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A Plan to Measure the Effectiveness of Connected Smart Work Zone Devices

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Introduction and Overview

According to a joint report from the Ohio Department of Transportation (ODOT) and the Ohio State Highway Patrol (OSHP)[1], Ohio recorded over 25,000 work zone crashes between 2017 and 2021. Many of these crashes were serious, with over 9,000 injuries and 97 fatalities. During the same period, OSHP issued over 44,000 work zone citations, mostly for excessive speed. Police enforcement alone does not appear to improve safety therefore novel methods to improve safety have been sought. In addition to safety, work zones often have a direct and adverse impact on traffic flow, whereby pursuing innovative solutions to decrease or eliminate incidents could lead to substantial improvements in maintaining flow. As an agency, ODOT has a history of embracing innovative technologies to solve transportation problems and such is the case for Smart Work Zone (SWZ) technologies. In addition, the Federal Highway Administration has started an initiative to collect data and assist state departments of transportation with the adoption and effectiveness measurements related to SWZ systems and devices.[2]

This document is focused on developing a plan to measure the effectiveness of using so-called 'connected' devices to reduce crashes, increase safety, and maintain reasonable traffic flow in and near work zones. The term connected can have several different meanings, but for the purposes of this plan, connected refers to the ability to inform either workers, drivers, or both of existing or impending conditions thru some form of wireless connectivity, as well as to collect data related to the operations of these devices. SWZ devices have been piloted as another potential avenue to notify drivers in advance of upcoming areas of concern hoping to improve roadway safety.

Specifically, ODOT is presently fielding and evaluating devices such as connected arrow boards, variable speed limit signs, and smart cones, all with the goal to increase motorist awareness of work zone and maintenance activities, and in certain cases, warn workers of an impending situation. Most of these devices report their position and status to connected cloud services which in turn provide alerts to drivers using smart phone guidance apps.

Given the limited experience with these different device types, ODOT is interested in measuring the effectiveness of SWZ implementations. Better understanding effectiveness could lead to more informed decisions related to the expansion or modification of their approach to SWZ technologies.

ODOT's primary goal in implementing SWZ devices is to improve safety and maintain reasonable traffic flow in and around work zones. The connected SWZ devices are designed to provide real-time alerts and warnings to drivers about upcoming work zones, with the

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[1] https://statepatrol.ohio.gov/static/links/WorkZone_Bulletin_2022.pdf

[2] https://www.transportation.gov/av/data/wzdx

assumption that these alerts will lead to safer driving behavior, reduced speeds, and fewer incidents. However, the effectiveness of these devices in achieving these goals has not been thoroughly validated. This plan aims to develop a framework for measuring the impact of SWZ devices on key metrics such as work zone speed, dangerous driving behavior, and overall safety. By validating the effectiveness of these devices, ODOT can make informed decisions about future investments and deployments of SWZ technologies.

The purpose of this report is to introduce a plan for measuring effectiveness of SWZ devices and is organized into the following sections:

1. **Current Implementations.** Overview of ODOT's current implementations including suppliers, sample reports, example deployments, use cases, and technological approaches.
2. **Project Approach.** Proposed research approach used for the development of the measurements of effectiveness plan.
3. **Methods to Evaluate Effectiveness.** Recommended measures of effectiveness, along with criteria and methods, to evaluate the effectiveness of SWZ device implementations.
4. **Data Sources to Support MOEs.** Data sources available to support the recommended measures of effectiveness along with which measures the data source could be applied to.
5. **Gap Analysis**. Tradeoffs of various approaches to measuring effectiveness, current gaps in data sources, and other considerations to inform ODOT's decision.
6. **Tangential Observations.** Other observations and issues to consider related to the SWZ device deployments.
7. **Implementation Roadmap.** Summary of our research recommendations into an actionable roadmap.

1. Current Implementations

Background and Locations

ODOT is currently undertaking several pilot projects to test connected — or "smart" — work zone devices along several corridors in the state. These include deployments in six of ODOT's 12 districts, Districts 3-6, 10 and 12. Additionally, the deployments are supported by ODOT's:

- Office of Roadway Engineering
- Office of Traffic Management & TSMO Program
- Highway Safety Program
- These deployments generally support two common types of work zones:
- More permanent, long-term construction projects
- Temporary maintenance activities

In addition to work zone related messages, ODOT is also evaluating the use of technologies installed on snowplow trucks to provide similar safety alerts, as snowplows are effectively a slow-moving transient work zone.

Several other states have performed studies on SWZ systems and devices with various differing measures of effectiveness. The Illinois Department of Transportation supported a study that reviewed other state's usage of SWZ and proposed a comprehensive multi-faceted assessment tool that included not only driver behavior but impacts to traffic flow[3]. This study did not perform any experiment to measure impact. Identification from this study that states such as Arizona, Arkansas, Connecticut, Florida, Iowa, Kansas, Michigan, Missouri, Montana, Nebraska, Nevada, North Carolina, Pennsylvania, South Caroline, South Dakota, Washington, and Wisconsin have all deployed SWZ devices. The Indiana Department of Transportation funded a study by Purdue University to measure the impact of SWZ devices and hard-braking events[4]. They found a significant reduction in these events at a controlled site due to the SWZ devices.

Technologies Deployed

The technologies currently being leveraged by ODOT include connected arrow boards (both standalone and on attenuator trucks), connected digital speed limit (DSL) signs, connected 'smart' cones, corresponding cloud services, and data-sharing with 3rd party traveler information applications. The longer-term construction projects have utilized DSLs and connected arrow boards. The maintenance activities have leveraged connected arrow boards, typically mounted on the same truck with a truck mounted attenuator (TMA). The

[3] https://doi.org/10.36501/0197-9191/24-001
[4] https://www.scirp.org/journal/paperinformation?paperid=111727

various suppliers involved include Vermac, Solar Tech, iCone, and Wanco. Example connected roadside devices are shown in Figures 1 through 3.

Figure 1: ODOT Connected Arrow Board

Figure 2: Connected Digital Speed Limit Sign

Figure 3: TMA with Connected Arrow Board

In general, SWZ devices share a common set of attributes. Each has a GPS receiver to determine its current location. Additionally, the current operational status (e.g. “Left Arrow Flashing”) is communicated via a cellular network and reported recurringly to cloud processing services. This allows for real-time monitoring and management of the devices.

Each device is connected via a cellular network to support data exchange with cloud processing services.

A core feature of these deployments is the distribution of work zone information to oncoming traffic via personal navigation apps. Work zones may have an unexpected impact to inform motorists approaching the hazards. Drivers may be required to shift lanes, crossover to the other direction, reduce speeds, merge, or take any combination of these actions. Ideally, motorists should be made aware of the work zone *before* approaching the area. The navigation-based alerts are meant to reduce surprises and inform drivers of work ahead using already available apps.

The SWZ devices share information to navigation apps, like Waze, approaching the hazards. The existing general flow of information is represented in Figure 4:

- **Inputs** are represented by the various smart devices that serve as data sources. These include stationary connected arrow boards, retrofitted arrow boards on crash trucks, snowplows with GPS AVL technology, and HAAS Alert devices deployed on maintenance vehicles to alert motorists of ongoing maintenance activities.

- **Processing** systems are software solutions integrating disparate technologies and preparing traveler information messages for navigation applications and other embedded systems.

- **Outputs** are represented by the individual embedded systems, such as personal navigation applications, used by motorists to receive safety alerts.

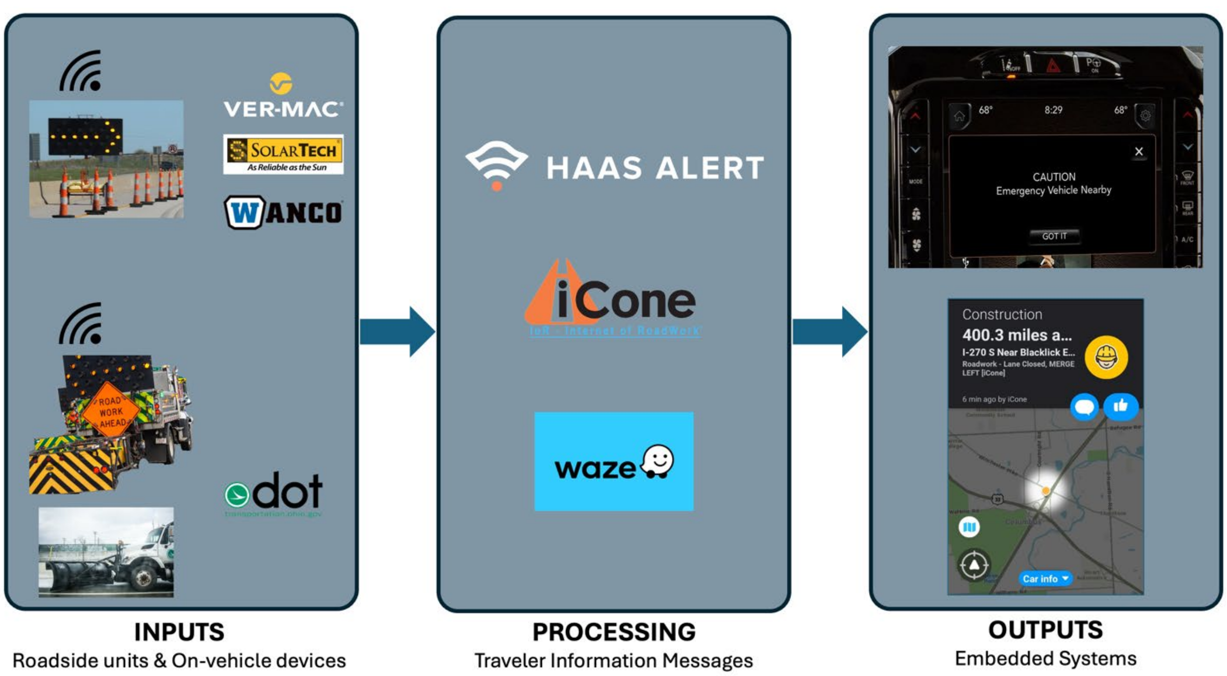

Figure 4: Work Zone Data Flow

Platform Access and Analytics

ODOT has access to platforms, analytics, and reports in support of their implementation tests. Different suppliers provide different solutions, however. In some cases, a web application is used to monitor device locations and device statuses in real time. Some of the suppliers provide access through a mobile app. Some suppliers also offer monthly usage reports. Examples of existing systems are shown in Figures 5 through 9.

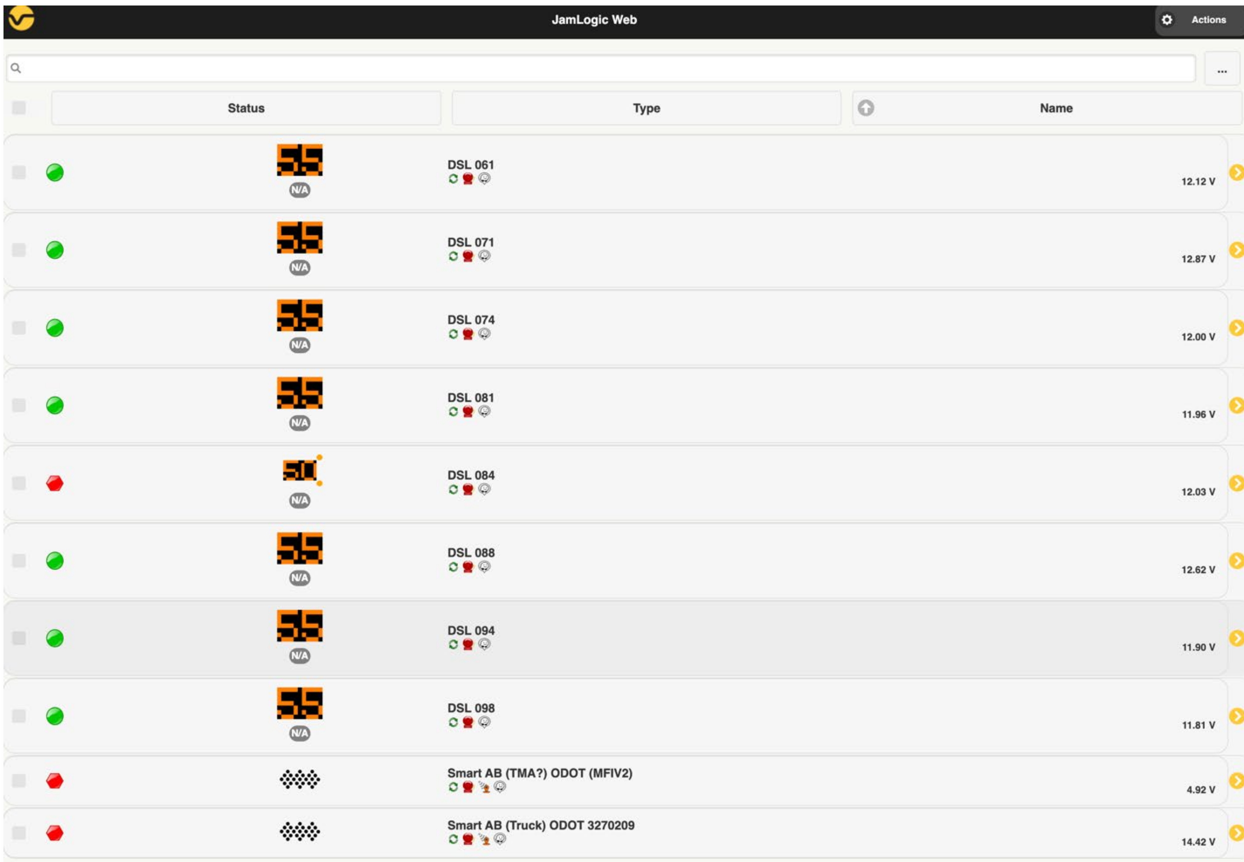

Figure 5: Existing Vermac web application device view.

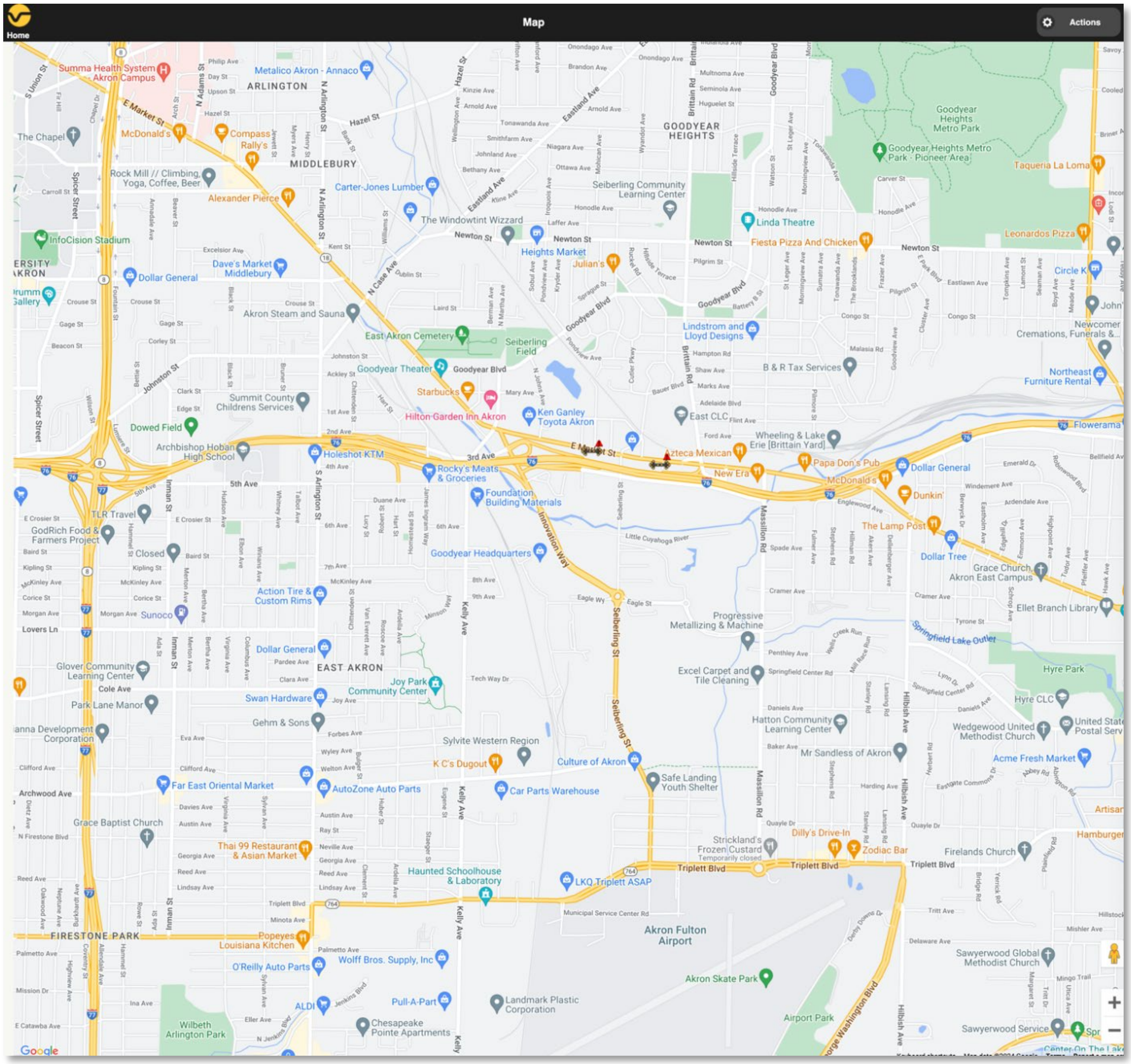

Figure 6: Existing Vermac web application map view.

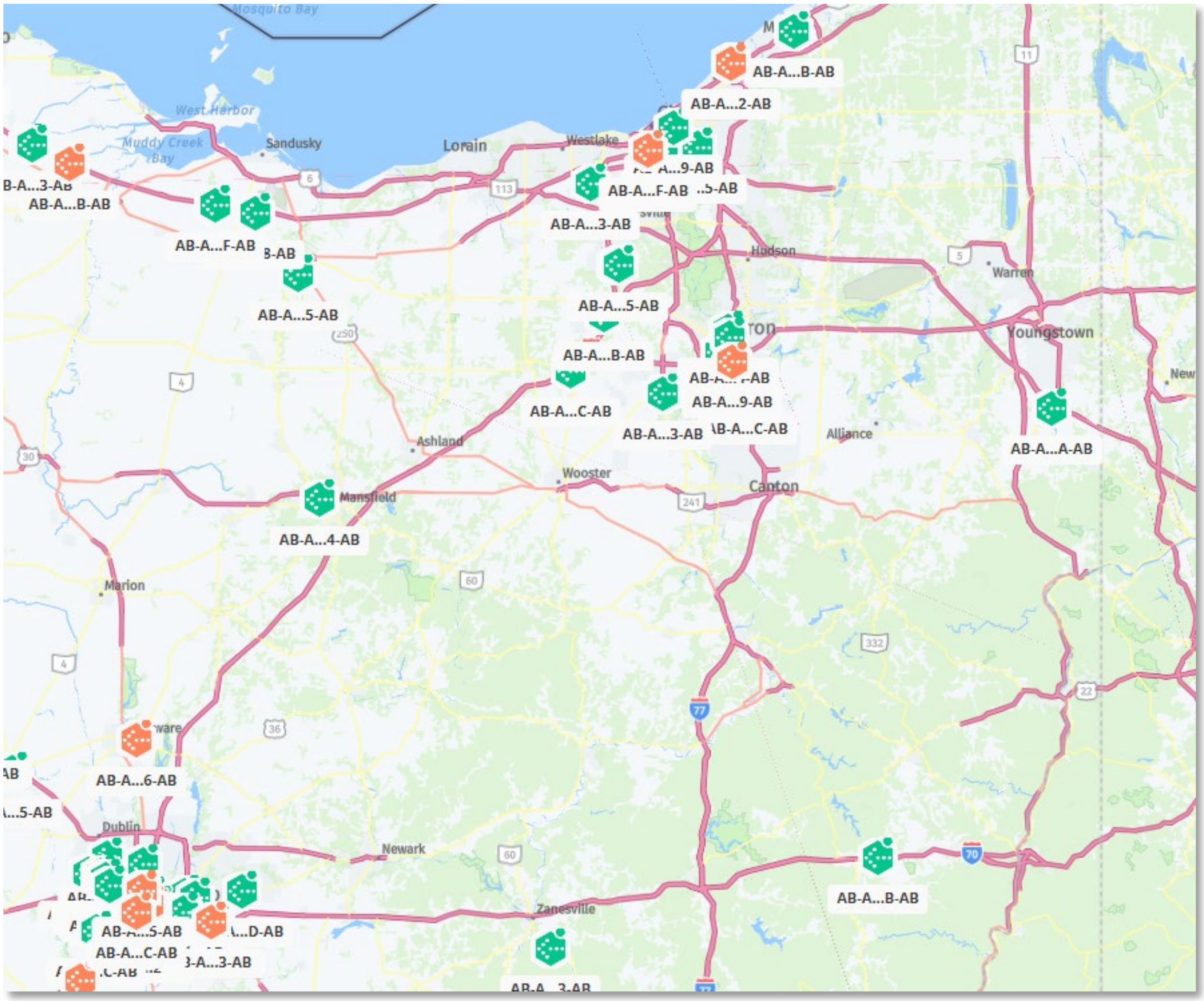

Figure 7: Existing iCone web application map view.

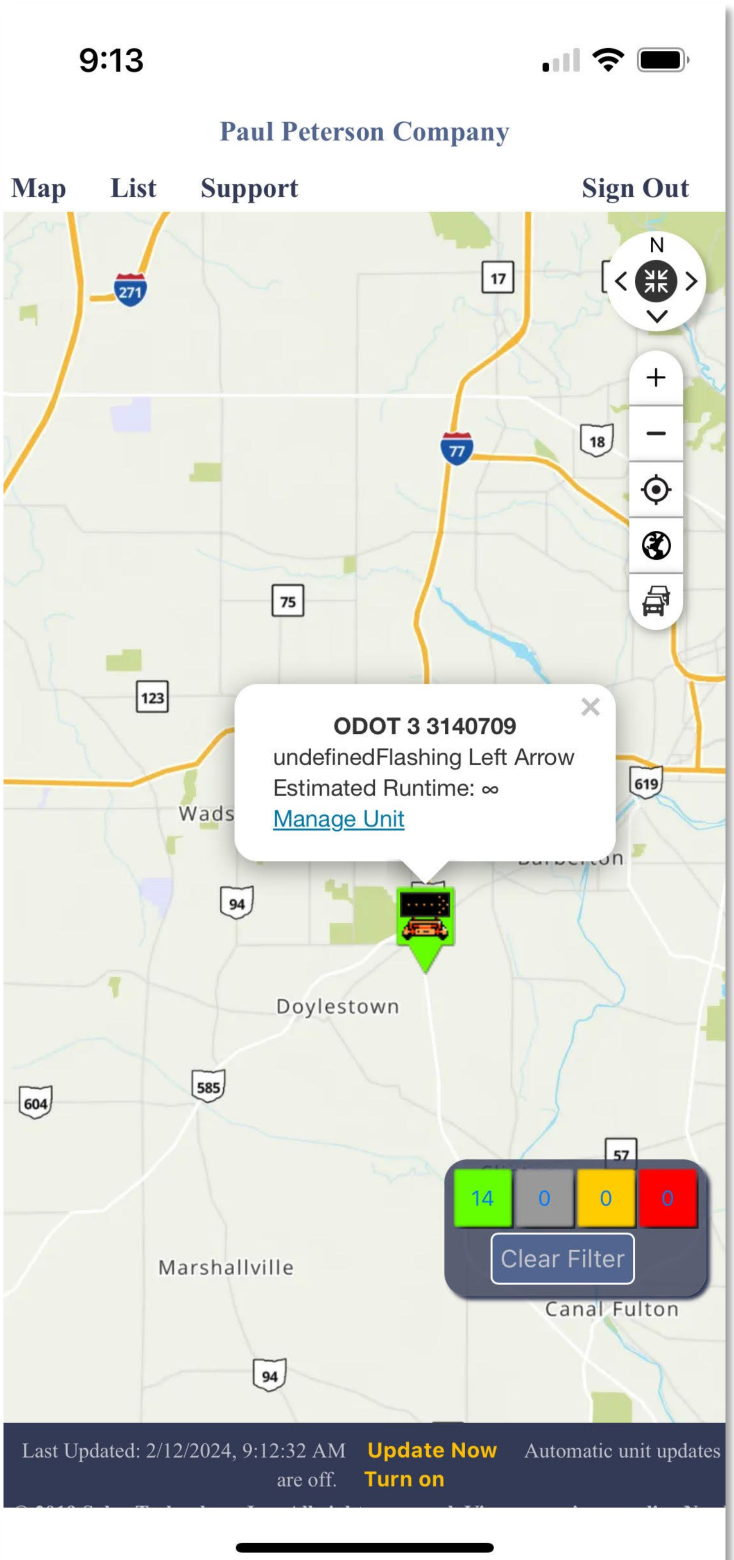

Figure 8: Example of SolarTech Devices through the Command Center mobile app.

From: iCone Notifications <alerts@iconeproducts.com>
Sent: Monday, May 6, 2024 6:03 AM
Subject: iCone Device Status Report: April 29 - May 6, 2024

iCone
IoR - Internet of RoadWork™

Weekly Device Status Report
ODOT
April 29 - May 6, 2024

Device Summary:

Total: **15**
Communicated: **11**
Active: **9**

Details:

Tag	Serial Number	Device Type	Access Group	Last Comm Time	Last Voltage Report	Comm	Active	Number of Activations	Total Active Hours	Anomaly
3140688	0xd004b3	Arrow Panel, Display Up	ODOT D6	2024-05-06 06:00 -0400 (EDT) (Monday)	12.98	YES	YES	3	1.50	
3270195	0xd005bc	Arrow Panel, Display Down	ODOT D12 - Euclid	2024-05-03 14:13 -0400 (EDT) (Friday)	11.78	YES	YES	8	17.35	
3270107	0xd005c3	Arrow Panel,	ODOT D12 -	2024-05-03 13:25	12.28	YES	YES	5	16.48	

Figure 9: Example weekly iCone summary report email.

Each vendor provides ODOT with varying levels of information related to the system status and accuracy of the implementation. This variance makes measurements of effectiveness across multiple platforms challenging, but not impossible. For instance, per conversations with HAAS, a data consumer and notice provider, the specific number of vehicles receiving alerts generated by Waze is not known. HAAS attempts to estimate this number in their monthly reports however, using AADT traffic volumes and educated guesses at penetration rates. With their Stelantis partnership, however, the exact number of vehicles receiving alerts can eventually be measured.

Navigation App Messaging

Through these pilot implementations, ODOT has created standardized messaging for display via personal navigation applications. Table 1 shows the most recent proposed standards. The first column indicates the known arrow board status. The second column depicts preferred messages to be displayed on navigation map views at the arrow board's location. The third column indicates preferred messages to be displayed in advance, for motorists approaching the hazard area. The third column simply adds the word “Ahead” to each message from the second column. An example of how these alerts appear on personal navigation apps is shown in Figure 10. This figure depicts a Waze alert triggered from a connected device using the iCone technology.

Table 1: ODOT Proposed Standard Smart Arrow Board Messaging for Navigation Apps

Active Arrow Board Mode	Message for Navigation Apps	Advanced message for Navigation apps
Left Flashing Arrow Sequential Arrow Sequential Chevron	Caution Roadwork Lane Closed Merge Left	Caution Roadwork Ahead Lane Closed Merge Left
Right Flashing Arrow Sequential Arrow Sequential Chevron	Caution Roadwork Lane Closed Merge Right	Caution Roadwork Ahead Lane Closed Merge Right
Double Arrow	Caution Roadwork Lane Closed Merge Left or Right	Caution Roadwork Ahead Lane Closed Merge Left or Right
Flashing Caution Alternating Diamond Caution	Caution Work	Caution Work Ahead

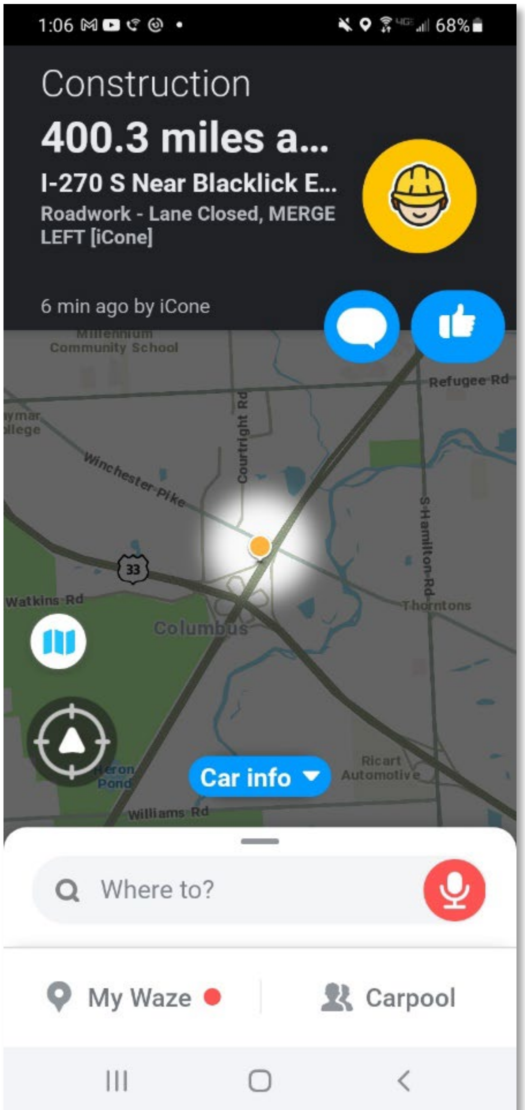

Figure 10: Example Waze Navigation Work Zone Alert

Personnel and Roles

Currently there are at least five known, and distinct, sets of users impacting or interacting with the SWZ implementations. These include:

- Program managers
- Standards engineers
- Maintenance personnel
- Contractors
- Motorists

Project Managers oversee the implementation and procurement of the various SWZ devices. They are often the group interacting with suppliers during procurement and deployment. The program managers are also provided with access to the supplier systems. Lastly, they are usually responsible for communicating the benefits and ongoing status of the pilot and advocating for future program development.

Standards Engineers are balancing between the pilot nature of the implementations with an eye towards foundational elements necessary for supporting potential future scaling of the solutions. This group is coordinating with relevant manuals, appropriate standards, and necessary procedures supporting any part of the deployment. They are also involved in internal communication and tracking adherence to standards.

Maintenance Personnel are ODOT district staff overseeing specific individual deployments. This staff often leads the operations at the end of the deployment. They handle any real-world issues with the technology and provide any feedback to the Program Managers.

Contractors are work zone construction personnel also responsible for overseeing and operating some of the individual deployments. They integrate the SWZ devices into their existing work zone traffic control plans or equipment. They may also provide some real-world feedback to the Program Managers.

Motorists are on the receiving end of the information, benefiting from the deployments. If using a supporting navigation app or system, they will receive advanced notice of potential issues in enough time to take appropriate actions. Motorists should also see the physical signs displayed on the roadside signs.

2. Project Approach

This section provides an overview of the process taken by the research team to deliver this report and arrive at the recommendations contained. Figure 11 provides an overview of the project phases and approximate timeline. The x-axis is represented by the number of days since starting the research task.

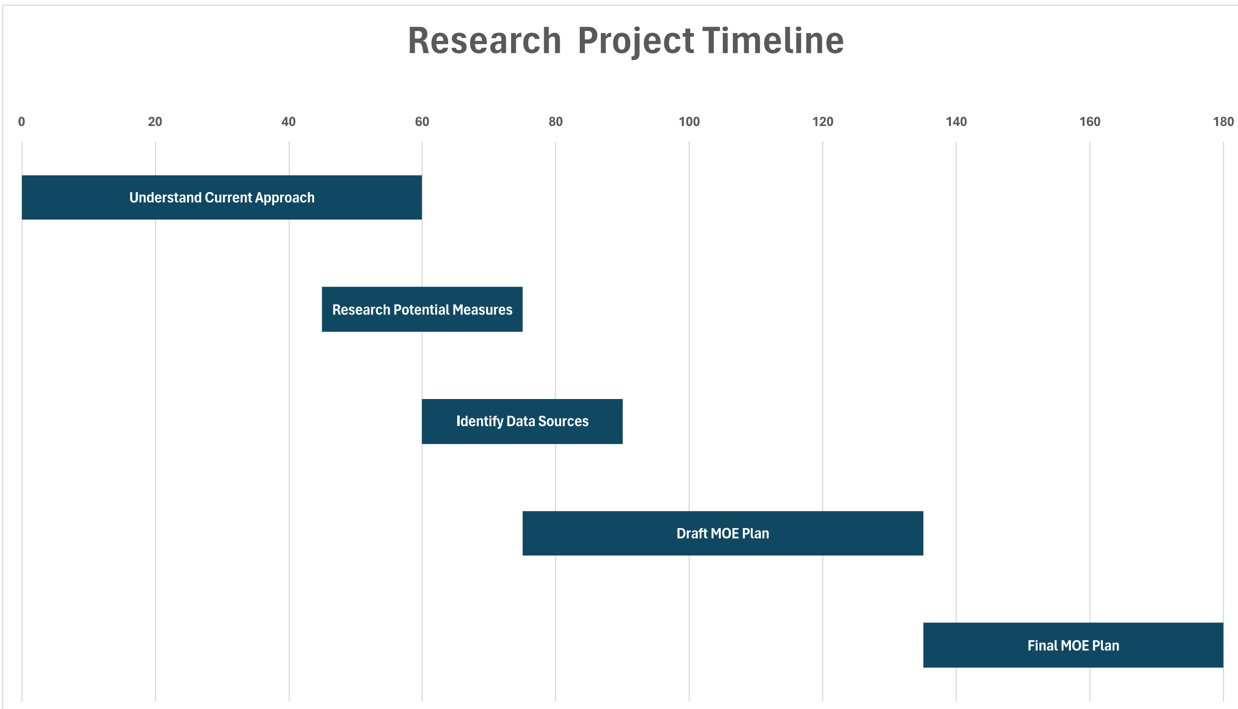

Figure 11: Project Timeline with Tasks

The research team broke this project into five distinct phases, or tasks, as indicated in Figure 11.

- **Understanding Current Approach:** During this phase, the research team reviewed existing ODOT documents related to their historical and current implementations. These documents included background information, supplier information, conference presentations, and one-pagers. The research team also interviewed various ODOT divisions and districts to ask questions and discuss current implementations. This phase provided the research team with a foundational understanding of the technologies, data flow, and implementation details. Lastly, the research team interviewed a number of the suppliers involved in the current ODOT pilot projects.

  The outcome of this phase was an understanding of the current ODOT SWZ implementations.

- **Research Potential Measures:** During this phase, the research team performed a literature review to identify potential performance measure or other meaningful ways of measuring effectiveness of the SWZ deployments. Most of this task was spent researching and reviewing potentially relevant reports. Some of this phase also included interviews with previous research teams — particularly when a relevant project was discovered. The research team also interviewed a few external parties specifically to identify potential measures of effectiveness. At times, discussions with suppliers during the previous phase also generated ideas for potential measures of effectiveness to consider.

  The outcome of this phase was a complete list of potential measures of effectiveness.

- **Identify Data Sources:** After compiling a list of potential measures of effectiveness, this phase identified relevant data sources available for ODOT. The research team interviewed various data providers to discuss the availability and practicality of existing datasets. The research team also interviewed internal ODOT staff with access to various data sources. This phase supported the filtering of potential measures of effectiveness identified previously — to ensure ODOT would realistically be able to track measures of effectiveness.

  The outcome of this phase was an updated list of measures that consider data availability.
- **Draft MOE Plan:** In this phase, the research team compiled results of all previous phases into a draft report and plan for ODOT to measure effectiveness. This phase was primarily spent writing and editing and included the occasional conversation with ODOT to guide recommendations.

  The outcome of this phase was a draft MOE Plan for ODOT's review.

- **Final MOE Plan:** After ODOT reviewed and commented on the Draft MOE Plan, the research team updated the plan in response to ODOT's feedback.

  The outcome of this phase was a complete and final MOE plan.

3. Methods to Evaluate Effectiveness

This section provides a comprehensive list of recommended methods to evaluate the effectiveness of ODOT's SWZ deployments. The recommendations are organized a few different ways:

- All recommendations (Table 2)
- By level of effort required (Table 3)
- By length of evaluation (Table 4)

Each recommendation includes a general overview of the approach, data sources available/required, recommended evaluation timeline, confidence level, and deployment types impacted. The methods of evaluating effectiveness were selected and prioritized based on:

- Applicability to ODOT's SWZ pilots.
- Availability of previous studies using this performance measure.
- Availability of data sources to support the measure.

Nearly every recommended measure of effectiveness is simpler to capture for stationary work zones. Any benefits from digital alerts originating from static work zone devices should also be expected from digital alerts originating from mobile data sources.

All Recommended Measures of Effectiveness

Table 2 provides an overview of all potential measures of effectiveness. The order of the measures in Table 2 matches the recommendation of the research group. This table includes a snapshot overview of every potential measure of effectiveness, and includes:

- Which data source supports the measure.
- Which of the deployment types is the measure applicable for.
- The relative cost, measured in additional ODOT expenses for data acquisition and consultant/research support, to complete a study.
- The measure's relevance to this application. Meaning: how much of a correlation is expected between the SWZ deployments and the measure of effectiveness.
- The level of effort required of ODOT staff to perform a study.
- The recommended length of evaluation. In most cases, this includes a "before" and "after" stage. For example, a 4-month evaluation period recommends 2 months without any smart work zone technology and 2 months with SWZ technology.

Table 2:All Recommended Measures of Effectiveness

Measure of Effectiveness	Data Source	Deployment Type(s)	Cost	Relevance	Level of Effort	Length of Evaluation
Reduction in hard braking occurrences	Connected vehicle hard braking data, Streetlight and Drivewyze, or GM and Drivewyze	Stationary SWZs Mobile Maint.	$$	Strong / Direct	Medium	4 months
Reduction in 'Dangerous Slow Down' events	Dangerous slow down feed, INRIX	Stationary SWZs Mobile Maint.	Free	Substantial	Low	4 months
Reduction in crashes	Crash reports, OSHP	Stationary SWZs	Free	Moderate	Medium	4 years
Reduction in average driver speed	Historical traffic data, INRIX	Stationary SWZs	Free	Moderate	Low	4 months
Reduction in hard braking activity	Estimated harsh braking events, MMI or INRIX Safety View	Stationary SWZs	$$	Moderate	Medium	4 months
Peace of mind for roadside workers	Surveys, interviews	Stationary SWZs	Free	Some	High	8 months
Reduction in near misses and struck-by events	Video Analytics, multiple	Stationary SWZs Mobile Maint. Snowplows	$	Some	Medium	4 months
Reduction in damages to equipment	ODOT	Stationary SWZs Mobile Maint. Snowplows	Free	Some	High	2 years
Lane change behavior	*No proven existing data source*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*

Table 3: Measures of Effectiveness by Level of Effort

Measure of Effectiveness	Data Source	Deployment Type(s)	Cost	Relevance	Level of Effort	Length of Evaluation
Reduction in 'Dangerous Slow Down' events	Dangerous slow down feed, INRIX	Stationary SWZs Mobile Maint.	Free	Substantial	Low	4 months
Reduction in average driver speed	Historical traffic data, INRIX	Stationary SWZs	Free	Moderate	Low	4 months
Reduction in hard braking occurrences	Connected vehicle hard braking data, Streetlight and Drivewyze, or GM and Drivewyze	Stationary SWZs Mobile Maint.	$$	Strong / Direct	Medium	4 months
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Table 4: Measures of Effectiveness by Length of Evaluation

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Reduction in damages to equipment	ODOT	Stationary SWZs Mobile Maint. Snowplows	Free	Some	High	2 years
Reduction in crashes	Crash reports, OSHP	Stationary SWZs	Free	Moderat e	Medium	4 years

Reduction in hard braking occurrences

The top recommended measure of effectiveness is derived from a study performed by the University of Purdue in 2022: *Evaluation of the Impact of Queue Trucks with Navigation Alerts Using Connected Vehicle Data*[5]. The study measured the impact of queue warning trucks in Indiana. The queue trucks were outfitted with SWZ technology, similar in nature to the ODOT deployments. And much like ODOT, when the arrow board was activated, a digital alert was distributed to the Waze application. The navigation alerts were received by Waze users via visual or audible alerts, depending on the specific Waze application being used. An overview of the architecture is shown in Figure 12.

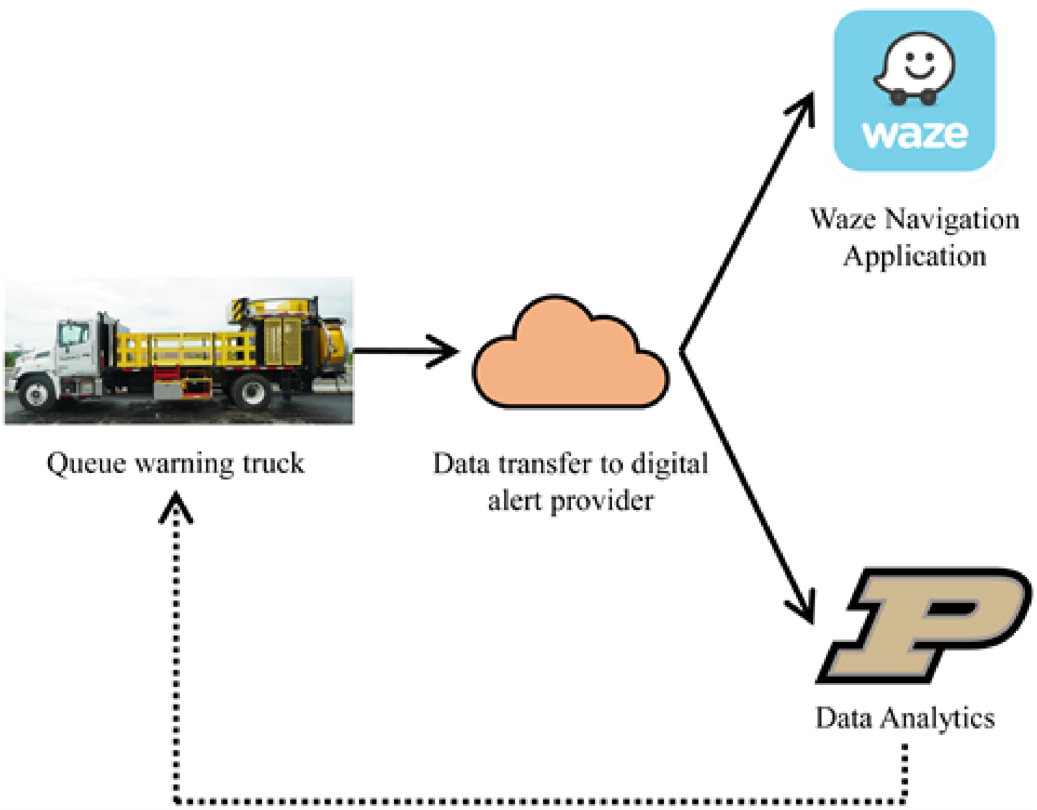

Figure 12: INDOT and Purdue SWZ Pilot Architecture

Purdue analyzed connected vehicle data — purchased through Wejo — to measure any changes in driver behavior approaching these work zones. They analyzed data for work zone approach queues both with queue trucks present and without queue trucks present. Approximately 370 hours of queueing with queue trucks present and 58 hours of queueing without queue trucks were evaluated. These technologies were implemented primarily in work zones where traffic queueing was observed or anticipated.

[5] https://www.scirp.org/journal/paperinformation?paperid=111727

The Purdue team measured hard-braking events as an indicator of queue safety and driver behavior. **Hard-braking events were found to decrease by approximately 80% when queue warning trucks were used to alert motorists of upcoming queues.**
The individual trajectories of vehicles approaching the queue was compared with and without alerts, shown in Figure 13. The results show a clear difference in driver behavior with the presence of queue warning trucks and navigation alerts.

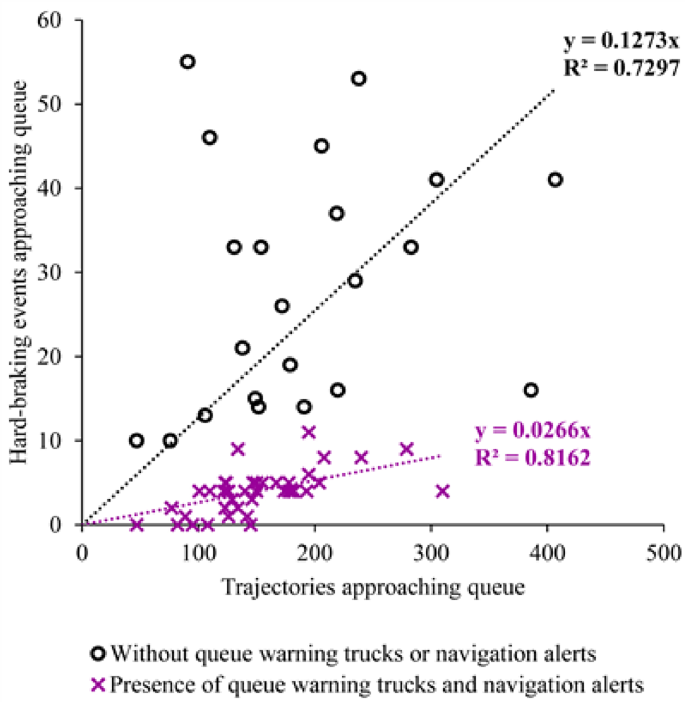

Figure 13: INDOT and Purdue Connected Vehicle Trajectories Approaching Queues

The conclusion of the Purdue study states "Hard-braking events were found to decrease approximately 80% when queue warning trucks were used to alert motorists of impending queues. Encouraging results support the deployment of queue trucks and integration of digital alerts for reducing the risks of secondary crashes on Interstates."

This Purdue study is the most relevant study directly measuring the exact type of implementation ODOT is testing. There are a few observations for ODOT's consideration:

- The INDOT "without" state is without either queue warning trucks or navigation alerts. It is not clear how much of the benefit comes from the queue trucks and how much of the benefit comes from the navigation alerts. Purdue essentially studied "connected" work zones versus "non-connected" work zones. ODOT could choose to study the same difference or attempt to isolate results of each.
- The technologies were only deployed in work zones where traffic queues were anticipated. The reduction in hard braking events was only studied along work zones impacting normal traffic flow.

- The Purdue study used full Wejo connected vehicle data. This data is no longer available for the industry. A subset of the data should be available later in 2024 from Streetlight. The data from Streetlight is expected to only come from GM sources, whereas Wejo data included multiple OEMs. However, the GM-based Streetlight data should suffice for a similar study in Ohio.

Depending on the data source ODOT selects for this measure, ODOT may also be able to capture other driver behavior changes. GM data, for example, will allow ODOT to capture activity such as forward collision alert events in addition to hard braking events.

Pros of this measure of effectiveness

- Directly measures driver behavior changes, which will impact many of the other measures of effectiveness. A reduction in hard braking events should also result in fewer crashes, fewer near misses, fewer struck-by events, etc.
- ODOT could supplement any OEM hard-braking data with hard-braking data from commercial vehicles. Through their existing partnership with Drivewyze, ODOT receives hard-braking event data from commercial vehicles alerted by the Drivewyze system.
- Previous studies indicate proof of effective results.

Cons of this measure of effectiveness

- Until Streetlight data is available (targeted for later in 2024), or until GM data is ready for purchase directly, there is currently no existing connected vehicle data source.
- ODOT will be required to purchase OEM data.
- ODOT will also likely need to pay for analysis of the connected vehicle data. The connected vehicle data is provided in a raw format, is an extremely large file size, and is difficult to analyze. For the state of Ohio, this data set is expected to generate roughly 20 billion records a month.

Reduction in dangerous slowdown events

The next recommended measure of effectiveness is similar in nature to the first measure. Using INRIX dangerous slowdown data, which ODOT has recently begun archiving, ODOT could measure changes in dangerous slowdown events approaching the queue.

As with the Purdue study, data from a zone without SWZ devices could be compared to data from the same zone with SWZ devices.

INRIX calculates dangerous end-of-queues in real time by comparing speeds on contiguous roadway segments. When differences in speed of greater than 35 mph are detected, INRIX marks this location as a dangerous end-of-queue.[6] This measure can be treated like a proxy

[6] https://docs.inrix.com/traffic/dangerousslowdowns/

for hard braking events. The assumption is made that an increased number of dangerous queues also increases the occurrences of other events such as hard braking or end-of-queue crashes.

INRIX uses a variety of probe data sources to capture this data in real time. Their data sources include roadside sensors, mobile applications, embedded navigation systems, cameras, and other telematics devices on a variety of vehicle types.

Pros of this measure of effectiveness

- ODOT already has access to INRIX dangerous slowdown data, both in real-time and as historically archived data.
- A reduction in dangerous slowdowns is a clear indication of driver behavior modification.

Cons of this measure of effectiveness

- Although this data is a good proxy for hard braking events, it is not as granular nor as direct a measure as hard braking events directly observed from connected vehicles or Drivewyze-enabled commercial vehicles.

Reduction in crashes

The next measure of effectiveness is derived from a TxDOT study performed in 2015: *Innovative End-of-Queue Warning System Reduces Crashes Up to 45%*[7]. This measure recommends comparing changes in crash trends over a longer period of time. TxDOT deployed end-of-queue warning systems designed to reduce the frequency and severity of read-end collisions in work zones shown in Figure 14.

The implementation included three main components:

- Portable rumble strips applied 3.75 miles before the merging taper.
- A single PCMS board positioned 3.5 miles before the merging taper.
- Four speed sensors distributed over the 2.5 miles leading up to the merging taper.

(a) Rumble strip deployment
(b) Speed sensor
(c) Pre-designed portable changeable message sign (PCMS)

[7] https://transops.s3.amazonaws.com/uploaded_files/TxDOT%20End%20of%20Queue%20Warning.pdf

Figure 14: TxDOT End-of-Queue Warning System

TxDOT indicates the following background implementation for these lane closures:

- The closures were only permitted at night-time.
- The routes were all rural, with no queues expected.
- Locations varied nightly.
- There was little room in the right-of-way to preposition queue warning systems ahead of time.
- The I-35 corridor is heavily used by large trucks, which increased the severity of any end-of-queue crash.

After deploying the end-of-queue warning systems for more than 200 nighttime lane closures along I-35, TxDOT noticed significant benefits:

- Crash reductions were estimated from an 18% to 45% reduction.
- Both severe crashes and rear-end crashes were reduced when compared to similar lane closures without this technology, as seen in Figure 15.

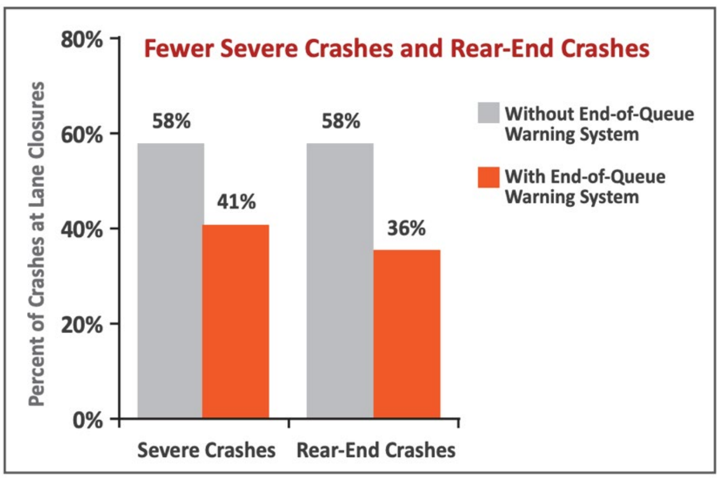

Figure 15: TxDOT End-of-Queue Crash Reductions

Pros of this measure of effectiveness

- End of queue notification systems have a history of reducing total crashes and crash severity.
- A reduction in crashes approaching work zones is a clear indication of effectiveness.

Cons of this measure of effectiveness

- Other factors, outside of queue warning systems, will impact crash rates. To isolate safety benefits of ODOT's work zone deployments, the recommended length of study is much longer than most other measures.

- Some of TxDOT study benefits were derived from estimates if the system had not been deployed. Directly measured benefits would be preferred to estimated benefits.
- The TxDOT study only measured the deployment of PCMS queue warnings and rumble strips. Navigation alerts were not included in the solution. Since ODOT already deploys advanced notice of lane closures, it is unclear how much the TxDOT benefits would translate to ODOT.

Reduction in average driver speed

The next recommended measure of effectiveness is based on a Wyoming CV pilot project published in April of 2023. This pilot project found that over half of drivers given a work zone or winter weather alert reduced their speed[8]. The WYDOT pilot project utilized DSRC to alert commercial truck drivers and fleet vehicles along 402 miles of I-80. The deployment included:

- 76 roadside units (RSUs) that can send and receive DSRC messages.
- 325 vehicles equipped with on-board units (OBUs) to receive alerts and broadcast basic safety messages (BSMs).
- Development of several vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) applications to enable communication with drivers for alerts and road condition advisories.

Like the ODOT notification system, the WYDOT pilot project informed approaching vehicles of unexpected conditions ahead. Two concepts of how the WYDOT alerts worked are shown in Figures 16 and 17.

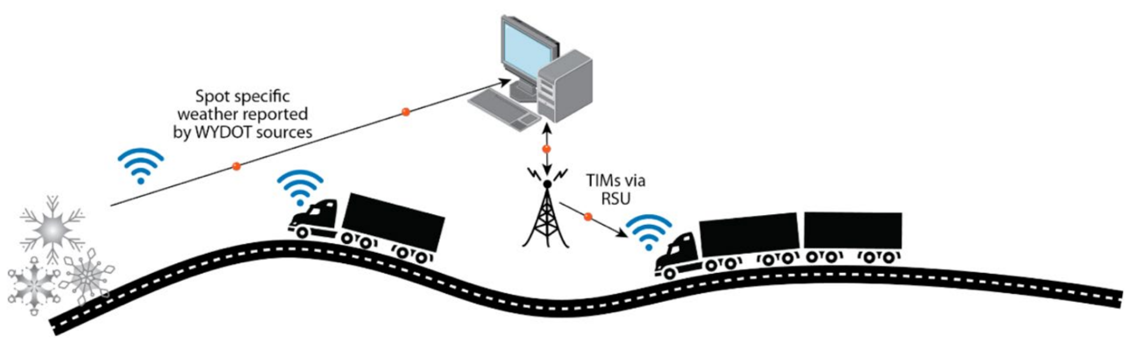

Figure 16: WYDOT Spot Weather Impact Warning Concept Diagram

[8] https://www.itskrs.its.dot.gov/2023-b01735

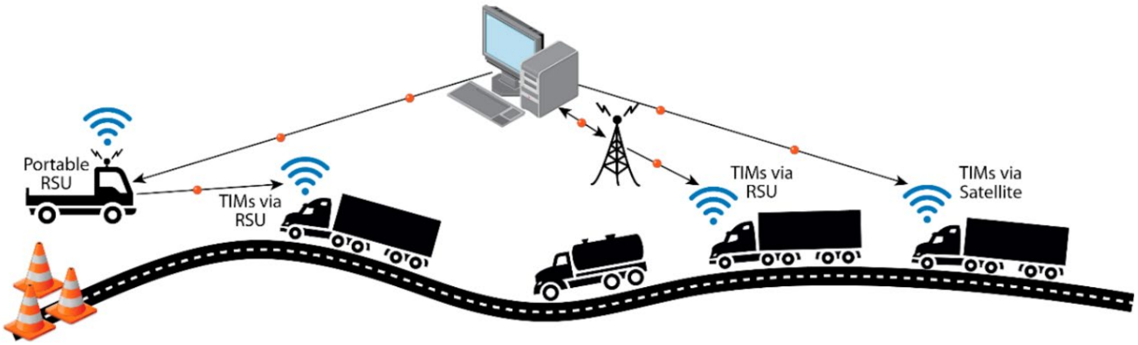

Figure 17: WYDOT Work Zone Warning Concept Diagram

The results of the WYDOT pilot included multiple measured benefits:

- A 20% improvement in total vehicles traveling within 5mph of the posted speed limit.
- A 25% reduction in the number of vehicles involved in a crash.
- A 10% reduction in the crash rate within work zones.

Pros of this measure of effectiveness

- Changes in driver speed are a direct measure of effectiveness for in-vehicle safety alerts.
- The technologies deployed in the WYDOT pilot project were implemented with full CV standards in mind, offering a solution that should translate well to any future CV implementations in Ohio.

Cons of this measure of effectiveness

- The technologies deployed in the WYDOT implementation were more thorough, provided more control over messaging, and provided more analytics for practitioners than the ODOT deployment. ODOT should not expect the results of their pilot to directly match those of the WYDOT pilot.

Reduction in hard braking activity

Another potential measure of effectiveness is to capture the reduction in hard braking activity. This measure is similar in nature to measuring the reduction in hard braking occurrences. The main difference is data source. Table 5 provides an overview of differences between the two measures of effectiveness.

Table 5: Hard Braking Measures of effectiveness

	Reduction in hard braking occurrences	Reduction in hard braking activity
Data source(s)	Connected vehicle hard braking data, Streetlight and Drivewyze or GM and Drivewyze	Estimated harsh braking events from MMI or INRIX Safety View
Analysis included?	No	Yes
Based on connected vehicle data?	Yes	No

The biggest difference is how the data is collected. Hard braking occurrences are directly measured from vehicle data as they approach the hazard. Hard braking activity is collected from mobile applications, or probe data, used inside of vehicles approaching the hazard — and post-processed into hard braking information.

Pros of this measure of effectiveness

- If there are barriers for ODOT to procure CV data, these data sources offer alternative solutions.
- These data sources require less time and effort to convert data into measures of effectiveness. Instead of providing raw data, both MMI and INRIX use proprietary algorithms to estimate hard braking activity for ODOT.

Cons of this performance measure

- Hard braking activity is not directly measured from the vehicle. Probe data will not be as accurate as connected vehicle data.

Peace of mind for roadside workers

This measure of effectiveness was derived from conversations with ODOT staff. Whereas the others are purely data driven, this measure depends on conversations — and potentially surveys — with roadside workers. Roadside workers are physically active within work zones. They are often working within feet of traffic moving through the zone. They are aware of erratic driver behavior. When vehicles are speeding excessively through a zone—or even intruding the zone—this behavior places roadside workers in harm's way.

Their experiences offer anecdotal insights into driver behavior. When major shifts are made in driver behavior, roadside workers notice.

Pros of this performance measure

- One of the primary goals for ODOT's SWZ technologies is to increase safety — for both the motoring public and roadside workers. If a deployment increases peace of mind for roadside workers, this serves as a strong lagging indicator of program success.

Cons of this measure of effectiveness

- Unlike most other recommendations, this measure of effectiveness is not data driven. It would be difficult for ODOT to use results of this measure to inform future decisions.

Reduction in near misses and struck-by events

This measure of effectiveness suggests using video analytics and machine learning to track changes in near miss events, struck-by events, or other dangerous driver behavior.

For emergency responders, "struck-by" events and traffic crashes are the leading causes of on-duty injuries and deaths for law enforcement, firefighters, and towing and recovery personnel[9]. For roadside workers and first responders, working near live traffic is extremely dangerous. Most roadside events—such as managing a traffic incident, performing maintenance tasks, or performing roadway construction—represent disruptions to normal traffic flow. Any unaware or distracted motorists put roadside workers and first responders at risk.

Video analytics, and object-based machine learning, have the capability of capturing unsafe driving behavior. Models could be developed to capture near miss events from live video cameras. Other factors could also be detected, such as congestion or excessive speeding.

Pros of this measure of effectiveness

- Near misses are a leading indicator of unsafe driving behavior. As the quantity of near misses increases, the likelihood of more serious, even fatal, crashes increase.
- Machine-learning based video analytics have reached an impressive level of maturity and accuracy. There are many solutions available for ODOT to leverage.
- Where a video camera is mounted, all vehicles passing through the view will be analyzed. Many of the other measures of effectiveness depend on data sources from a limited percentage of vehicles.

Cons of this measure of effectiveness

[9] https://ops.fhwa.dot.gov/tim/publications/timhandbook/chap1.htm

- ODOT would only be able to capture video analytics at specific locations where cameras are mounted.
- ODOT, or a vendor, would need to validate the accuracy of video analytics detection and classification algorithms.
- Depending on the length of zone, and the desire to capture approaching traffic, ODOT may need to install multiple cameras at each zone.

Reduction in damages to equipment

Another potential measure of effectiveness is to capture damages to equipment — including either maintenance vehicles or work zone equipment. All of ODOT's SWZ technology is used to support important work. When these operations are impacted by traffic incidents, ODOT incurs costs—both financially and temporally—to recover. Safer driving behavior should correlate to a reduction in damages to equipment.

Pros of this measure of effectiveness

- This is one of the few suggested measures of effectiveness that also applies to the snowplow deployments. Most measures are more relevant for the stationary work zone deployments.

Cons of this measure of effectiveness

- There is no existing data source for ODOT to use. Tracking this measure of effectiveness would require intensive manual efforts.
- Given the randomness of property damage, and varying costs of equipment, simply tracking total costs over time could be somewhat difficult to convert into changes in driver behavior.

4. Data Sources to Support MOEs

There are many data sources to support ODOT's ability to directly measure effectiveness of their SWZ implementations. Additionally, some data sources can support measuring other quantitative information about the work zones. And, in some cases, ancillary data can be leveraged for quality assurance of ODOT's work zone implementations.

Connected Vehicle Data

One of the most direct data sources is derived from OEMs collecting data on individual vehicles. Modern vehicles equipped with sensors and connectivity provide data generated by the vehicle itself. This can include vehicle speed, location, brake usage, and other telematics data. GM is one example of a company providing this data directly to DOTs. Also, GM recently entered into an agreement with Streetlight. Streetlight plans to make this data available for DOTs and other transportation agencies soon. Other data providers may also have plans to make OEM data available to DOTs.

ODOT is currently in a contractual relationship with Drivewyze and receives driver behavior data for these commercial vehicles. The Drivewyze system is connected to commercial vehicle telematics through the electronic logging device. They capture and provide similar information derived from trucks.

Table 6: Connected vehicle data sources

Data Sources	Real-time or Historical	ODOT Owned	ODOT Data Analysis Required
Direct OEM data (e.g. GM)	Historical	No	Yes
OEM data through data providers (e.g. Streetlight)	Historical	No	Yes
Commercial vehicle driver behavior (e.g. Drivewyze)	Historical	Yes	No

Connected vehicle data can be used to support these recommended measures of effectiveness:

- Reduction in hard braking events.

- Reduction in average driver speed.
- Reduction in hard braking activity.
- (Potentially) Reduction in lane change behavior.

According to GM, they would have data collected from roughly 10% of the passenger vehicle fleet in Ohio. According to Streetlight, they expect roughly 7% to 10% coverage in Ohio. According to Drivewyze, up to 30% of trucks in Ohio are connected to their system.

Both GM and Streetlight would also be offering their analysis services, in addition to raw data. Drivewyze provides ODOT with hard braking data and analytics as shown in Figures 18 and 19.

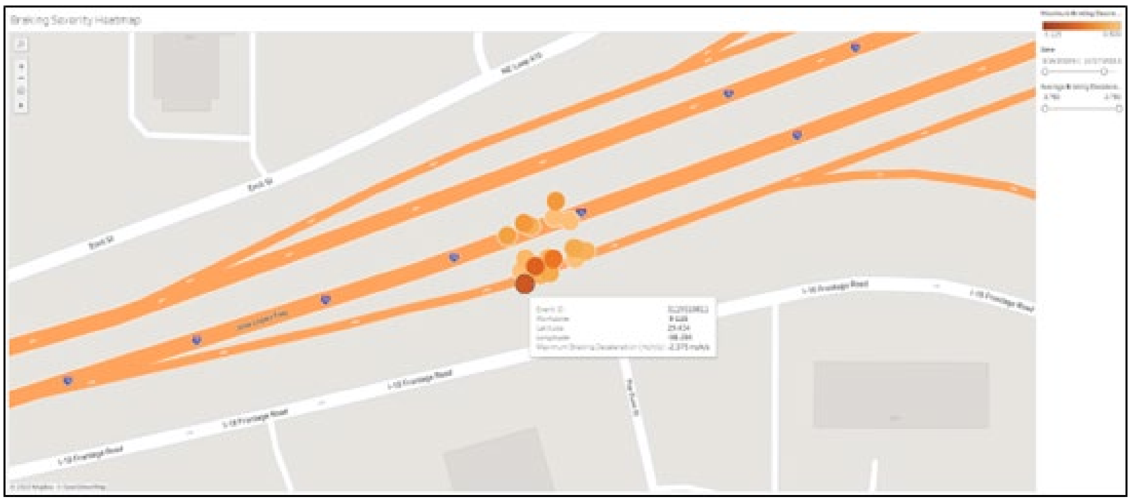

Figure 18: Drivewyze ODOT hard braking heatmap.

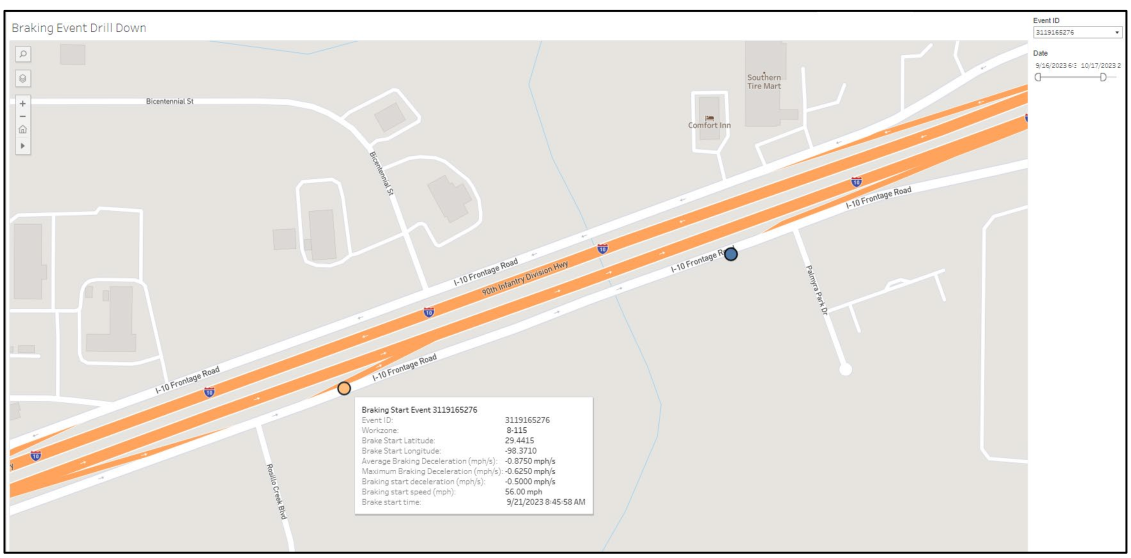

Figure 19: Drivewyze ODOT hard braking incident detail.

All connected vehicle data sources have higher penetration on freeways and any routes with increased traffic volumes. Drivewyze skews heavily towards freight routes.

GM data would need to be purchased by ODOT, either directly from GM or through Streetlight. Additionally, ODOT would need to pay for the analysis of this data to convert raw data into driver behavior analytics.

GM may also be able to provide other driver behavior information to ODOT, including:

- Forward collision alerts
- Hard braking alerts
- Aggressive lane change behavior

In all these instances, GM captures raw data from the vehicles, and post-processes (upon request) the data into driver behavior insights. It is worth noting, to date only hard braking data has been included in a study measuring driver behavior. The other driver behavior data—such as measuring changes in forward collision alerts—have not been tested or included in any published studies. If ODOT were the first to use these newly available data sources, they should expect some growing pains as the proprietary algorithms defining these driver events have not previously been vetted at scale.

Drivewyze driver behavior data is only captured from trucks when alerts are sent. ODOT will only receive driver behavior data when a truck receives an INRIX-based congestion or queue alert, a work-zone based alert, or a HAAS-based roadside worker alert. Drivewyze driver behavior data is not captured unless an alert is sent to trucks.

Probe Traffic Data

An alternative to connected vehicle data is probe traffic data from any of the traffic data providers such as INRIX, HERE, Michelin Mobility Intelligence, Arity or Streetlight. These data providers use a combination of data sources to create data products for DOTs. One of their most common data sources is personal mobile phones and mobile applications. Other data sources include navigation systems, other embedded in-vehicle systems, and roadside sensors. The data companies combine multiple data sources with proprietary algorithms to provide high quality real-time and historical data feeds. Common types of data include:

- Speed data
- Congestion and bottleneck data
- Traffic volume data
- User delay cost information
- Traffic signal performance data

Unlike connected vehicle data from OEMs, this data is not new. Probe data has been used by DOTs for years to support analytics, before and after studies, and other transportation planning efforts. ODOT has a strong history relying on traffic data to guide investment decisions, tell meaningful stories through data, and prove effectiveness of various implementations.

Probe traffic data can be used to support these recommended measures of effectiveness:

- Reduction in ‘Dangerous Slow Down’ events.
- Reduction in average driver speed.
- Reduction in hard braking activity.

ODOT already has a subscription to INRIX probe traffic data for real-time and historical analysis. They also have access to the INRIX Dangerous Slowdown real-time API. Additionally, ODOT has been archiving the INRIX Dangerous slowdown feed since early 2024.

ODOT also has access to the Streetlight Origin / Destination planning data.

It is worth noting that ODOT has experienced recent issues with INRIX probe data. The industry has seen a change in data providers. This has impacted the quality and coverage of INRIX probe data. Additionally, a few API and algorithmic changes have impacted the quality of INRIX real-time APIs. The real-time and historical speed data seems to have been impacted the most. It appears the dangerous slowdown data has not been impacted as much and remains reliable.

Probe data providers are also offering several additional analytics for ODOT’s consideration. These include:

- The ability to estimate harsh braking events or harsh acceleration.
  - The Michelin Mobility Intelligence (MMI) platform has recently begun offering this.
  - INRIX Safety View, in partnership with GM Future Roads, has also recently begun offering this.
- The ability to estimate near misses or potential crashes.

It is worth noting that these estimations are not as accurate as similar driver behavior events directly measured by OEMs. Probe data providers are estimating driver behavior activity from probe data sources, not directly from vehicle telematics.

Video Analytics Data

Video Analytics using machine learning is another data source to potentially support some of the recommended MOEs.

The researchers spoke with Currux Vision to discuss this data source. This conversation centered around the typical analytics from video-based machine learning. In urban environments, video analytics is typically used to capture events such as:

- Red light running

- Wrong way driving
- Pedestrian crossings

For freeway operations, typical events detected by video analytics include:

- High speeds
- Collisions
- Congestion

For the recommended MOEs, there are other higher fidelity data sources than video analytics. However, for a couple of driver behavior related events, video analytics is the best current data source. Specifically, near misses. One of the MOE recommendations is to measure reductions in occurrences of near misses approaching the work zone. Figures 20 and 21 show how video analytics use object detection to capture some of these events.

Video analytics data can be used to support these recommended measures of effectiveness:

- Reduction in near misses and struck-by events.
- Reduction in average driver speed.
- Reduction in hard braking activity.
- (Potentially) Reduction in lane change behavior.

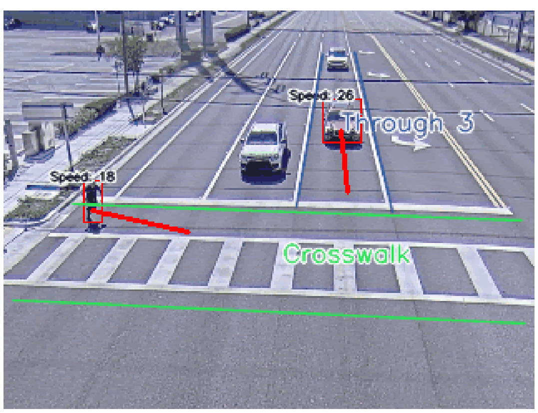

Figure 20: Another video analytics near miss event

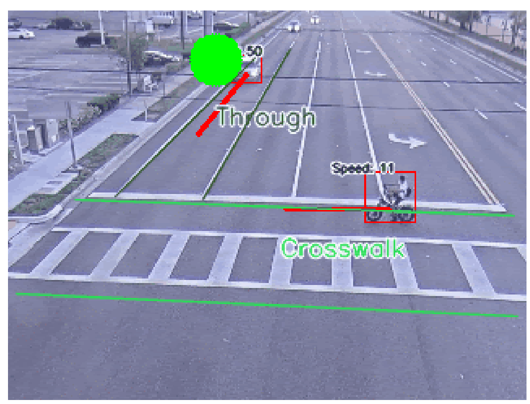

Figure 21: Video analytics near miss event

The video analytics providers cautioned about the accuracy of lane change behavior. However, work zone intrusion, ends of queues, and other video analytics could be captured with a higher degree of accuracy. Additionally, video data may be useful for quality assurance reviews, testing accuracy of ODOT's SWZ implementations.

Crash Data

Crash statistics data is available from a few sources including the Ohio State Highway Patrol and ODOT GCAT system. ODOT has extensive experience collecting, analyzing, and leveraging crash data. ODOT's crash data would primarily support one measure of effectiveness:

- Reduction in crashes

A major benefit of using crash data is completely owning the data and information. ODOT would not need to engage a third party. Additionally, ODOT could analyze the crash narratives to further understand the causes of crashes — singling out any crashes directly related to work zone or maintenance activities.

The biggest downside to relying on crash data is the length of time required to see a statistically meaningful difference. Before and after studies are typically comparing three years "before" to three years after. Differences in other measures of effectiveness can be noticed within weeks or months.

Survey Data

Survey data is another potential source to support some of the recommended measures of effectiveness, particularly those that are more anecdotal or qualitative in nature. Surveys can be used to gather insights directly from stakeholders involved in SWZ implementations, such as roadside workers, drivers, and ODOT personnel.

Survey data can be used to support these recommended measures of effectiveness:

- Peace of mind for roadside workers

Surveys can be designed to capture the subjective experiences and opinions of those directly impacted by SWZ technologies. For example, roadside workers can be asked about their perceived sense of safety and peace of mind when working in connected work zones compared to traditional work zones. Drivers can be surveyed about their awareness of SWZ alerts and their perception of how these alerts influence their driving behavior and overall safety. ODOT personnel can provide their insights on the effectiveness of SWZ devices based on their observations and experiences.

One advantage of using survey data is that it provides a direct line of communication with the people most affected by SWZ implementations. This can offer valuable context and nuance that may not be captured by quantitative data sources alone. Surveys also allow for the collection of data on more subjective measures of effectiveness, such as peace of mind and perceived safety improvements.

However, there are some limitations to consider when using survey data. Surveys rely on self-reported information, which can be subject to biases and inaccuracies. Additionally, designing and administering surveys can be time-consuming and resource-intensive, requiring careful planning and execution to ensure meaningful results. ODOT would need to allocate resources to develop, distribute, and analyze surveys to effectively leverage this data source.

5. Gap Analysis

This report suggests multiple potential measures of effectiveness, along with many different sources of data. Each data source has potential gaps, or challenges, to consider.

Connected Vehicle data has two primary concerns to consider:

- **Penetration**. A small percentage of vehicles are captured in the currently available data sets. ODOT should expect 10% or less. However, especially along routes with higher traffic volumes, this may be enough for ODOT to notice a meaningful change in driver behavior.
- **Analysis Effort**. Connected vehicle data is currently provided as an extremely large data set. Even for a short period of time, ODOT would be provided with billions of data points. Data analysis would need to be handled separately, in addition to data procurement. This would add time and cost to ODOT's efforts.

Probe data has a few concerns to consider:

- **Data Quality**. In the past year, probe data quality and reliability has come into question. ODOT may need to spend some time validating the accuracy of these data sources. In some cases, the data may not be high enough quality on certain routes.
- **Penetration**. While likely covering a higher percentage of vehicles than OEM data, probe data still represents a minority of traffic vehicles. ODOT should not expect much higher than 15% of vehicles represented in probe data sources, on average.

Other issues worth noting include:

- **Quantifying Alert Reach**. Currently, there is no guaranteed way to know how many drivers are receiving the digital work zone alerts through their navigation systems or apps. To determine the number of motorists using the available tools to receive these alerts, ODOT would need to solicit and oversee a study to poll drivers and gain a sense of the reach of the work zone alert system.
- **Removing Anomalies**. When analyzing before and after data, it is desirable to compare similar before and after conditions. When attempting to isolate the impact of the SWZ technology, ODOT may have to cleanse the data of any anomalies such as crashes or unexpected weather. The impacts of these events should not be counted in the overall "before" or "after" conditions.
- **Deployment Validation**. Each implementation has some amount of variation including different suppliers, different public messaging, and different staff controlling the technology. At times, ODOT has experienced false positives being deployed. It may be beneficial for ODOT to validate the accuracy of their alerts. A solution like Blyncsy's may provide a potential validation option for ODOT. Their system provides near real-time video snapshots from vehicles driving through any

ODOT route. Figure 22 shows an example snapshot from a work zone near Akron, Ohio. ODOT could use this system to validate the accuracy of their work zone alerts.

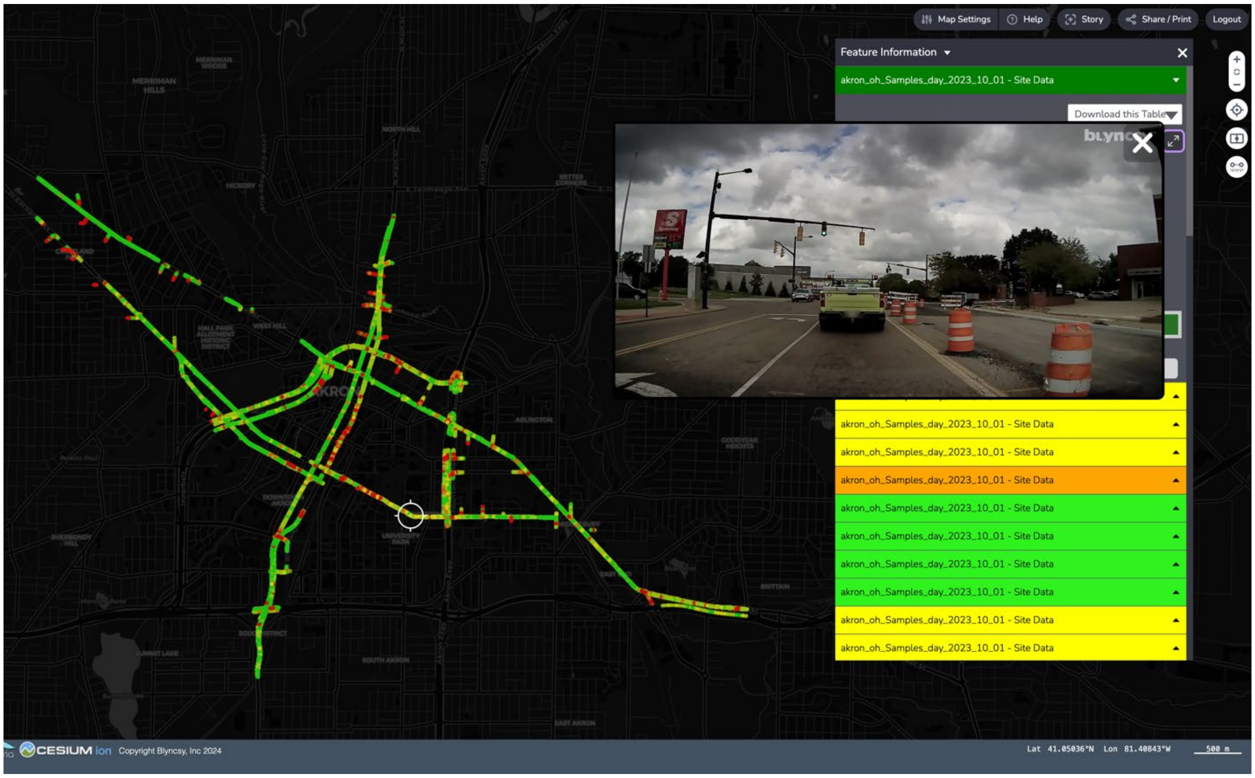

Figure 22: Example Blyncsy work zone validation.

6. Tangential Observations

While not directly necessary for measuring effectiveness, other potential issues and opportunities were discovered by the project team during this task. These issues may impact ODOT's decision to scale any SWZ devices further across the state.

This section captures other observations and issues to consider related to the SWZ deployments. At a glance, these are the tangential observations for consideration:

- Managing disparate systems
- Standardization of implementation
- Standardization of public messaging
- Integrating data into the Event Streaming Platform (ESP)

Managing Disparate Systems

ODOT currently has multiple systems to monitor each deployment. Some are provided as web applications, with custom accounts, providing some information. Others offer executable applications for installation on personal computers. There are also mobile applications available for accessing information from other deployments. Some implementations provide recurring reports. Others do not. Some of these applications provide management control within the same system. Other applications require a separate system for changing and configuration items. Most, but not all, of the suppliers push information to Waze.

ODOT would benefit from one single system to manage the disparate systems and technologies. Butterfly Junctions is one example of a company with experience in this area. Their technology can integrate with multiple data devices, and provide command, control, and reporting from a unified system and interface. Consolidating efforts into a single application should streamline ODOT's management efforts and improve quality long-term.

Additionally, there is benefit to having a single cohesive interface for viewing and managing all of the SWZ devices. ODOT can strategically and efficiently control quality, manage public messaging, and better QA each implementation.

Standardization of Implementation

As with the different systems to monitor each implementation, the technologies deployed in Ohio also have varying implementations. Each device is calibrated somewhat differently. Some systems have alarms whereas others do not. Some systems can adapt to being physically moved while others cannot. Polling frequencies vary. Each supplier offers different levels of training for contractors installing their devices.

These differences have led to occasional issues. For example, arrow boards have pushed information to Waze when in the down position.

To ODOT's credit, they have attempted to standardize some of these items. Before scaling, ODOT would benefit from creating a standard implementation that includes:

- Preferred hardware
- Preferred configuration
- Standardized training
- Integrated through a single management system

Integrating Data into the Event Streaming Platform

In addition to command and control capabilities, ODOT should consider integrating the data from SWZ devices and vehicles into the Event Streaming Platform (ESP) for enhanced analysis and insights. The ESP, built by ODOT and DriveOhio, is designed to manage real-time data streams, provide analytics, and share data with other systems and platforms.

Integrating SWZ data into the ESP offers several advantages:

1. **Real-time insights**: The ESP can process and analyze the high volume of data generated by SWZ devices and vehicles in real-time. This enables ODOT to gain immediate insights into work zone performance, safety, and driver behavior.

2. **Advanced analytics**: The ESP's data processing capabilities, such as KSQL for low-code data aggregation and Kafka Streams for more complex processing, can be leveraged to perform advanced analytics on SWZ data.

3. **Data sharing and collaboration**: By integrating SWZ data into the ESP, ODOT can easily share this data with other agencies, jurisdictions, and stakeholders through the ESP's data marketplace.

4. **Integration with other data sources**: The ESP can combine SWZ data with other relevant data streams, such as traffic, weather, and incident data, to provide a holistic view of work zone safety and efficiency.

5. **Scalability and flexibility**: The ESP's architecture, built on principles like infrastructure as code and containerization, allows for easy scaling and adaptation as SWZ deployments expand.

Standardization of Messaging to Drivers

Another tangential concern is the lack of control over how messages are distributed to drivers. When relying on third-party navigation systems, ODOT loses some control over how the messages are delivered to drivers. Occasionally, inconsistent messages have been pushed to navigation apps. Figure 23 shows an example of inconsistent messages being pushed to drivers, via the Waze application. The messaging on the left is correct, mentioning the correct lane closure. The message on the right is incorrect and could lead to driver confusion.

To address this issue, ODOT can leverage the ESP to ingest, validate, and publish connected work zone data for consumption by third parties. By centralizing the data management and validation process within the ESP, ODOT can ensure that accurate and consistent information is being shared with navigation apps and other third-party systems. This approach could reduce the reliance on multiple system integrations and help maintain a unified and cohesive message to drivers.

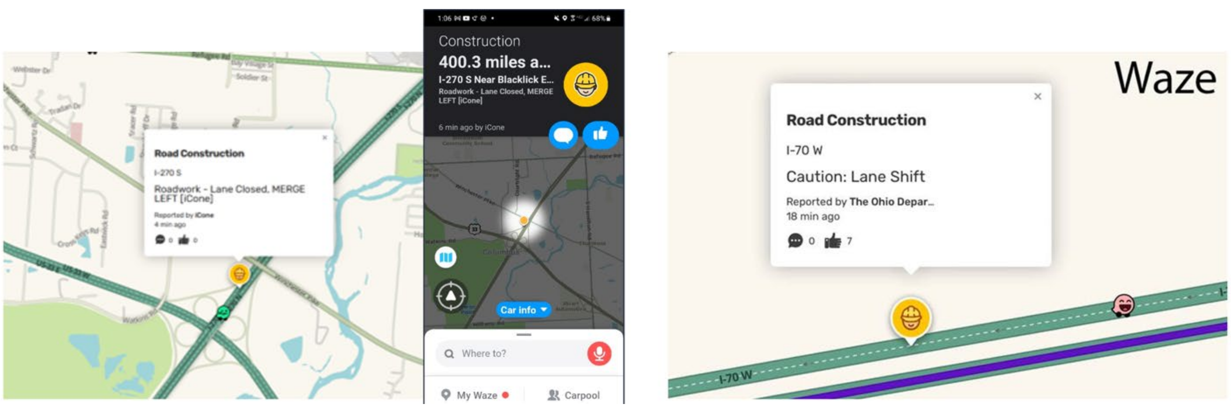

Figure 23: Example of inconsistent messaging to drivers.

Standardization of implementation should also benefit ODOT's desire to standardize the messaging to drivers. The fewer system integrations involved, the more likely ODOT presents a unified and cohesive message to drivers.

7. Implementation Roadmap

This section provides a clear roadmap for measuring the effectiveness of SWZ devices. By following these steps, meaningful insights can be generated to guide future connected work zone investment decisions. The suggested roadmap contains the following recommended steps:

1. Select corridors and work zones for testing
2. Procure data to support the MOEs.
3. Begin with a “before” period for the study
4. Analyze the “before” data
5. Begin an “after” period for the study
6. Analyze the “after” data
7. Compare the results and measure the impact
8. Document the results and determine criteria for scaling the program

Select corridors and work zones for testing

First, candidate locations for performing the study should be identified. Ideally, these locations would have SWZ devices currently in operation. Having existing deployments in place will speed up the study timeline.

The selected locations should have a history of maintenance or construction activities expected to continue for the next few months. The ability to measure driver behavior approaching these work zones with the SWZ technology enabled **and** disabled is required.

Additionally, it will be important to select work zone locations with similar characteristics before and after the technology is enabled. Major traffic pattern changes during the study period should be avoided. Isolating the SWZ technology impact is key.

Procure data to support the MOEs (if needed)

After selecting the corridors and work zones to study, the data sources required for the selected MOEs need to be procured. In some cases, the necessary data may already be accessible. In other cases, such as using connected vehicle data, data may need to be purchased from providers like GM or Streetlight.

When procuring new data for this effort, consider:

- The length of time data is needed for. Enough data is needed to cover the study period before and after the SWZ technologies are enabled.
- The specific data attributes needed. In some cases, data providers offer different levels of data. Ensure all necessary information is received to calculate the MOEs.

- Data format and size. Probe data sources are often provided as CSVs or through APIs that are easier to work with. Connected vehicle data sources may be much larger and require big data processing tools.

Perform the “before” period of the study

With locations selected and data sources procured, the "before" period for the study can begin. During this time, the SWZ devices should be disabled, and no in-vehicle work zone alerts should be distributed to drivers.

To minimize fluctuations due to seasonality, a before period matching the length of the after period is recommended. For example, if the impact is to be studied over a 2-month period, the before data should also be collected for 2 months.

Analyze the “before” data

Once the before period is over, the data needs to be analyzed to calculate the selected MOEs. For example, if studying hard braking events, the total number of hard braking events or number of hard braking events per mile approaching the work zone will need to be calculated.

When analyzing the before data, it is recommended to:

- Remove any outliers or anomalies from the data. Crashes, inclement weather, special events, or other traffic incidents could skew the analysis.
- Segment data into different time periods and areas of interest. The impact during peak and off-peak periods may need to be studied separately. Additionally, data may need to be segmented at varying distances approaching the work zone.
- Document all assumptions. When comparing before and after results, consistency in analysis methodology should be ensured.

Begin an “after” period for the study

After analyzing the before data and ensuring the work zones remain similar, the after period for the study should begin. During this time period, the SWZ devices should be activated and distributing alerts to drivers. It is critical to ensure the work zone setup is as similar to the before period as possible. The "after" period could also start while finishing the analysis of the "before" data.

Analyze the “after” data

Once the after period is over, the data should be analyzed and the same MOEs and segments as the before period should be calculated. The goal of the after analysis is to be as consistent with the before analysis as possible.

Compare the results and measure the impact

With both before and after analyses complete, the MOEs can be compared, and the effectiveness of the SWZ devices can be measured. It is recommended to measure the impact in a few ways:

- Percent improvement in each MOE from before to after.
- Percent improvement in each MOE from before to after, segmented by time of day and distance to work zone.
- Tests for statistical significance. Given the MOE, the same hypothesis test should be used on both the before and after data to determine if the difference in MOEs is statistically significant.

Document the results and determine criteria for scaling the program

Using the results of the study, the criteria for determining future work zones to deploy SWZ devices should be documented. Criteria could include:

- Minimum traffic volumes
- Length of the work zone
- Duration of the work zone
- Type of work zone
- Presence of existing ITS infrastructure

Additionally, the anticipated benefits for each criterion should be documented. For example, if the study reveals an 11% reduction in hard braking events for work zones over 3 miles in length on routes with AADT greater than 50,000 vehicles per day, those results should be documented for future reference. When deciding where else to deploy the SWZ devices, the criteria can be used to estimate the potential benefits.

Expected research team qualifications

Measuring the effectiveness of SWZ devices is a complex and specialized task. It is recommended to procure the services of a researcher or consultant team to support this effort. DOTs often hire external experts to perform MOE studies due to the specific expertise and resources required. Engaging a researcher or consultant can ensure the study is conducted rigorously, the data is analyzed correctly, and the results are interpreted appropriately to inform future SWZ deployment decisions. The suggested team member expertise and qualifications should include:

1) Work zone planning engineer
2) Traffic engineer
3) Data scientist
4) Cloud data storage and processing engineer
5) Data portal or visualization capabilities (ex. Tableau, PowerBI)