common use in previous studies, as well as its use as a congestion threshold for QWS in Iowa. Figure 2 and Figure 3 respectively show the count and distribution of the speed data after applying this filter. The results show that the minimum simple average speed captured the most time with reduced speeds compared to the other metrics, making it the most “cautious” performance measure in terms of identifying congestion and providing a queue warning. For this reason, the minimum simple average speed was selected as the ground truth sensor metric that the SSD and CVD performance measures were compared against in subsequent analysis.

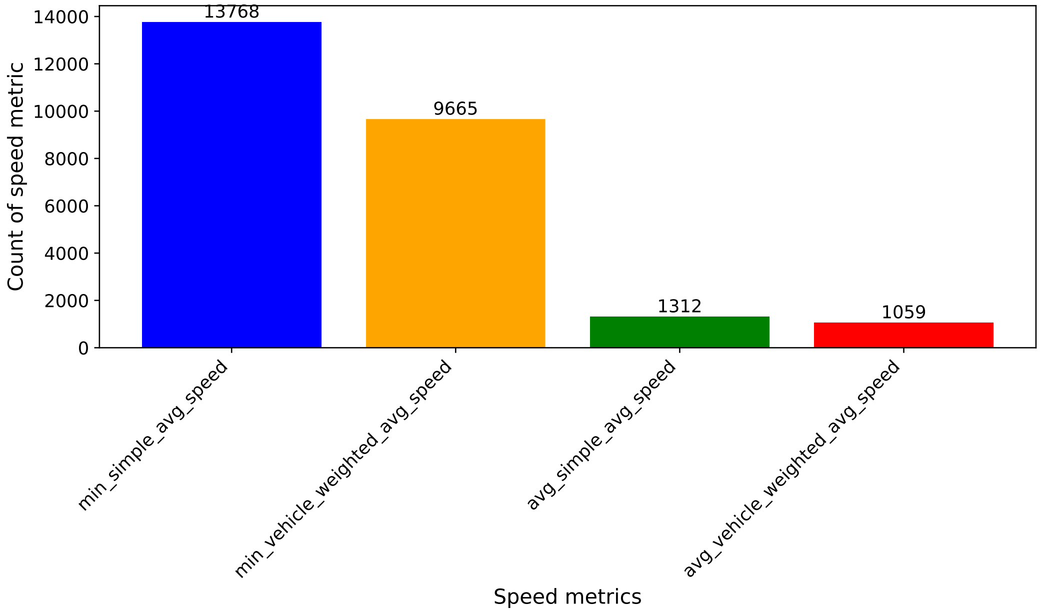


Figure 2. Count of speed observations below 45 mph by performance measure

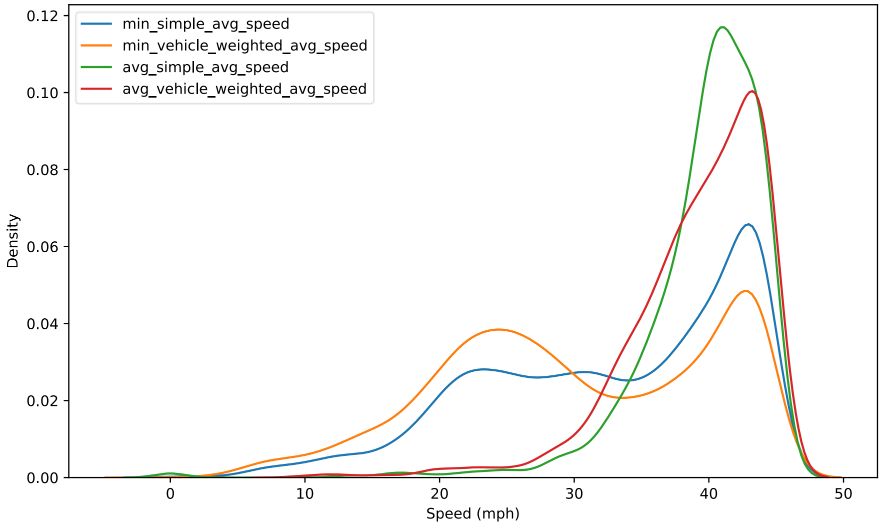


Figure 3. Distribution of speeds under 45 mph by performance measure

4.1.2 Segment Speed Data

SSD were obtained from INRIX. This data set consists of minute-by-minute average speed readings for predefined road segments. The proprietary XD segment scheme was used for this study. This scheme uses segments that are largely 1 mile or shorter in length. An alternative scheme is the TMC scheme, which for freeway sections extends between interchanges and includes very long segments. For QWS applications, the shorter lengths of the XD segmentation scheme would be appropriate, since the longer the segment, the more likely it becomes that slower speeds are hidden in an average speed taken over a greater distance.

Each data point comes with a score that indicates whether it is based on actual real-time measurements, a mix of real-time and historical/estimated data, or purely historical or estimated information. For this study, all scores were included in the analysis. Table 4 presents the definition of the columns available in the data table.

Table 4. Segment speed data definitions

Probe Data Set	Definition
CST Time	The timestamp (central standard time) at which data were recorded
Code	Unique identifier for a segment
C-Value	Confidence value, which indicates reliability against historical trends
Score	The source of the data, where 30 represents that the measurement is based on real traffic observations, 20 represents some use of historical data, and 10 represents an estimate based on historical data
Speed	The average segment speed (mph)
Average	The average speed of vehicles on the segment (mph)
Reference	Speed under free-flow conditions (mph)
Travel Time (min)	The travel time in minutes for a vehicle to traverse the specific road segment. It is calculated based on the speed and length of the segment.

As explained in the table, the score value indicates whether a measurement is based more on real data or historical data. For this study, all three score values were included. As will be seen later, most of the data had a score indicating that real traffic observations were available. An example of raw data is shown in **Error! Not a valid bookmark self-reference.**.

Table 5. Example of raw SSD

CST Time	Code	C-Value	Score	Speed (mph)	Average Speed (mph)	Reference Speed (mph)	Travel Time (min)
6/11/2022 14:51	1485536650	100	30	66	60	60	0.354
6/11/2022 14:51	1485513219	100	30	64	60	60	0.399
6/11/2022 14:51	1485688402	100	30	63	65	64	0.294
6/11/2022 14:51	1485688387	100	30	68	65	64	0.329
6/11/2022 14:51	1485688356	100	30	69	66	59	0.592
6/11/2022 14:51	1485688372	100	30	69	66	58	0.541

On average, there were 3 segments spanning the 0.5-mile sensor geofence approaching the work zones by direction. There were 118 unique segments across all six work zones for both directions of travel.

To develop performance measures that would indicate when to provide a queue warning, the minimum and average speeds were calculated across the segments included in a work zone-direction pair. **Error! Not a valid bookmark self-reference.** shows an example of processed data. Figure 4 shows the count of observations with speeds under 45 mph for the two different performance measures; taking the minimum value yields many more observations with speeds under 45 mph compared to the average value. Figure 5 compares the distribution of speed values for the two performance measures, showing that the minimum value occupies a lower speed range.

Table 6. Example SSD joined to work zone information

CST Time	Minimum Speed (mph)	Average Speed (mph)	WZ Name	Direction
6/1/2022 0:00	57.3	59.1	Group6wI80	Eastbound
6/1/2022 0:01	58.0	59.5	Group6wI80	Eastbound
6/1/2022 0:02	58.3	59.8	Group6wI80	Eastbound
6/1/2022 0:03	58.3	59.6	Group6wI80	Eastbound
6/1/2022 0:04	58.3	59.5	Group6wI80	Eastbound
6/1/2022 0:05	59.0	59.6	Group6wI80	Eastbound

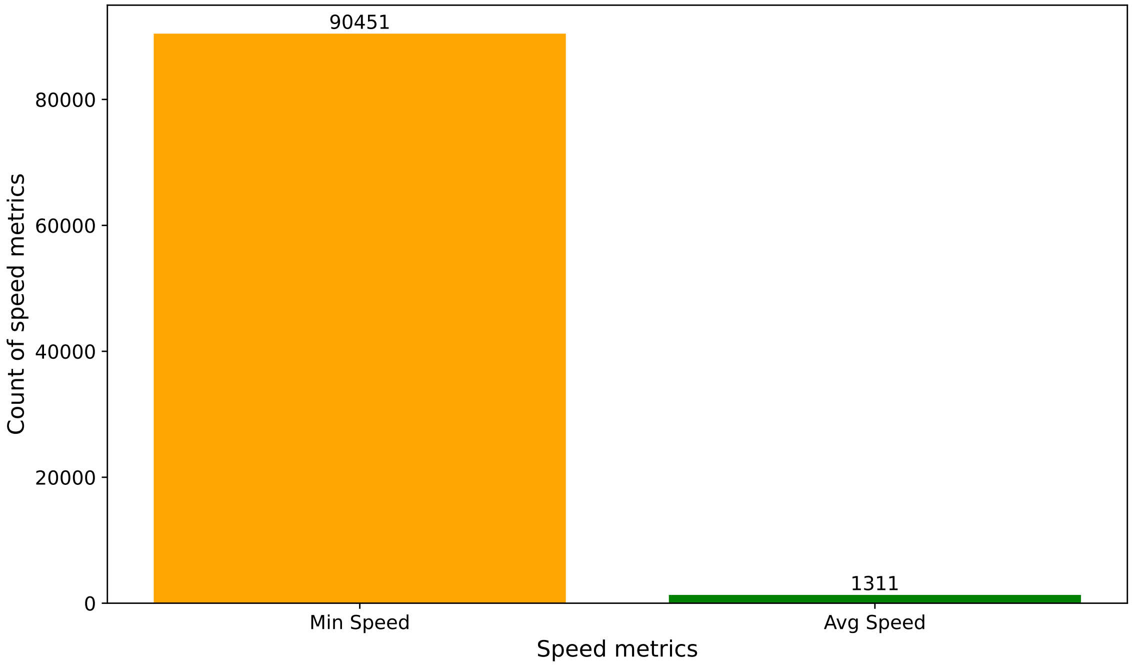


Figure 4. Count of speed metric below 45 mph

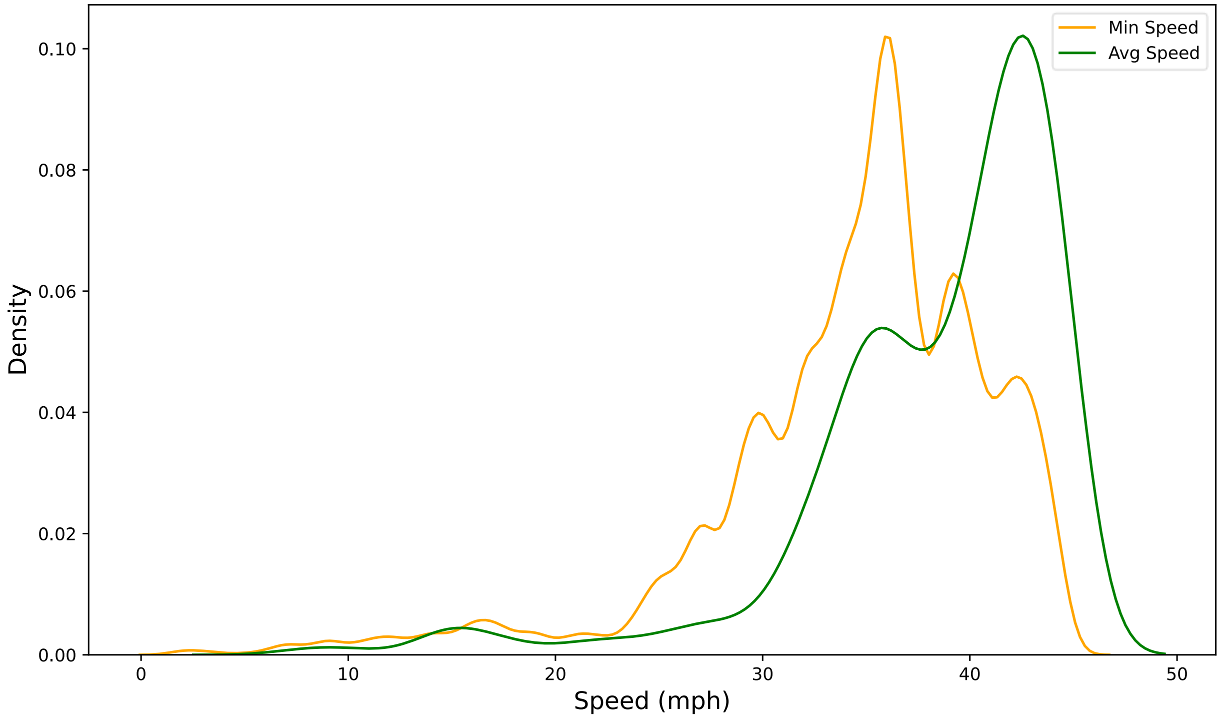


Figure 5. Distribution of speed metric below 45 mph

4.1.3. Connected Vehicle Data

For this study, CVD were obtained from Wejo. CVD consist of individual waypoints reported from CVs equipped with GPS devices and onboard units permitting the transmission of their locations in real time over cellular networks. The data are collected by auto manufacturers and resold by vendors. The CVD thus provide a detailed geographic record of individual vehicle movements, with waypoints reported every 3 seconds. Figure 6 shows an example view of the CVD from one of the work zones. In this figure, the outer boundary shows geohash blocks that were used to partition the data table for easier data retrieval. A sample of selected raw CVD, showing several waypoints for various journey IDs within the same timestamp, is presented in Table 7.

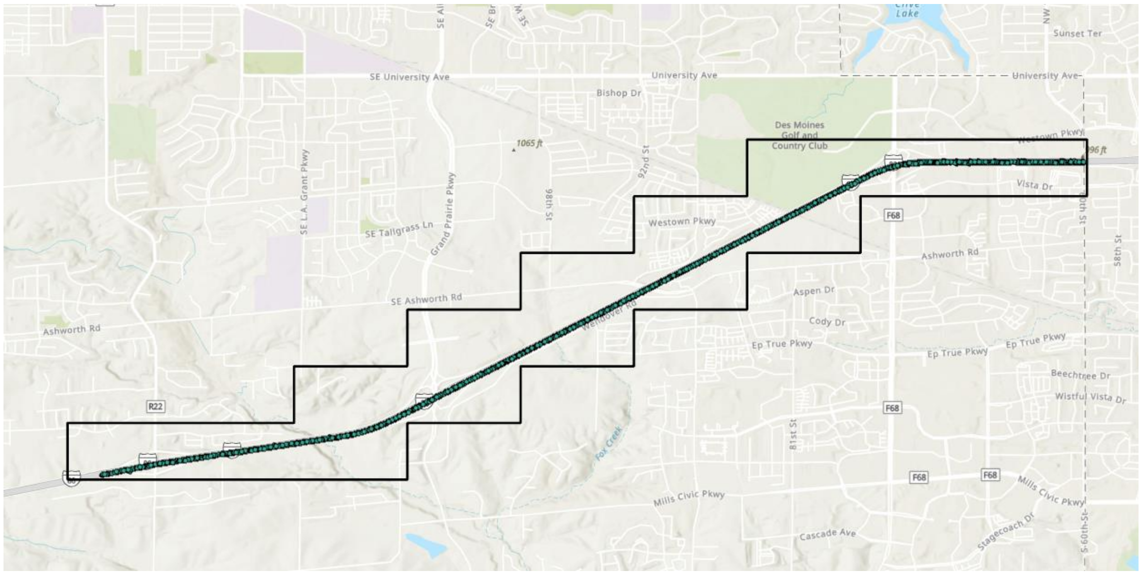


Figure 6. Example CVD from Work Zone Group 4cd

Table 7. Example CVD

Timestamp	Journey ID	Postcode	Latitude	Longitude	Speed (km/h)
2022-06-17 15:42:00	90b071fa…	50208	41.6735	-92.9608	33.4
2022-06-17 15:42:00	dbf543e4…	50208	41.7272	-93.0291	55.3
2022-06-17 15:42:00	ca75eedb…	50208	41.7014	-93.0538	2.3
2022-06-17 15:42:00	e7b70b11…	50208	41.7012	-93.0628	47.2
2022-06-17 15:42:00	fa3eefe7…	50208	41.6966	-93.0324	0.0
2022-06-17 15:42:00	69f11704…	50208	41.6956	-93.1364	92.2

A few irregularities were identified on visual inspection of the data that required some modification of the initial data selection process to ensure that the correct waypoints were selected for the work zone and direction of interest. Figure 7 illustrates some of these. Figure 7a shows the influence of shifting lanes on the location of data relative to the existing road. Figure 7b shows another example in which lane shifting has occurred, with no waypoints being recorded for one of the two roadways. The result is that the data were misaligned with the base map. To correct these problems, the data were manually cleaned to identify GPS points for the relevant direction of travel. Figure 7c shows a different problem related to the shortest distance logic applied in the map matching process used during data ingestion, where points that were in proximity to an overpass or underpass of another public road were sometimes attributed to the crossing street. For this problem, the small extent of the affected area was not considered to affect the analysis. In all figures, the apparent abrupt end of data coverage is due to the boundaries of the link definitions for data selection and is not reflective of a problem with the data set. However, it is clear that lane changes would need to be addressed in the implementation of QWS with CVD.

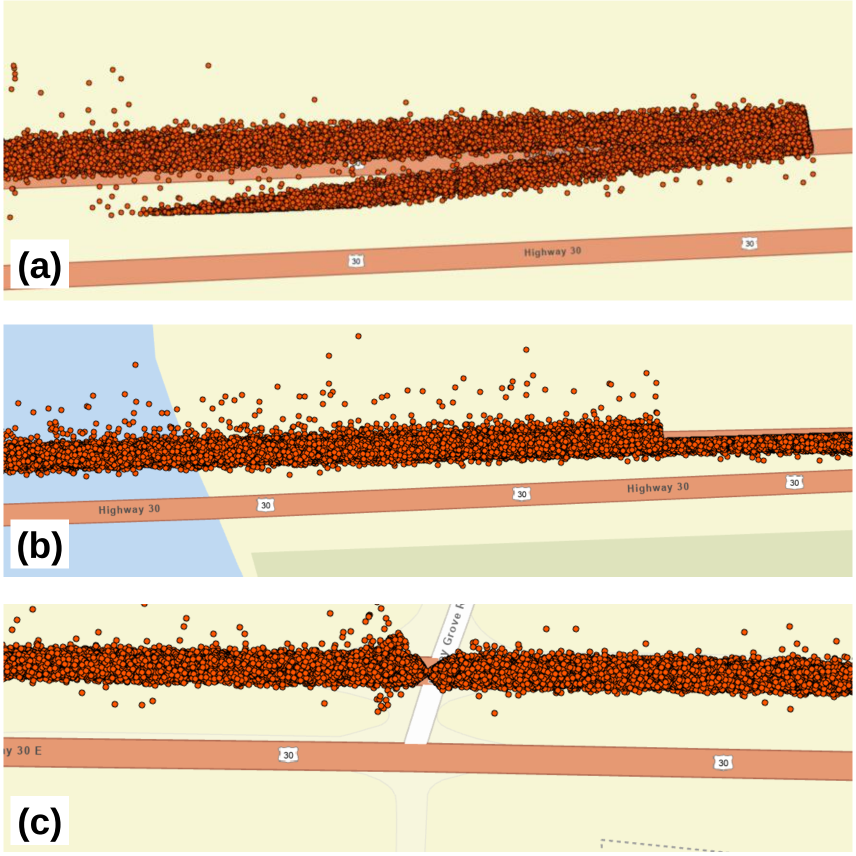


Figure 7. Illustration of CV data issues

To support a QWS application, it is necessary to develop performance measures that could be used to trigger the queue warning. Because the goal is to detect slow or stopped traffic, for this study it was decided to use the same criterion as the existing sensor-based QWS, namely when traffic speeds fall below 45 mph. However, there are many ways to determine the presence of slow traffic using CVD. It was not immediately clear whether the minimum value across all observations, some percentile, or the average value would be a good indicator. Since each vehicle provides multiple records, it was also not clear whether it would be advantageous to first find the average vehicle speed (i.e., per journey ID) before calculating these metrics or simply use the average across all data points regardless of the vehicle. There was an additional problem with low numbers of journey IDs during certain hours of the day, which might be resolved by considering not only the most recent minute but also multiple previous minutes.

To explore different possibilities, 36 different variations of CVD performance measures were developed:

- First, six performance measures were developed by aggregating all waypoints within the last minute (not considering the journey ID). These included the minimum, 5th percentile, 15th percentile, 25th percentile, 50th percentile, and average value.
- Next, two aggregation options were tried for determining the speed for each vehicle (journey ID). These included the 25th percentile and the average value. After first aggregating by journey ID, the same six aggregations used for the first option were applied.
- Finally, two options were considered to investigate the value of examining multiple minutes of data, or the length of the data collection interval: the most recent minute and the most recent three minutes of data.

Table 8 lists all 36 CVD performance measures and the variations in data collection interval, aggregation at the journey ID level, and final aggregation (either all waypoints or across values for all journey IDs).

Table 8. Methods of aggregation used for CV data

Label	Data Collection Interval (min)	Journey ID level aggregation*	Final aggregation
1-min, min	1	N/A	Minimum
1-min, min(25p)	1	25th percentile	Minimum
1-min, min(avg)	1	Average	Minimum
1-min, p05	1	N/A	5th Percentile
1-min, p05(avg)	1	25th percentile	5th Percentile
1-min, p05(p25)	1	Average	5th Percentile
1-min, p15	1	N/A	15th Percentile
1-min, p15(avg)	1	25th percentile	15th Percentile
1-min, p15(p25)	1	Average	15th Percentile
1-min, p25	1	N/A	25th Percentile
1-min, p25(avg)	1	25th percentile	25th Percentile
1-min, p25(p25)	1	Average	25th Percentile
1-min, p50	1	N/A	50th Percentile
1-min, p50(avg)	1	25th percentile	50th Percentile
1-min, p50(p25)	1	Average	50th Percentile
1-min, avg	1	N/A	Average
1-min, avg(avg)	1	25th percentile	Average
1-min, avg(p25)	1	Average	Average
3-min, min	3	N/A	Minimum
3-min, min(25p)	3	25th percentile	Minimum
3-min, min(avg)	3	Average	Minimum
3-min, p05	3	N/A	5th Percentile
3-min, p05(avg)	3	25th percentile	5th Percentile
3-min, p05(p25)	3	Average	5th Percentile
3-min, p15	3	N/A	15th Percentile
3-min, p15(avg)	3	25th percentile	15th Percentile
3-min, p15(p25)	3	Average	15th Percentile
3-min, p25	3	N/A	25th Percentile
3-min, p25(avg)	3	25th percentile	25th Percentile
3-min, p25(p25)	3	Average	25th Percentile
3-min, p50	3	N/A	50th Percentile
3-min, p50(avg)	3	25th percentile	50th Percentile
3-min, p50(p25)	3	Average	50th Percentile
3-min, avg	3	N/A	Average
3-min, avg(avg)	3	25th percentile	Average
3-min, avg(p25)	3	Average	Average

* N/A indicates that there was no aggregation of waypoints by journey ID.

One additional variation in the processing of CVD was the spatial extent to use. For this study, two variations were used, depending on the specific test application:

- One option was to use only waypoints located near the sensors. For this purpose, a 0.5-mile buffer around each sensor location was created.
- The other option was to use waypoints across the entire work zone. This used the entire length of the work zone as defined in Iowa DOT records of work zone locations.

As mentioned earlier, it was not possible to obtain an independent record of congestion, such as through video recordings or other means, because new data were not available during the project period due to the data vendor’s business difficulties. Therefore, it was necessary to accept the sensor data as ground truth. To evaluate whether CVD could identify periods of congestion reported by the sensors, data from the entire work zone were used. If no slow speeds were reported anywhere in the work zone while the sensor data were reporting slow speeds, then this unequivocally showed that the comparison data failed to identify congestion. To determine whether CVD reported congestion that did not exist, data from near the sensors were used.

Error! Not a valid bookmark self-reference., Table 10, and Table 11 show examples of the processed CVD for the same example minute for all work zones. The number of journey IDs and the number of waypoints were also calculated.

Data from June 2022 were used, comprising 65,243,680 waypoints and 4,578,538 journey IDs from the complete lengths of all work zones. Of these, the near-sensor data included 22,882,585 waypoints and 2,108,240 journey IDs.

Table 9. Example of processed CVD: aggregation across all waypoints without respect to journey ID

					Performance Measures (all waypoints)					
Work Zone	**Direction**	**Timestamp**	**Journey IDs**	**Waypoints**	**1-min, min**	**1-min, p05**	**1-min, p15**	**1-min, p25**	**1-min, p50**	**1-min, avg**
Group6wI80	Westbound	2022-06-01 00:00:00	1	20	60.1	63.7	60.1	61.6	63.0	63.7
Group1cq	Eastbound	2022-06-01 00:00:00	2	37	52.3	63.4	54.7	59.0	60.1	67.3
Group6wI380	Northbound	2022-06-01 00:00:00	2	34	50.1	63.8	53.7	55.1	57.3	61.6
Group4ch	Eastbound	2022-06-01 00:00:00	1	19	37.2	46.7	37.2	38.4	39.0	45.1
Group4ch	Westbound	2022-06-01 00:00:00	1	3	68.0	69.7	68.1	68.4	68.7	69.4
Group1cr	Eastbound	2022-06-01 00:00:00	2	18	53.0	64.0	56.0	64.6	64.7	65.0
Group4cd	Westbound	2022-06-01 00:00:00	1	3	60.8	61.6	60.9	61.1	61.2	61.6

Table 10. Example of processed CVD: 25th percentile by journey ID before aggregation across journey IDs

			Performance Measures (25th percentile for each journey ID)					
Work Zone	**Direction**	**Timestamp**	**1-min, min(25p)**	**1-min, p05(25p)**	**1-min, p15(25p)**	**1-min, p25(25p)**	**1-min, p50(25p)**	**1-min, avg(25p)**
Group6wI80	Westbound	2022-06-01 00:00:00	63.0	63.0	63.0	63.0	63.0	63.0
Group1cq	Eastbound	2022-06-01 00:00:00	58.7	59.1	60.0	60.8	63.0	63.0
Group6wI380	Northbound	2022-06-01 00:00:00	55.1	55.9	57.4	59.0	62.8	62.8
Group4ch	Eastbound	2022-06-01 00:00:00	39.0	39.0	39.0	39.0	39.0	39.0
Group4ch	Westbound	2022-06-01 00:00:00	68.7	68.7	68.7	68.7	68.7	68.7
Group1cr	Eastbound	2022-06-01 00:00:00	53.9	54.4	55.5	56.6	59.4	59.4
Group4cd	Westbound	2022-06-01 00:00:00	61.2	61.2	61.2	61.2	61.2	61.2

Table 11. Example of processed CVD: average by journey ID before aggregation across journey IDs

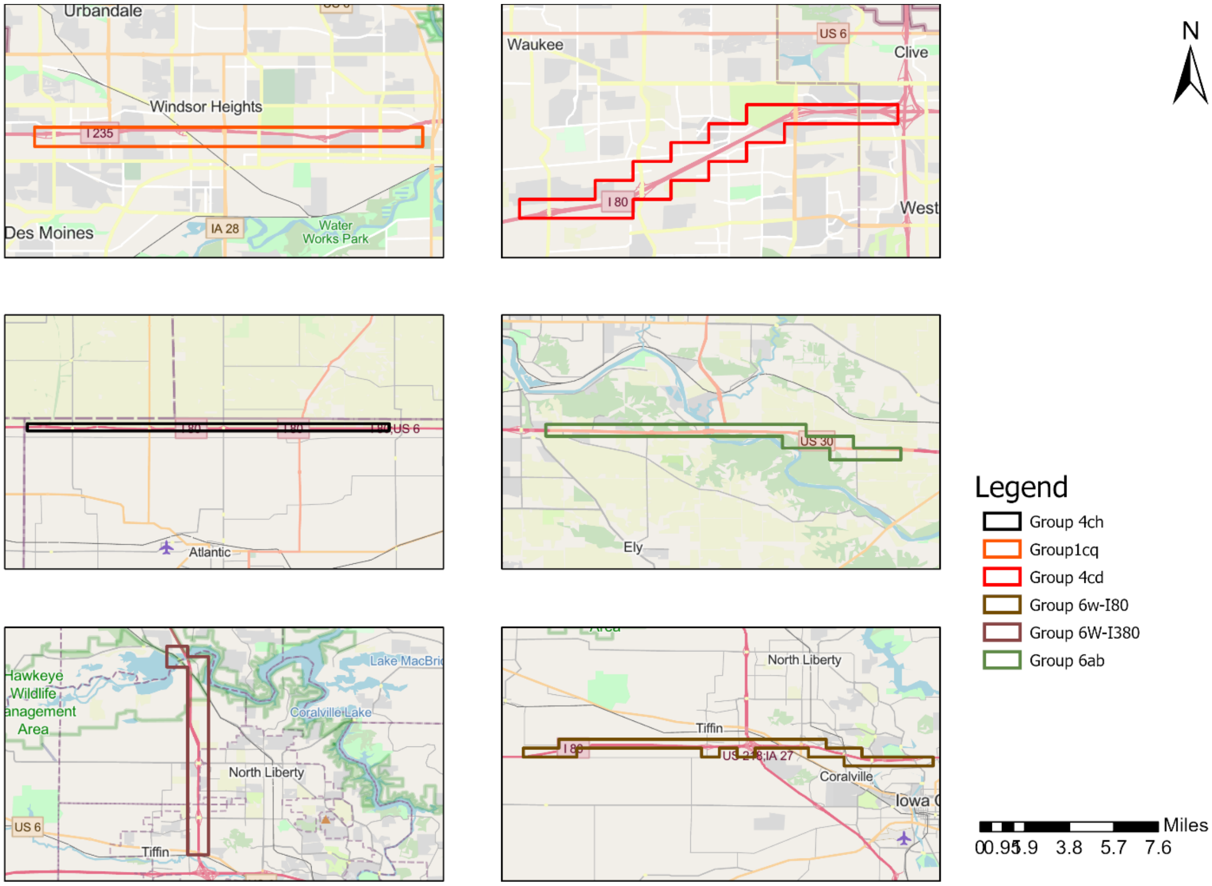
			Performance Measures (Average for each journey ID)					
Work Zone	**Direction**	**Timestamp**	**1-min, min(avg)**	**1-min, p05(avg)**	**1-min, p15(avg)**	**1-min, p25(avg)**	**1-min, p50(avg)**	**1-min, avg(avg)**
Group6wI80	Westbound	2022-06-01 00:00:00	63.7	63.7	63.7	63.7	63.7	63.7
Group1cq	Eastbound	2022-06-01 00:00:00	58.9	59.3	60.1	61.0	63.1	63.1
Group6wI380	Northbound	2022-06-01 00:00:00	57.8	58.5	60.0	61.4	65.1	65.1
Group4ch	Eastbound	2022-06-01 00:00:00	46.7	46.7	46.7	46.7	46.7	46.7
Group4ch	Westbound	2022-06-01 00:00:00	69.7	69.7	69.7	69.7	69.7	69.7
Group1cr	Eastbound	2022-06-01 00:00:00	54.8	55.3	56.3	57.3	59.9	59.9
Group4cd	Westbound	2022-06-01 00:00:00	61.6	61.6	61.6	61.6	61.6	61.6

4.2. Site Selection

To identify work zones, a record of work zone locations maintained by the Iowa DOT was used. This record included project names, start and end mileposts, start and end dates, and other information such as whether sensors were used. The start and end mileposts were used to establish the boundaries for the collection of SSD and CVD. Six work zones were selected for data collection. Table 12 lists these, and maps are presented in Figure 8. The blocks encircling the work zone locations represent the geohashes used for partitioning the data table, as explained earlier.

Table 12. Work zones included in this study

Work Zone Name	Direction	General Location Description
Group Icq	Eastbound/Westbound	I-235, 0.2 mi east of IA 28 in Des Moines
Group 4cd	Eastbound/Westbound	Ashworth Rd, 3.0 mi west of W Jct I-35
Group 4ch	Eastbound/Westbound	I-80, 1.9 mi east of JCT IA 173
Group 6ab	Eastbound/Westbound	US 30, 0.5 mi west of E Jct US 151 (EB)
Group 6wI380	Northbound/Southbound	I-380, near I-80 & I-380 Systems Interchange & Forevergreen Rd Interchange
Group 6wI80	Eastbound/Westbound	I-80, near I-80 & I-380 Systems Interchange & Forevergreen Rd Interchange



Map data © OpenStreetMap contributors, Microsoft, Facebook, Google, Esri Community Maps contributors, Map layer by Esri

Figure 8. Work zone study locations

4.3. Completeness of SSD and CVD

To operate a QWS, it is of course essential for data to be available to determine whether slow or stopped traffic is present in the work zone. Therefore, the completeness of the data set is an important consideration in determining the readiness of the data for this application. In this study, completeness was evaluated by examining the amount of time that data were available for the work zones.

4.3.1. Segment Speed Data Completeness

To evaluate the completeness of SSD, the confidence score provided by the data vendor was used. This number provides information on the source of the data used to develop an average speed reading. A score of 10 indicates that the data were estimated based on historical data. A score of 20 indicates that the data were developed from a mix of historical and real-time data. A score of 30 indicates that the data were developed from real-time data only. Readings were available for every minute for the work zone segments in the study.

Figure 9 shows the distribution of confidence score values across all minutes of data in all work zones for June 2022. This chart reveals that for most hours of the day, less than 5% of the minutes have data with a confidence score of 10 or 20, meaning that most of the time, real-time data are available. Most of the data with scores of 10 or 20 occur between 01:00 and 05:00. Figure 10 shows the breakdown of data for only those minutes with scores of 10 or 20. This shows that data with a score of 10 are present only between 18:00 and 07:00. The category "Other" includes minutes for which no score was available, thus indicating missing data. There were very few minutes for which no data were available.

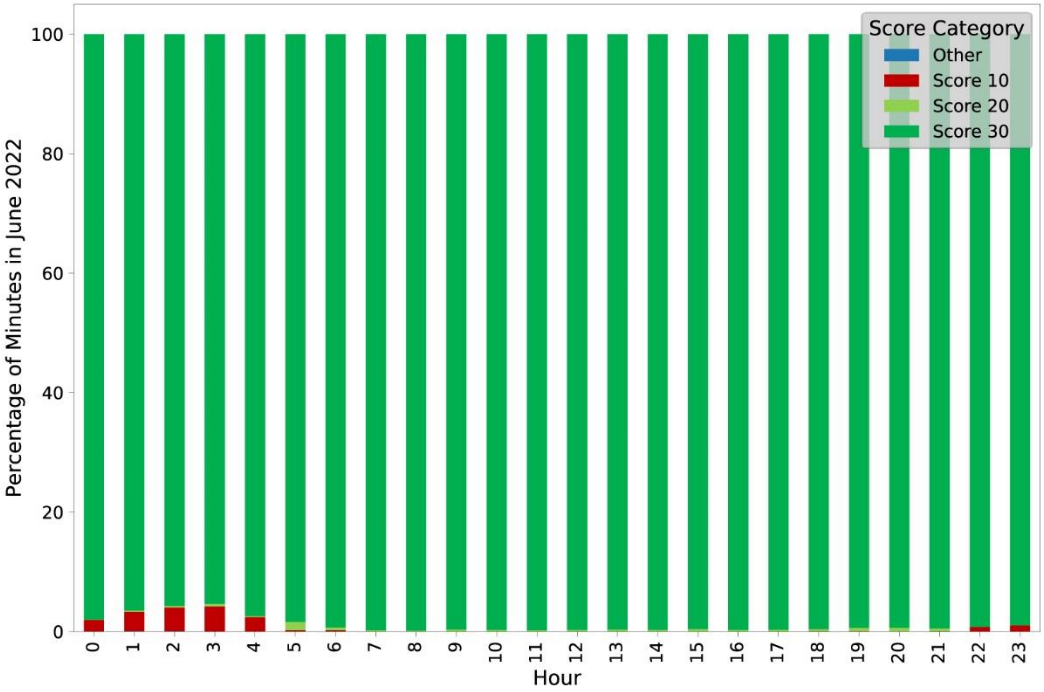


Figure 9. Percentage of minutes by all score categories

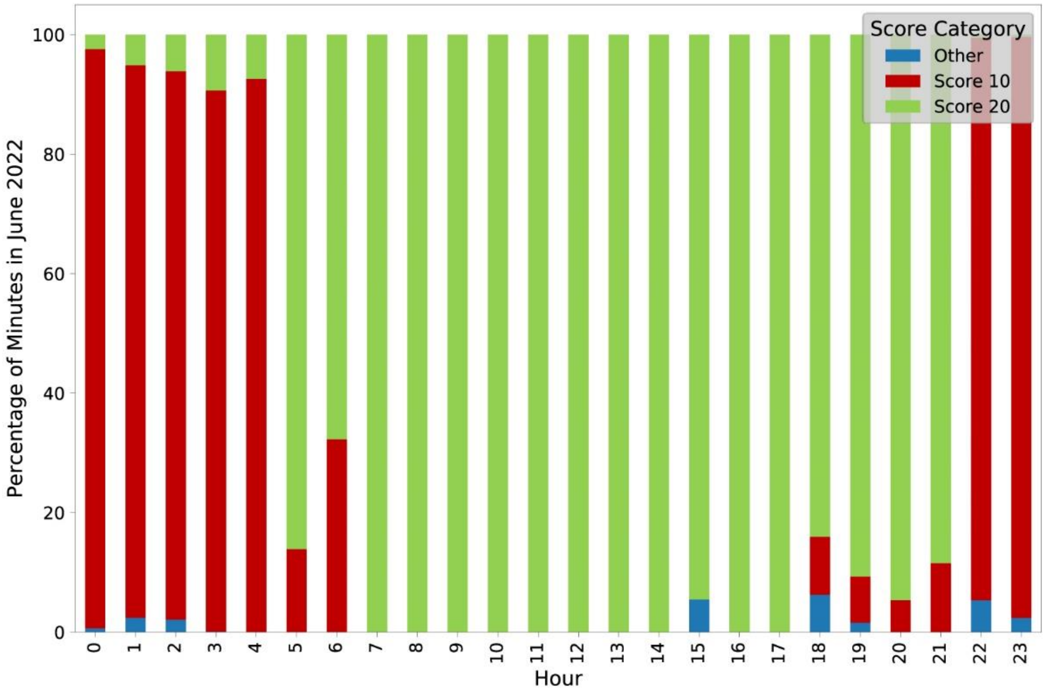


Figure 10. Percentage of minutes by score categories 10 and 20

From these views of the confidence scores, we can conclude that the SSD have a high degree of data completeness. Not only were records available for each minute during the study period, but the overwhelming majority of these were based on real-time data, according to the data vendor. It should be noted that this study considered only Interstate work zone locations. Other types of roads might not have the same level of coverage with real-time data.

4.3.2. Connected Vehicle Data Completeness

To evaluate CVD completeness, the numbers of journey IDs were used along with the numbers of waypoints, as shown in One additional variation in the processing of CVD was the spatial extent to use. For this study, two variations were used, depending on the specific test application:

- One option was to use only waypoints located near the sensors. For this purpose, a 0.5-mile buffer around each sensor location was created.
- The other option was to use waypoints across the entire work zone. This used the entire length of the work zone as defined in Iowa DOT records of work zone locations.

As mentioned earlier, it was not possible to obtain an independent record of congestion, such as through video recordings or other means, because new data were not available during the project period due to the data vendor’s business difficulties. Therefore, it was necessary to accept the sensor data as ground truth. To evaluate whether CVD could identify periods of congestion reported by the sensors, data from the entire work zone were used. If no slow speeds were reported anywhere in the work zone while the sensor data were reporting slow speeds, then this unequivocally showed that the comparison data failed to identify congestion. To determine whether CVD reported congestion that did not exist, data from near the sensors were used.

Error! Not a valid bookmark self-reference., Table 10, and Table 11 show examples of the processed CVD for the same example minute for all work zones. The number of journey IDs and the number of waypoints were also calculated.

Data from June 2022 were used, comprising 65,243,680 waypoints and 4,578,538 journey IDs from the complete lengths of all work zones. Of these, the near-sensor data included 22,882,585 waypoints and 2,108,240 journey IDs.

Table 9. These data were summarized for each minute for which CVD existed in June 2022. From this, it was possible to count the number of minutes for which CVD existed and compare this to the total number of minutes in the month.

Figure 11 and Figure 12 respectively illustrate CVD completeness for weekdays and weekends. Each bar represents the overall total across all work zones included in the study for the given hour of the day. "No Data" indicates that no waypoints were available within the minute. The charts also show the percentage of minutes for which data were reported from only one journey ID. This chart shows that the CVD has low data coverage during early morning and overnight hours. From midnight until 5:00 on weekdays or 6:00 on weekends, data coverage is particularly poor. However, during the day, from 6:00 through 19:00, there is very good data coverage, with many of the hours during this time period including CVD from two or more journey IDs.

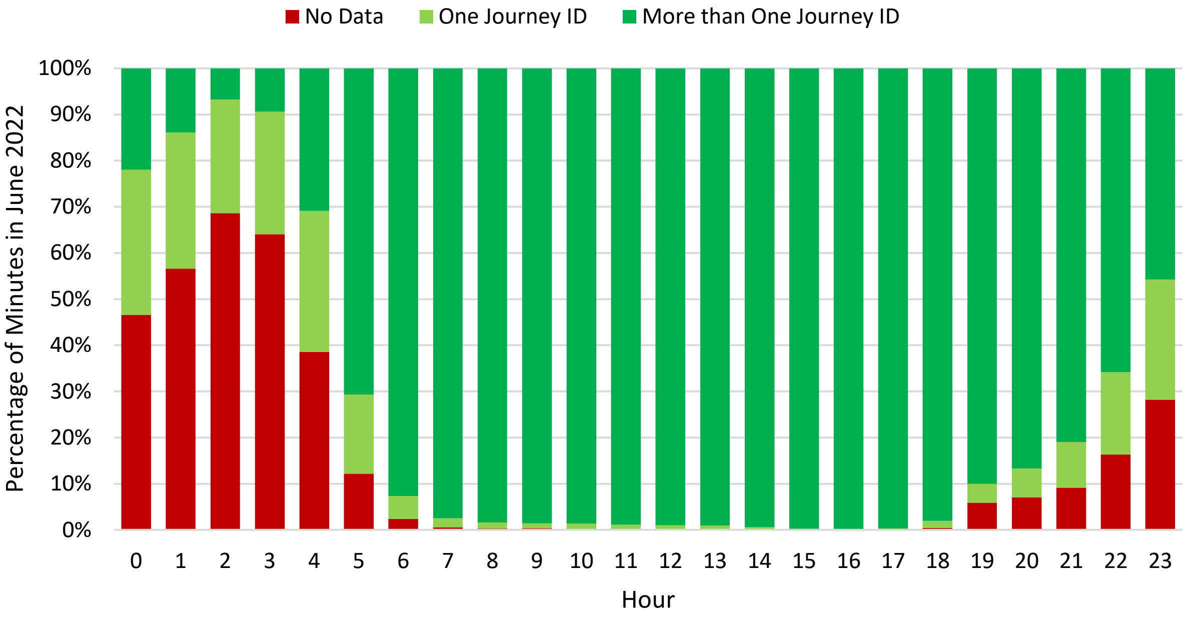


Figure 11. Availability of CVD by hour for weekdays (total across all work zones)

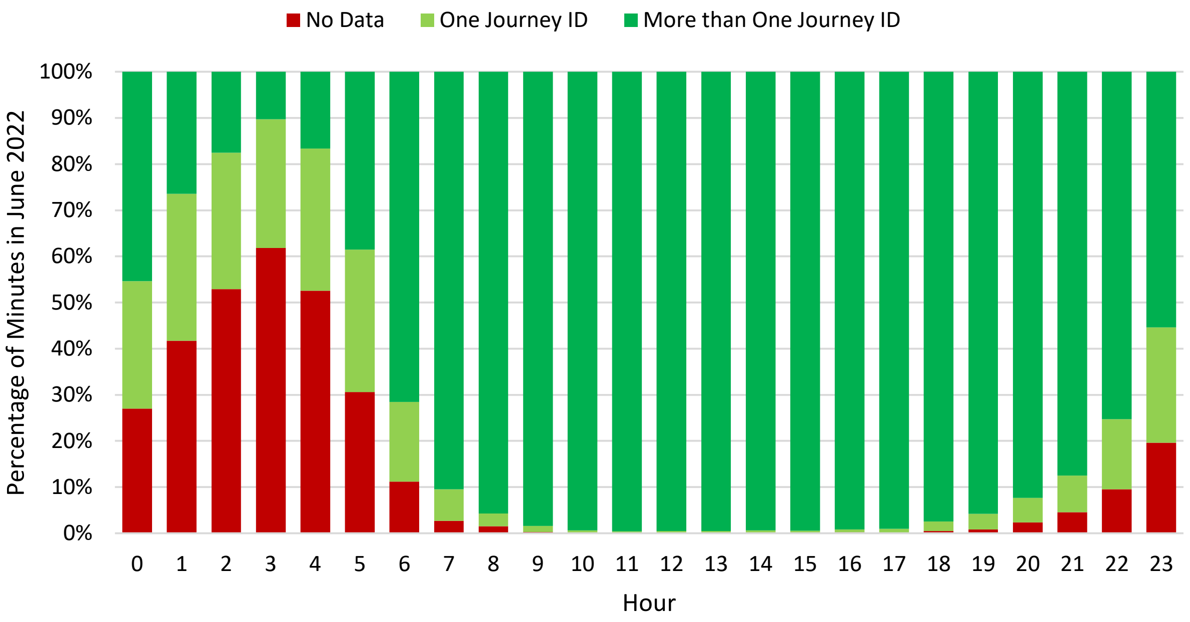


Figure 12. Availability of CVD by hour for weekends (total across all work zones)

Reduced data coverage during overnight and early morning hours is somewhat expected because the overall traffic volumes are lower during these hours, thus reducing the total number of vehicle probes on the road at these times. However, this may prove challenging for a QWS application because work zones are often more active during these hours. However, it was seen that the SSD are able to cover these hours, suggesting the possibility of a QWS application that uses both data sets. The CVD would be able to capture individual vehicles that slowed or stopped in the work zone, while the SSD would provide an alternative source of this information, covering overnight hours. This option was explored later in the study during a virtual application for QWS.

4.4. Identification of Congestion

Next, the ability of the data to identify congestion was assessed. To conduct this assessment, each data set was examined as a potential source of queue warning data. That is, since each data set represented a work zone speed measurement, it was possible to use it to determine whether an alert would have been displayed if the data were streaming in real time. The sensor data served as the ground truth for this analysis. The alternative data sets (SSD and CVD) were also examined to determine what times they would have generated an alert. Then, the alert activations were compared to identify the amount of agreement between the SSD and CVD for the same work zone in the same time period. For this purpose, the numbers of missed calls and false calls for each alternative data set were calculated.

To avoid including detections due to noise from transient detections of low speed, as well as to reduce the potential impacts of latency, only incidents of congestion where speeds remained under 45 mph for longer than 5 minutes were considered in the missed call/false call analysis.

There was no upper bound to the duration of an incident. Figure 11 shows a histogram of the durations of incidents as identified by the sensor data.

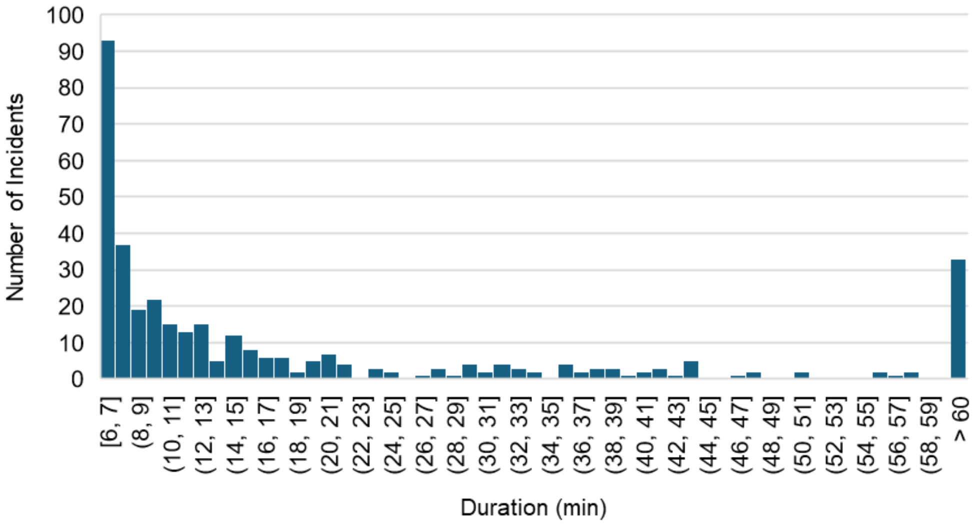


Figure 13. Incident durations

To assess missed calls, incident data were identified by finding times when the sensor-measured speeds were under 45 mph. After filtering out events less than 6 minutes in duration, the data from the alternative data sets were examined to determine whether each of those was reporting a speed under 45 mph. For this analysis, missed calls were considered to occur when the alternative data set did not report congestion for even one minute within the duration of the incident.

The false call analysis was done in the same way, only with the data sets swapped. That is, first the incidents were identified from each of the alternative data sets to determine when each would have reported congestion. This generated a separate list of incidents and durations for each alternative data set. Each of these incident lists was then cross-referenced to the sensor data to check whether the sensors were reporting congestion at the same time. An incident was considered to be a false call when the sensor data did not report any congestion during the entire interval.

For the missed call analysis, for the SSD and CVD, we considered data from the full extent of each work zone, since this should have captured slow speeds detected at any of the work zone sensors. For the false call analysis, for the SSD and CVD, we considered only data from the locations filtered to within the ranges of the sensors. This was intended to avoid false calls being generated by slow traffic events measured by the SSD and CVD that were not within the ranges of the sensors. Overall, the test conditions were arguably somewhat favorable to the SSD and CVD under examination. However, it was appropriate to select a lower performance threshold for the initial test given the exploratory nature of this initial examination, since if the data sets were not able to achieve high performance at the lower threshold, they would not be expected to perform well under more rigorous standards. Therefore, this test evaluated whether SSD and

CVD can be minimally ready for QWS applications. This strategy was chosen since it was already observed in the previous test that the CVD has spotty coverage during overnight hours.

The results of the analysis are shown in Figure 14. The vertical axis (missed calls) represents the percentage of incidents identified by the sensors that were completely missed by the alternative data sets, while the horizontal axis (false calls) represents the percentage of incidents identified by the alternative data sets that were completely unreported by the sensors during the same time frame. The labels are explained above in Table 8.

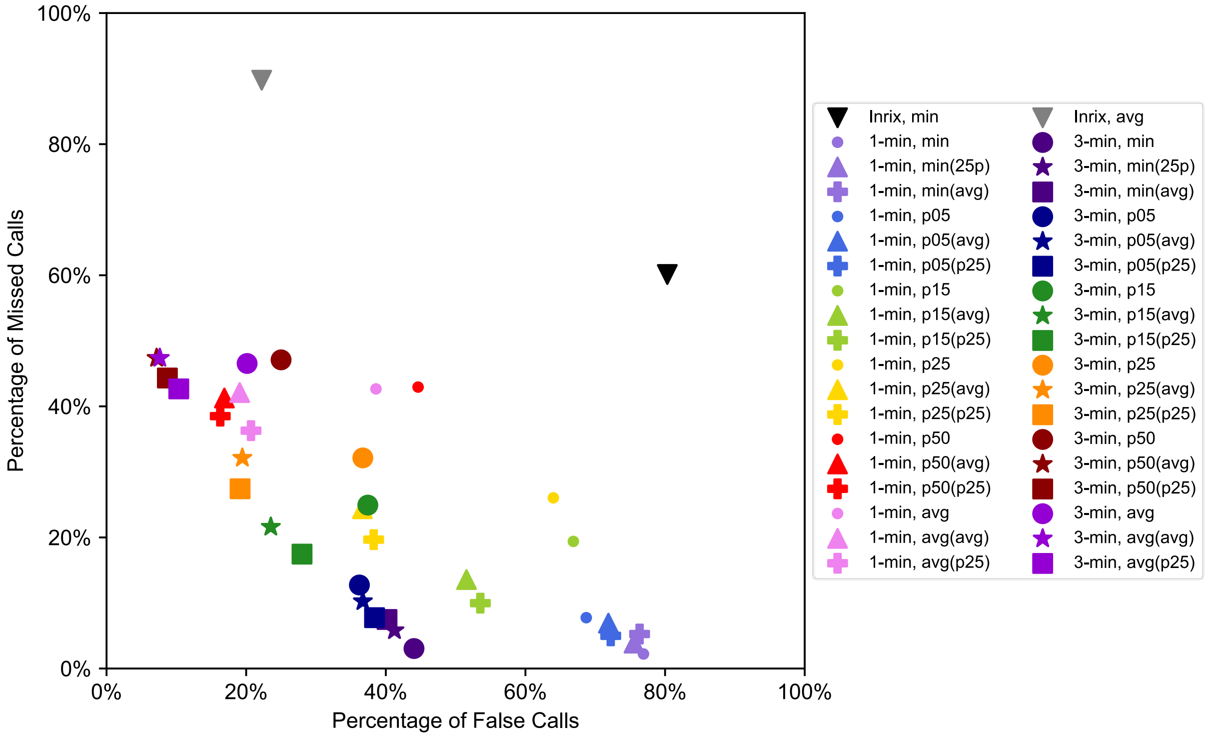


Figure 14. Missed calls versus false calls and selection of performance measure for identifying congestion

Altogether, 38 alternative metrics were tested, including two SSD metrics (minimum or average speed value of all segments in the work zone) and 36 CVD metrics. The 36 CVD metrics represent variations on the use of a rolling window (1 minute versus 3 minutes), six options for aggregating across all available speed data (minimum, 5th percentile, 15th percentile, 25th percentile, 50th percentile, or average), and three options for aggregating at the journey ID level (no journey ID aggregation, 25th percentile of all waypoints for each journey ID, and average waypoint speed for each journey ID).

Aggregation methods were selected to test whether it is more effective to target the central tendency of the distribution (e.g., 50th percentile, average) or the left end of the distribution (e.g., minimum, 5th percentile) to avoid as many missed calls as possible without generating an excessive number of false calls. Overall, those methods targeting the central tendency tended to have fewer false calls but more missed calls, while those targeting the left end had fewer missed calls and more false calls. In Figure 14, the labels are color coded using a spectrum to represent those closer to the middle (more red) or closer to the lower percentiles (more blue). Aggregations that favor the middle of the distribution tend to have more missed calls and fewer false calls, while aggregations that favor the low end of the distribution tend to have fewer missed calls but more false calls. The options considered here seem to form a spectrum ranging between the two, but no options were able to achieve lower than 40% of either false calls or missed calls. Both of the SSD performance measures exhibit much higher numbers of missed calls and false calls compared to the CVD performance measures.

The chart shows that adding the journey ID-level aggregation may be helpful in some circumstances. That is, the circular symbols (all of which indicate that no journey ID-level aggregation took place) are generally to the right of the other symbols with the same work zone-level aggregation, meaning that they have slightly more false calls. In some cases, the addition of journey ID-level aggregation reduces the number of missed calls, but in some cases this aggregation increases the number of missed calls, especially for the minimum and 5th percentile work zone-level aggregations. Although aggregation by journey ID appears to be useful among some groups of options, the option that yields the lowest numbers of missed calls is the minimum value across all waypoints, with no aggregation by journey ID.

In addition, the chart shows that the use of a 3-minute rolling window can reduce the number of false calls compared to the same aggregation options for 1-minute data. For example, the “1-min, min” option (minimum value of all waypoints within 1 minute) has 2.2% missed calls and 76.9% false calls. The “3-min, min” option (3-minute moving average of the 1-minute minimum speed) has 3.0% missed calls but 44.0% false calls. Thus, the number of false calls is greatly reduced, yet there are only a few more missed calls.

Ultimately, for QWS applications, missed calls and false calls are both undesirable, but a missed call is more undesirable. For this reason, to proceed with the latency and alerting analyses, it was decided to use the “3-min, min” option for the CVD, since this aggregation option achieved the lowest number of missed calls while the 3-minute aggregation option was able to substantially reduce the number of false calls.

4.5. Latency of SSD and CVD

The next test in this study concerned data latency. Latency refers to the delay between changes in traffic conditions in the field and when the data are able to show these changes. For this study, because the sensor data were used as the ground truth data, latency was defined as the amount of time between the detection of traffic by work zone sensors and the identification of congestion by the comparison data (SSD or CVD). Because it is desirable to report slowed or stopped traffic as soon as possible, it is desirable for latency to be as low as possible.

To evaluate latency, congestion incidents were identified by examining the sensor data using the minimum simple average speed described earlier (average across lanes, minimum across sensors). As in the previous tests, speeds under 45 mph were considered to indicate congested conditions. Incidents were used for latency evaluation when speeds were sustained under this threshold for 5 minutes or longer. Data were also retrieved from the SSD and CVD. Based on the results of the preceding test, the minimum segment speed was used for the SSD, while the minimum speed across a 3-minute rolling window (labeled as “3-min, min” in Table 8) was used for the CVD. For each incident, data were tabulated going back to 10 minutes before the start of congestion detected by the sensors and going up to 20 minutes beyond the end of congestion detected by the sensors. This was done in case the SSD or CVD detected congestion before the sensors and to permit sufficient time for the SSD or CVD to “catch up” to the sensors. This enabled latency to be separately measured for congestion onset and for congestion recovery. Figure 15 shows an example incident, conceptually illustrating the latency measurement.

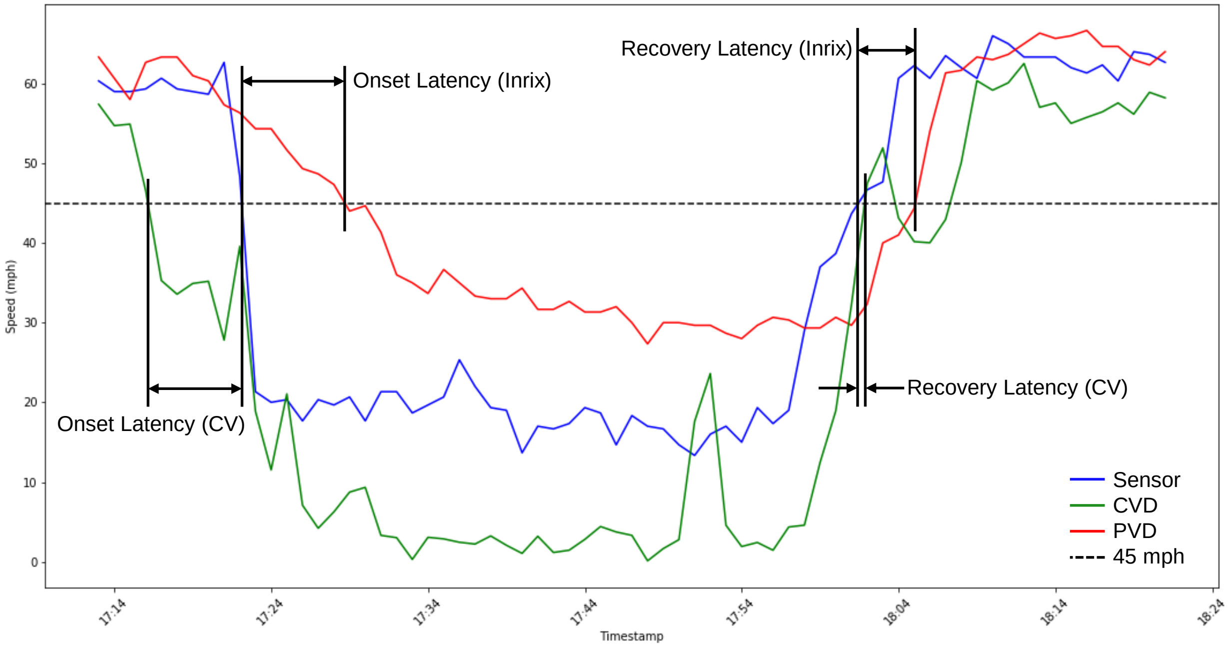


Figure 15. Example congestion incident illustrating latency in the data sets

To perform the latency calculation, the data for each incident were considered for each minute in succession to determine the congestion reporting status for the SSD and CVD relative to the sensor data. The process is explained below:

- **Congestion onset**. The key time in this analysis was the time when the sensors first reported congestion for the incident, the sensor onset time. The corresponding SSD onset time and CVD onset time were identified as either the *last time* when speeds fell below 45 mph *before* the sensor onset time or the *first time* when speeds fell below 45 mph *after* the sensor onset time.

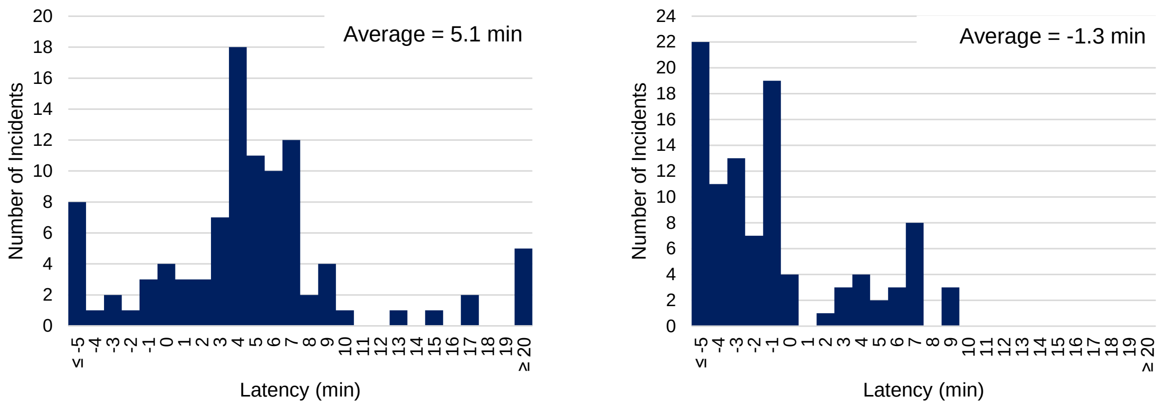
- **Congestion recovery**. Detection of recovery from congestion was only possible if congestion was first identified by the SSD or CVD in the first place. To measure recovery latency, the key time was the last time the sensors reported congestion for the incident, the sensor recovery time. The corresponding SSD recovery time and CVD recovery time were identified as the time when speeds rose above 45 mph and subsequently remained above 45 mph for at least five minutes. This criterion was needed because there were numerous instances where the SSD or CVD would rise above the threshold for a brief period. This is similar to the criterion used for QWS applications, where the queue warning is removed only after a certain number of minutes have elapsed where speeds remained above the threshold.

It was challenging to distinguish between valid latency measurements and discrepancies in the detection of congestion. To characterize latency, a focus was placed on times when multiple data sets detected congestion onset or recovery around the same time, as illustrated in Figure 15. Observations were excluded when the time differences between the sensor data and the comparison data were excessive, since these were reflective of the ability of SSD or CVD to detect congestion rather than of differences in detection time. The maximum onset latency observation was 40 minutes, and the maximum recovery latency observation was 20 minutes.

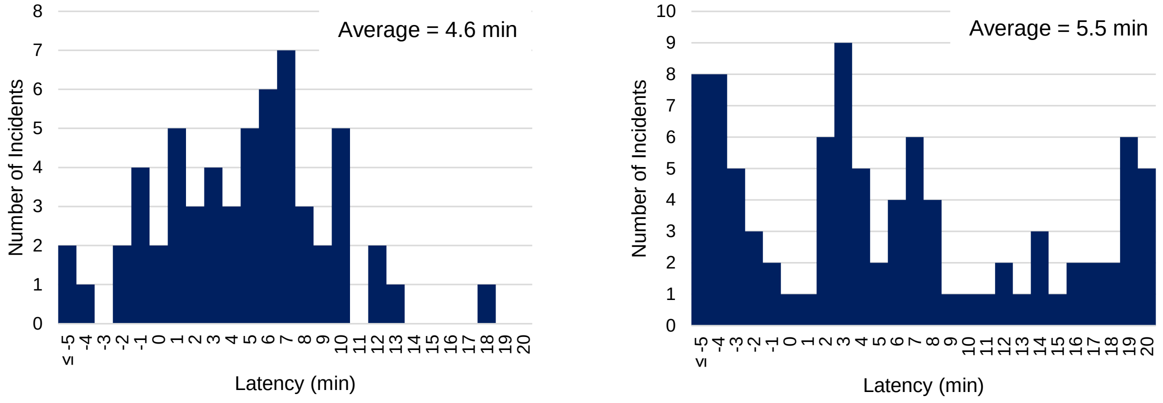
Altogether, 227 incidents were identified from the sensor data using the criteria described earlier. The incidents varied in duration from 5 to 331 minutes, with an average of 30.5 minutes and a median of 12 minutes. There were 95 incidents for which the SSD did not detect congestion and 29 incidents for which the CVD did not detect congestion. These are similar to the numbers of missed calls in the analysis presented earlier. In some cases, the SSD and CVD were already detecting congestion 10 minutes prior to the sensor onset time. This occurred for 33 incidents for the SSD and for 98 incidents for the CVD. Although data near the sensors were used for this comparison, it was still possible that the SSD or CVD may have included observations away from the sensor locations. In these cases, the results would have led to a misleading latency calculation, so they were excluded from latency onset calculations. This left a remaining 99 incidents with valid SSD and 100 incidents with valid CVD for measuring the latency of congestion onset.

For latency recovery, there were 125 incidents where recovery was not detected by the SSD and 118 incidents where recovery was not detected by the CVD, either because congestion was never identified in the first place or because the comparison data sets did not identify recovery within 20 minutes of the sensor recovery time. For some incidents, the CVD or SSD stopped reporting congestion much earlier than the sensor data. Observations where the time difference was greater than 10 minutes before the sensor recovery time were excluded from the latency calculation. There were 58 valid observations of congestion recovery with SSD and 91 with CVD.

The results of the latency analysis are presented in Figure 16. This figure shows histograms of latency in the detection of congestion onset by the SSD (Figure 16a) and the CVD (Figure 16b) and latency in the detection of congestion recovery by the SSD (Figure 16c) and the CVD (Figure 16d). The average values are also shown. Note that for latency in the detection of congestion recovery, the maximum value considered is 20 minutes based on the incident data selection process described earlier.



(a) SSD onset latency (b) CVD onset latency



(c) SSD recovery latency (d) CVD recovery latency

Figure 16. Histograms of latency in the detection of congestion onset and recovery from congestion using SSD and CVD, with average values

For detecting congestion onset, the SSD exhibits greater latency than the CVD, with respective average values of 5.1 minutes and -1.3 minutes. The negative CVD value reflects many scenarios where the CVD detected latency for several minutes prior to detection by the sensors. The longest latency time for the CVD was 9 minutes, whereas for the SSD there were 5 incidents (out of 99) where congestion was not detected for 20 minutes or more after detection by the sensors.

For latency in the detection of recovery, the SSD had a lower latency, with an average value of 4.6 minutes, compared to the CVD, which had an average value of 5.5 minutes. For the SSD, the distribution is rather evenly distributed around the average value, as shown in Figure 16c, while the corresponding distribution for the CVD in Figure 16d shows that the data include many observations on both the low and high end of the range of values considered. This demonstrates that the detection of congestion recovery by the CVD was much more variable than that of the SSD, with about as many incidents where the CVD stopped detecting congestion much earlier than the sensor data as there were incidents where the CVD continued to detect congestion well after the sensor data indicated recovery.

4.6. Queue Warning Performance

The last dimension of performance examined in this study was the ability of the selected data sets to provide a queue warning. To evaluate the SSD and CVD for this application, a virtual queue warning technique was used. The sensor data reflect the available data that would have been used to supply a queue warning in the field. Thus, it was possible to go through the archived data in sequence to determine when such a warning would have been supplied using a similar strategy to that currently used in the field. The same process was also undertaken using the selected SSD and CVD metrics. The outcomes of the queue warning were then assessed to identify when the SSD and CVD metrics would have been in agreement with the sensor data. Because the SSD and CVD may be able to identify congestion that is not located near the sensors but both should be able to detect any congestion near the sensors, the performance measure for agreement was based on the successful detection rate of the SSD and CVD in identifying congestion observed by the sensor data.

The first step was to organize all of the data in a format that would permit a queue warning algorithm to step through the data in a minute-by-minute fashion and determine whether a queue warning would be displayed. For this purpose, a master table of all applicable time periods in June 2022 was created by developing a list of each minute in the month for each work zone. Next, the selected sensor, SSD, and CVD metrics for each work zone and each minute were joined to this table. This process was necessary to identify the minutes with missing data so that they would be included in the analysis.

A virtual queue warning algorithm was then developed. This algorithm processed the data from each direction in each work zone separately, stepping through all of the minutes in June 2022 to determine whether a queue warning would have been displayed during each minute as a function of the data that would have been known to the algorithm at that time if it had been operating in the field. The algorithm works as follows:

1. **Initialization.** At the start of the analysis for each work zone/direction, initialize all of the variables and set congestion entry and exit thresholds.

2. **Step Through the Data.** Go through each minute (row) in the source data table and perform the following substeps:

    a. **Retrieve Data and Create a Data History.** The most recent observations are obtained for the sensor data, SSD, and CVD. A set of variables is defined to store these data for the current minute and the previous four minutes, thus creating a five-minute history. As each new observation is obtained, the others are pushed one position backward in a cascading manner and the oldest observation is discarded. If there are missing data, then the most recent observation is retained.

    b. **If No Active Queue Warning, Determine Congestion Onset.** The default setting is for there to be no active warning. In this mode, the algorithm examines the most recent observation for the sensor data, SSD, and CVD. A warning is put into effect if the data show that speeds have fallen below 45 mph. Separate warning statuses are created for the sensor data, SSD, and CVD, along with a fusion warning that incorporates both SSD and CVD, which will be described later.

c. **If Active Queue Warning, Determine Congestion Recovery.** If the system is currently supplying a warning (for a given data set), then the algorithm will look at the past five minutes of data from the relevant data set to determine if the congestion has subsided and the warning should be removed. For the warning to be deactivated, the data must show that speeds are above the 45 mph threshold for the entire five-minute interval.

The algorithm populated four warning status columns indicating whether a warning would have been displayed for the given minute based on the sensor data, SSD, CVD, and the fusion warning option mentioned above. The fusion warning used both the SSD and CVD to supply the warning based on the following criteria: the warning would be activated if either the SSD or CVD indicated that speeds had fallen below 45 mph, and an active warning would be deactivated if both the SSD and CVD agreed that speeds had risen above 45 mph for each minute in the past five minutes.

The overall results of the analysis are shown in Table 13 for five work zone-direction pairs. One of the work zones was excluded from this analysis because it exhibited the largest number of congestion incidents that were not detected by the SSD. The first set of columns in the table shows the total number of minutes in June 2022 where a queue warning would have been displayed for each data type. The next set of columns shows the percentage of minutes where the SSD, CVD, and fusion alerts agreed with the sensor data. The percent agreement values are also shown in Figure 17, which clearly shows the differences between the three alert types. For each work zone-direction pair, the CVD and fusion options had higher levels of agreement than the SSD. With the exception of direction 0 on Group4ch, the agreement was much higher. For some work zones, the SSD captured very little of the congestion reported by the sensor data. The CVD were able to capture between 39% and 92% of the sensor-reported congestion, varying by work zone-direction pair. The use of both SSD and CVD in the fusion warning was able to marginally increase this level by a few percentage points in many cases.

Table 13. Results of virtual queue warning analysis

		Minutes with Active Alert				Agreement with Sensor Data		
Work Zone	**Direction**	**Sensor**	**SSD**	**CVD**	**Fusion**	**SSD**	**CVD**	**Fusion**
Group1cq	0	2588	415	1797	1839	16.0%	69.4%	71.1%
Group1cq	1	2735	374	1617	1636	13.7%	59.1%	59.8%
Group4ch	0	1809	457	697	790	25.3%	38.5%	43.7%
Group4ch	1	5671	3165	4703	4779	55.8%	82.9%	84.3%
Group6ab	0	6951	1763	4278	4445	25.4%	61.5%	63.9%
Group6ab	1	413	30	145	157	7.3%	35.1%	38.0%
Group6wI380	0	379	12	347	347	3.2%	91.6%	91.6%
Group6wI380	1	252	44	202	202	17.5%	80.2%	80.2%
Group6wI80	0	768	11	500	500	1.4%	65.1%	65.1%
Group6wI80	1	467	11	247	252	2.4%	52.9%	54.0%

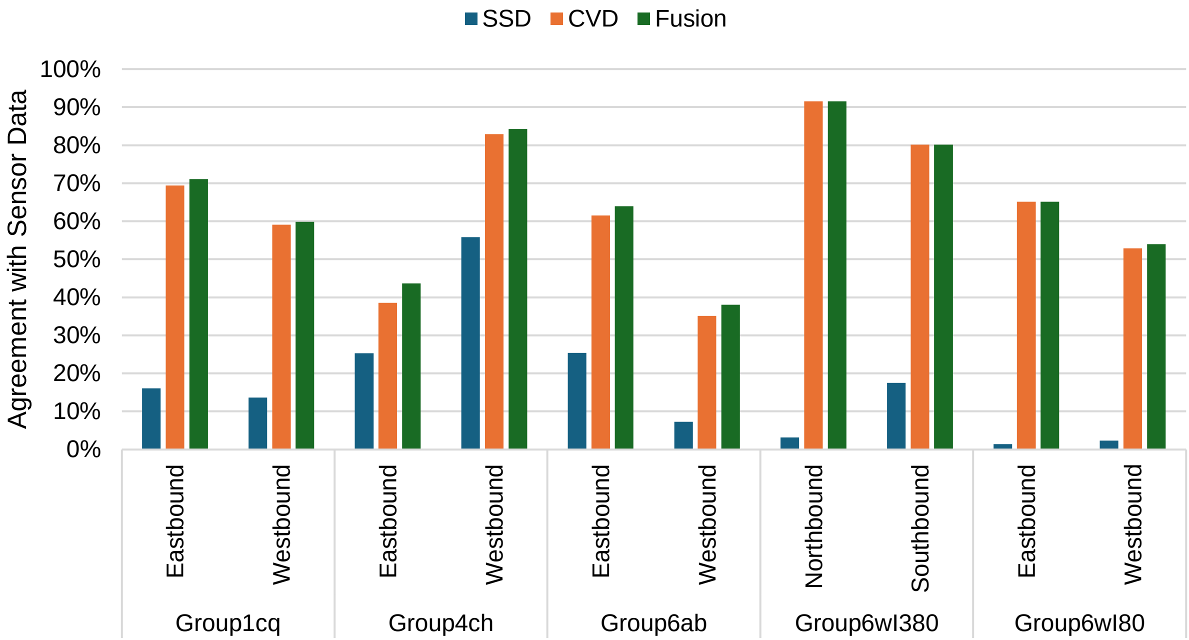


Figure 17. Agreement between SSD, CVD, and fusion alerts with sensor data

4.7. Conclusion

The objective of this study was to determine the readiness of SSD and CVD for their use in QWS. To accomplish this, the SSD and CVD were compared to sensor data for six work zones in Iowa. Data from the month of June 2022 were used. This chapter described the data sets used for the study and how the data were selected and prepared for testing, including the determination of values for the most recent minute from numerous waypoints in CVD, with 38 different performance measures in total calculated for SSD and CVD. The spatial dimensions of data selection were also described.

Four tests were employed to assess the readiness of the SSD and CVD, with outcomes as follows:

- Data completeness was evaluated by determining the number of minutes for which the SSD and CVD were available for the month of June 2022. The SSD had very good coverage with real-time data, while the CVD had spotty coverage for overnight hours.

- Missed calls and false calls were evaluated using the 38 performance measures for the SSD and CVD. Missed calls were incidents reported by the sensors that the SSD or CVD completely missed, while false calls were incidents reported by the SSD or CVD that were completely unreported by the sensors. The results (Figure 14) showed that the lower bound on either false or missed calls was approximately 45%. Some of the CVD performance measures were able to achieve low numbers of missed calls, which are more critical; the selected CVD performance measure (3-minute rolling window, minimum value of all waypoints) had approximately 3% missed calls using the incident data selected for this test. The SSD performance measures had much higher numbers of both missed and false calls.

- Latency was evaluated using the selected CVD and SSD performance measures with the best characteristics in the preceding test. They were compared against the sensor data for selected incidents. The CVD had lower latency than the SSD; the CVD detected congestion slightly before the sensors, on average, while the SSD had an average latency of about 5 minutes. For congestion recovery, the SSD had a shorter average latency and more reliable performance compared to the CVD. The distribution for the CVD showed that these data reported the end of congestion well before or well after the sensors for many incidents. While the SSD performed better than the CVD for congestion latency, the SSD failed to detect congestion for a much higher number of incidents than the CVD.

- The last test compared the performance of the CVD and SSD to the sensor data in a virtual QWS application. This test was intended to determine how each data set would supply a queue warning in real time and compare the performance to that of the sensor data. Agreement between the sensor data and the CVD or SSD was measured by calculating the percentage of minutes when the sensor data would have displayed a warning where the CVD or SSD also would have displayed a warning. A third fusion option was also tested where both the CVD and SSD were used in tandem to supply a warning. The SSD performed poorly in this test, with low agreement values for most of the work zone-direction pairs. The CVD performed much better, although there were some work zone-direction pairs where the amount of agreement was less than 50%. The fusion option performed similarly to the CVD, with only a few additional minutes of agreement.

Altogether, some strengths and weaknesses of the SSD and CVD were identified. The next chapter presents conclusions about the readiness of the SSD and CVD for application to QWS based on these findings.

5. CONCLUSIONS

5.1. Criteria for Selecting Data for Providing Public Information about Work Zones

Effective management of traffic in work zones relies on accurate and timely information about traffic conditions. This study sought to determine the effectiveness of widely available data sets that can be obtained without field infrastructure: SSD and CVD. Based on input from practitioners in the interviews presented in Chapter 3, most work zone operators focus more on the operation of QWS or the provision of similar information by a variety of means than on the reporting of travel time data. Therefore, this study focused on the applicability of SSD and CVD for QWS.

To draw conclusions from the results presented earlier, the desirable characteristics of data sets for QWS should be considered. From the literature review and interviews, these would include the following:

- The data should be available for all hours of the day and days of the week. The data should be available on a widespread geographic basis, covering roads in urban and rural environments where QWS would be applied. The highest priority roads for most agencies are major arterial routes such as Interstate highways, making them a good starting point for evaluating data sets for QWS.

- Data for QWS should be highly accurate to ensure that slow and stopped traffic conditions are correctly identified and that public information reflects actual conditions. Warning drivers about downstream congestion on freeways has been proven to be an effective means of reducing crashes and crash severity. It is desirable to provide accurate warnings whenever congestion exists while avoiding false calls as much as possible. However, it is generally better to err on the side of caution.

- Data should be able to detect changes in traffic conditions quickly, with as little latency as possible.

- Data must be available in real time to facilitate QWS. It must further be possible to process the data and provide an alert quickly. Systems for delivering the data in real time should be highly reliable and responsive.

- It is desirable for the data and QWS processes to be integrable with existing tools, including existing QWS components and traffic management systems. The QWS methodology must be scalable to a regional or statewide level to incorporate a large number of work zones and other potential use cases.

- The cost of the data should be feasible for transportation agencies.

This study focused on the first three points, since the need for data completeness, accuracy, and latency must first be demonstrated before the matters of real-time implementation, integration, and cost can be considered. Therefore, the study results and conclusions focus on identifying coverage, accuracy, and latency for work zones on Interstate highways.

5.2. Effectiveness of SSD and CVD for Delivering Public Information about Work Zones

5.2.1 Summary of the Four Tests

To examine data accuracy and coverage, four tests were executed, as presented in the previous chapter. To support these tests, data were collected for June 2022 from six work zones in Iowa, including sensor data, SSD, and CVD. Data from this period were used because the CVD vendor ceased operation in May 2023. For tests concerning data accuracy and latency, the sensor data were considered to be the ground truth record of whether congestion was present in the work zones.

Data coverage was the focus of the first test. The amounts of available SSD and CVD were evaluated by considering all of the possible 1-minute intervals in the month of June 2022 and examining whether data were available from each data set. The SSD were complete, with real-time information available for the vast majority of minutes during the 1-month test period. There were very few minutes with no data and relatively few minutes that used any amount of historical data. The CVD, on the other hand, had a considerable amount of missing data during overnight hours.

The second test looked at the number of missed calls and false calls from the SSD and CVD. The speed data from these comparison data sets were used to identify times when congestion occurred. These were compared against sensor data from the various work zone locations. For missed calls, the sensor data were used to identify congestion, and the SSD and CVD were examined during the same time periods to see whether they also reported congestion. For false calls, the SSD and CVD were used to identify congestion, and the sensor data were checked to see if congestion was actually present. Because there were many options for aggregating the SSD and CVD, 36 different performance measures were considered. Two different performance measures were tested for the SSD, since there were fewer options for aggregating average speeds for a smaller number of recent minutes.

The results of this test showed a tradeoff between missed calls and false calls among the different options tested. The minimal values for either missed or false calls appeared to be around 45% (Figure 14). That is, the best option for minimizing the number of missed calls generated a large number of false calls, while the best option for minimizing the number of false calls generated a large number of missed calls. Because missed calls are more critical than false calls, a performance measure was identified among the 36 tested options for the CVD that achieved a low number of missed calls while having a lower amount of false calls compared to other options. This aggregation method took the minimum value of all of the speeds reported in the CVD for the past 3 minutes. The use of the 3-minute rolling window helped to mitigate the effects of missing data observed earlier. The SSD performance measures had much higher numbers of missed and false calls compared to the CVD performance measures.

The third test focused on latency. Work zone congestion incidents were identified using the sensor data, and the selected CVD and SSD performance measures from the second test were examined to see whether these also reported congestion during the same time period and to measure their latency in reporting congestion (i.e., how long they took to report congestion compared to the sensor). The test examined latency in the detection of congestion onset and recovery separately. For congestion onset, the CVD had much lower latency than the SSD; the average value, in fact, showed that the CVD were able to report congestion slightly before the sensor data. The SSD had an average latency of about 5 minutes but in many cases did not identify congestion reported by the sensors. For congestion recovery, however, the SSD had slightly less latency than the CVD and exhibited more predictable behavior, with the distribution of latency values mostly clustered around the central peak. The distribution of the CVD recovery latencies showed much more variation, with the CVD in some cases reporting the end of congestion earlier than the sensors and in other cases much later than the sensors, with roughly equal likelihood, along with a portion of the distribution in the middle.

The fourth test used a virtual QWS approach where the selected data were applied in a simulation to determine when the QWS would provide a warning to traffic. This was done by stepping through all of the minutes in June 2022 for five work zones. The sensor data and the best-performing performance measures (from the results of the second test) for the SSD and CVD were all fed into this process to see when each data set would lead to the provision of a queue warning. In addition, a third option that incorporated both the SSD and CVD was tested, which was called the fusion option. To assess the effectiveness of the test data, the amount of agreement with the sensor data was calculated by tabulating the number of minutes of sensor-driven queue warning where the CVD, SSD, or fusion data would have also provided a warning. The results (Figure 17) showed that for most work zones, the SSD had low amounts of agreement; for most of the work zone-direction pairs, the SSD had less than 50% agreement. The CVD and fusion options had much higher values, usually above 50%, although there were two work zone-direction pairs with values less than 50%. The fusion option had marginally better performance (i.e., a few percentage points) compared to the CVD.

5.2.2 Overall Conclusions

The most promising results of this study found that some options for the CVD were able to achieve very low numbers of missed calls, ranging from 2% to 3%, when compared to the sensor data. The fact that these results were seen in spite of low overnight data completeness is further encouraging. However, these results came with rather high numbers of false calls, with approximately 45% being the lowest number. While this reflects a high number of false calls, these initial results might be further improved upon by additional cleaning of the input data, exploration of additional performance measures, and other future refinement. Within this study, using a 3-minute rolling window instead of only the most recent minute was able to substantially reduce the number of false calls. Thus, it seems likely that CVD could be used to drive a QWS with further refinement of the data processing techniques. The numbers of missed calls could likely be reduced by additional refinement of the geographic definitions for data selection.

Data coverage, as mentioned before, is a challenge for CVD, with the overnight hours having higher amounts of missing data. However, despite the lack of data during these hours, certain options for the use of the CVD were still able to yield low amounts of missed calls. As fleet turnover introduces greater numbers of new vehicles equipped with CV2X onboard units onto public roads, it seems likely that problems of low data coverage during these hours will be mitigated. In comparison with the CVD, the SSD had excellent data coverage at all hours of the day.

The results of these tests showed that the SSD did not perform well in a QWS application. The SSD did not detect many of the congestion incidents in the second and fourth tests. This is likely because the data reflect the average speed on relatively long (approximately 0.5- to 1-mile) segments and thus are less sensitive to localized slowed or stopped traffic. That is, congestion must be severe and must also propagate across most of the segment before the SSD starts to report low segment average speeds. Given that SSD coverage appears to be better than CVD coverage, it may be possible to mitigate these effects in cooperation with data vendors by using other existing products or perhaps by exploring new products. For example, the data vendor in this study offers sub-XD segments, which report data for shorter segments. These may be more sensitive to the onset of congestion. Another option may be for the vendor to supply additional statistics besides the average speed specifically for QWS applications.

5.3. Study Limitations and Future Research

This study assumed that sensor data collected in the field represented the ground truth conditions (i.e., presence of congestion). This assumption was necessary because data from previous years had to be used for the study, owing to the fact that the CVD vendor ceased data delivery in 2023 because of financial difficulties. Thus, the results are limited by the fact that sensor data are imperfect, and it was not possible to independently assess the data by other means such as video recordings for data from the previous years. To mitigate the effects of erroneous sensor data, data from several work zones were included in the analysis. However, it is possible that some of the test results could have been affected by occurrences where the sensor data incorrectly reported congestion. During the screening of sites for selection, sensor data were observed in some cases that appeared to become “stuck” at a fixed value of speed, perhaps due to an obstruction of the sensor during work zone activities. Locations exhibiting obvious problems were avoided, but it is possible that minor sensor data errors may still have occurred.

There are several opportunities for additional research that could make QWS driven by infrastructure-free data sources possible. The results showed that CVD can be effective at avoiding missed calls. The large number of false calls observed in the initial set of performance measures evaluated in this study could potentially be reduced by further refinement of the data processing methods or by considering additional performance measures. There are opportunities to explore other SSD offerings, given that the data had excellent coverage but missed many times when speeds fell below 45 mph, especially if the speeds did not fall very far below the threshold.

If a sufficient number of transportation agencies request a new data product specifically for QWS, vendors may be willing to deliver this product. Finally, further investigation of a combination of CVD and SSD to drive a QWS would be worthwhile.

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