CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

Final Report #ICT-23-016
August 2023

Enhancing Construction Work-Zone Safety by Passive Pavement-to-Vehicle Communication

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ILLINOIS CENTER FOR TRANSPORTATION

DISCLAIMER

Funding for this research was provided by the Center for Connected and Automated Transportation under Grant No. 69A3551747105 of the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology (OST-R), University Transportation Centers Program. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

Suggested APA Format Citation:

Sakulneya, A., & Roesler, J. (2023). *Enhancing construction work-zone safety by passive pavement-to-vehicle communication* (Report No. ICT-23-016). Illinois Center for Transportation. https://doi.org/10.36501/0197-9191/23-016

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. ICT-23-016	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A

4. Title and Subtitle
Enhancing Construction Work-Zone Safety by Passive Pavement-to-Vehicle Communication

5. Report Date
August 2023

6. Performing Organization Code
N/A

7. Authors
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8. Performing Organization Report No.
ICT-23-016
UILU-ENG-2023-2016

9. Performing Organization Name and Address
Illinois Center for Transportation
Department of Civil and Environmental Engineering
University of Illinois at Urbana–Champaign
205 North Mathews Avenue, MC-250
Urbana, IL 61801

10. Work Unit No.
N/A

11. Contract or Grant No.
Grant No. 69A3551747105

12. Sponsoring Agency Name and Address
Center for Connected and Automated Transportation
University of Michigan Transportation Research Institute
2901 Baxter Road
Ann Arbor, MI 48152

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.
https://doi.org/10.36501/0197-9191/23-016

16. Abstract

Construction work zones for roads pose significant safety challenges for drivers and workers, which can lead to accidents, injuries, fatalities, and property damage. Enhancing construction work-zone safety requires an understanding of the factors influencing accidents and fatalities and an evaluation of existing safety and traffic-management measures. The objective of this study was to improve work-zone safety for roadways, by connecting passive material sensing in the road with vehicle communication systems. A review of the main roadway work-zone safety literature found driver behavior, traffic congestion, and signage effectiveness to be the most significant factors. Vehicle speed, type of vehicles, type of collisions, and environmental conditions were found to have the most impact on the fatality rate in work zones. Past attempts to improve work-zone safety include adding rumble strips, more warning signs, and implementing smart-work-zone (SWZ) technologies. SWZ communication in-vehicle was found to reduce traffic speeds and promote faster and more consistent merging in the work-zone transition area. Pavement-assisted passive sensing, coupled with vehicle-to-infrastructure (V2I) communication, may offer enhanced in-vehicle speed and lane-merge warnings, which could improve driver awareness, reduce vehicle speeds, and improve work-zone safety. A laboratory-based experiment was developed to validate the theoretical configurations of smart work zones (SWZ) using passive pavement sensing, with the objective being to determine suitable spacings and inclination angles for the electromagnetic (EM) strips as speed and lane-merge warning systems, respectively. The experimental results revealed that these EM strips can estimate vehicle speed with sufficient accuracy, and the spacing of the EM-sensing strips influences the signal intensity. Additionally, the spacing and inclination angle of the EM strips influence the captured signals. This lab pilot study clearly demonstrated the potential of EM-based strips in enhancing speed and lane-merge warning systems using V2I technology for improved safety in roadway work zones.

17. Key Words
Construction Work-Zone Safety, Smart-Work-Zone Technology, Pavement-Assisted Passive Sensing

18. Distribution Statement
No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 37	**22. Price** N/A

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

ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS' NAMES

This project was conducted in cooperation with the Center for Connected and Automated Transportation and the Illinois Center for Transportation. The contents of this report reflect the view of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of CCAT or ICT. This report does not constitute a standard, specification, or regulation. Trademark or manufacturers' names appear in this report only because they are considered essential to the object of this document and do not constitute an endorsement of the product by CCAT or ICT.

EXECUTIVE SUMMARY

Construction work zones on roadways have been identified as vulnerable areas due to prevalent issues of speeding and unsafe driving behavior. Drivers consistently fail to adjust their speed to posted speed limits within work zones and disregard the warning signs and traffic-control devices, which significantly increases the risks and potential for accidents, injuries, and fatalities. This project conducted research and experimentation to provide evidence of the potential benefits of implementing pavement-assisted passive-sensing technology to enhance the safety performance of construction work zones on roadways. It was established that the implementation of pavement-assisted, passive-sensing technology has the capability to enhance work-zone safety by effectively addressing the challenges posed by speeding and unsafe driving behavior.

For both workers and drivers, collisions and fatalities in construction work zones have been a significant concern for roadway agencies as they strive for “Vision Zero.” Multiple studies have shown work zones generally have higher rates of traffic-related accidents and fatalities. Data revealed that speeding, driver inattention, and failure to obey traffic control devices were the primary contributing factors to these adverse incidents. Despite efforts to enhance work-zone safety through increased signage, improved traffic-control measures, and public-awareness campaigns, the number of collisions and fatalities has remained unacceptably high. Several studies have demonstrated that the application of in-vehicle message warning could enhance the driver response when approaching the work zone and reduce the risks of failing to merge at the appropriate time.

An experimental plan was developed and executed to test the responses of electromagnetic (EM) signatures from several EM passive-sensing strip configurations, including varying strip spacing and inclination angle. The laboratory proof-of-concept results demonstrated that the responses of EM signatures exhibited potential for the establishment of a vehicle-to-infrastructure (V2I) system that includes an in-vehicle speed and lane-merge warning system. Each EM-strip configuration generated response signatures at different intensities and offsets, depending on the setup. The clarity of the passive-sensing signatures was primarily influenced by the spacing between the EM sensing strips. Specifically, the passive-sensing signatures obtained from the 2-ft strip spacing exhibited superior intensity and clarity, as compared to those obtained from the 1-ft strip spacing. As the strip spacings were tightened, the distinctiveness of each peak in the signatures was compromised, presenting challenges in accurately identifying the actual peaks from each individual strip. The moving sensor array was able to detect the inclined EM sensing strips from 45° to 90° if they were spaced at least 2-ft apart. This finding confirmed the ability of pavement-assisted passive sensing to deliver tailored and meaningful information to drivers, thereby contributing to improved work-zone safety and heightened driver awareness.

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CHAPTER 1: INTRODUCTION

BACKGROUND

Work zones are dynamic areas where road construction and maintenance activities take place. These zones present unique safety challenges due to the combination of ongoing construction activities, altered traffic patterns, and presence of workers and heavy machinery. Therefore, ensuring the safety of both workers and road users is a critical priority within construction work zones.

Accidents in work zones can have severe consequences, including injuries, fatalities, and property damage. According to American Road and Transportation Builders Association (ARTBA, 2022), a substantial number of fatal accidents occur within work zones every year, making it a critical area of concern for transportation agencies and policymakers. Understanding the background and key factors contributing to work-zone accidents is essential for developing effective strategies to enhance safety.

Several factors influence accidents in work zones. Driver behavior is a significant contributor, with speeding, distracted driving, and improper lane changes being common causes of accidents (Pigman & Agent, 1990; Raub et al., 2001; Bai & Li, 2006). Traffic congestion in work zones can also increase the likelihood of collisions (Pigman & Agent, 1990). Inadequate signage or improper signage placement can further contribute to accidents by failing to provide clear instructions to drivers (El-Rayes et al., 2014).

In regard to the fatality rate in construction work zones, vehicle speed plays a crucial role, with higher speeds increasing the severity of accidents (Bai & Li, 2006; Dissanayake & Lu, 2002). The types of vehicles involved in work-zone accidents, such as passenger cars, commercial trucks, or construction vehicles, can also impact the fatality rate (IDOT, 2023). The nature of collisions, such as rear-end crashes involving heavy vehicles, influences the likelihood of fatalities (IDOT, 2023).

To mitigate accidents and enhance safety in work zones, various safety measures have been implemented. For example, rumble strips are installed on the pavement to produce vehicle vibration and audible warnings to alert drivers of an upcoming work zone. Warning signs placed in strategic locations provide important information and instructions to drivers that guide them through the work zone safely (El-Rayes et al., 2014; Fontaine & Carlson, 2001). Furthermore, intelligent transportation systems, including advance-warning systems and real-time traffic information, have also been employed to enhance safety (Azimi et al., 2021; Darwesh et al., 2021; Li et al., 2018).

There has been increasing interest by departments of transportation (DOTs) in exploring innovative approaches to enhance work-zone safety for both drivers and workers. A 2023 customer survey by Roesler and Dahal sent to DOT engineers on the biggest safety issues for roadways found that most DOT strategies focused on improving work-zone safety. One approach is to use new vehicle technologies and passive roadway-sensing technology, e.g., embedding electromagnetic signatures in the pavement (Dahal, 2022), to provide in-vehicle warnings and assistance to drivers to alter unsafe driving maneuvers or other actions. Applying passive-sensing technology within the roadway infrastructure has the potential to enhance driver awareness, promote speed reduction, and improve overall safety in work zones.

Understanding the background of work-zone safety, including the factors influencing accidents and fatalities, and reviewing current safety measures are crucial for identifying gaps and developing effective V2I strategies. By addressing the most pressing challenges with innovative V2I approaches such as passive-sensing technology, the aim is to create safer work zones that protect both workers and road users and ensure the smooth flow of traffic through construction areas.

Research Objectives

The initial research objectives of this study were to conduct a review of the factors that contribute to accidents and fatalities in roadway work zones and to identify the key elements that significantly impact work-zone safety. The other objective of this research was to propose potential V2I technologies that have the capabilities to reduce significantly the risk of accidents, injuries, fatalities, and property damage in construction work zones.

Overview of the Report

This report is structured into four chapters, with Chapter 1 introducing the background, objectives, and scope of the report. Chapter 1 provides a comprehensive overview of construction work-zone safety. Chapter 2 provides a detailed review of work-zone safety, including the various factors, underlying causes, and risks contributing to work-zone incidents, as well as explores the factors that lead to fatalities in work zones. Chapter 3 focuses on exploring the potential for pavement-assisted, passive-sensing technology as one type of solution to enhanced work-zone safety and addresses the factors identified in Chapter 2. The capabilities and benefits of the pavement-assisted, passive-sensing technology are analyzed in relation to its potential to mitigate risks and enhance safety in construction work zones. Last, Chapter 4 synthesizes the key findings of this pilot study and provides recommendations for the implementation and utilization of pavement-assisted, passive-sensing technology to improve work-zone safety.

CHAPTER 2: WORK-ZONE SAFETY

The work zone in this report refers to both construction and maintenance projects that take place on a roadway. According to the *Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD)*, the work zone can be divided into four areas: the advance-warning area, the transition area, the activity area, and the termination area (FHWA, 2003). As described in Figure 1, the purpose of the advance-warning area is to notify road users about an upcoming hazard zone; and the transition area redirects vehicles from their normal path. The activity area is the specific roadway section where the maintenance or construction work is being performed, and the termination area indicates the point at which drivers completely exit the work zone and resume their normal driving speed and lane-changing options.

Work-zone safety is important because significant risks and severe consequences are associated with accidents that occur within these zones. Accidents within work zones tend to be more severe, due to a higher occurrence of rear-end and sideswipe collisions (Pigman & Agent, 1990). The unique combination of ongoing construction or maintenance activities, limited space, changing traffic patterns, and involvement of heavy vehicles and machinery creates a challenging and less predictable environment. The aforementioned factors significantly increase the likelihood of collisions, leading to serious injuries, property damage, and even loss of life.

Several factors have been identified as contributing to the higher accident rates within work zones relative to statewide accident rates such as improper use of traffic-control devices, ineffective traffic-management practices, insufficient overall work-zone layout, and a general lack of awareness regarding the specific challenges inherent in these environments (Pigman & Agent, 1990). The inappropriate use of traffic-control devices can lead to confusion and misinterpretation by drivers, compromising safety within the work zone. Poor traffic management further exacerbates the risks by failing to ensure smooth and efficient traffic flow through the work site. Inadequate layout of the work zone may cause hazards such as limited visibility, narrow lanes, or unclear signage, which increases the potential for accidents. Moreover, a lack of understanding and appreciation for the unique complexities of construction and maintenance work zones can contribute to suboptimal safety measures and practices. Extensive research has been conducted regarding safety aspects related to work zones. Previous studies have focused on various key areas, including the appropriate utilization of traffic-control devices, efficient work-activity scheduling, and comprehensive personnel training. These studies have recognized the critical importance of employing effective traffic-control devices to ensure clear communication and guidance for drivers navigating through work zones. Additionally, optimizing work-activity schedules has been highlighted as a crucial factor in minimizing congestion and reducing potential hazards. Finally, providing comprehensive training to work-zone personnel is essential, as it equips them with the necessary knowledge and skills to perform their tasks safely (Pigman & Agent, 1990).

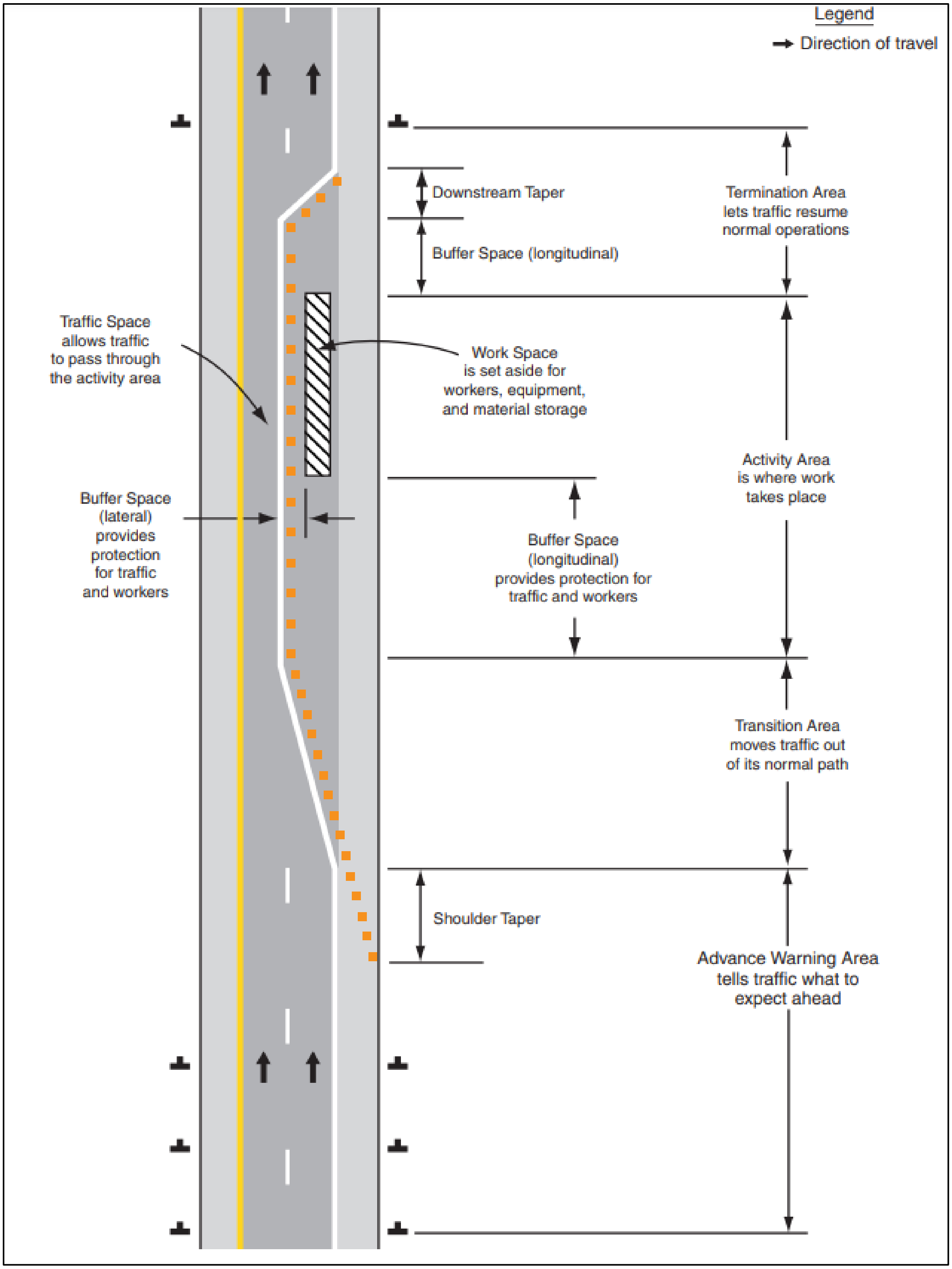


Figure 1. Diagram. Four components of a construction work zone.

Source: FHWA, 2003

COLLISIONS IN THE WORK ZONE

This section presents a comprehensive review of factors influencing accidents/collisions within work zones. An analysis of factors affecting accidents in work zones between 1983 and 1986 in Kentucky is first presented to provide an historical context and to identify recurring patterns. Subsequently, a review of factors influencing collisions in work zones in the past two decades is also summarized, identifying recent developments in work-zone management practices and their implications to accident rates. By examining historical and recent factors, it is possible to identify emerging trends, challenges, and potential opportunities to improve work-zone safety measures.

Pigman and Agent (1990) conducted a study to identify the variables influencing Kentucky work-zone accidents and statewide accidents from 1983 to 1986, as summarized in Table 1. The first observation was that work-zone accidents during the construction season exceeded statewide accident rates, specifically between June and October. Second, weekday accidents in work zones were more prevalent than weekend accidents due to reduced work-zone activity on the weekends. Third, work-zone accidents were found to be more severe in nature when compared to statewide accidents overall. Next, the contribution of work-zone accidents was higher in rural areas than in urban areas, with horizontal-curves having higher occurrence rates within work zones, as compared to statewide accidents. This finding indicated the sight distance of drivers in work zones may be compromised. Finally, the data indicated that work-zone accidents were less likely to occur in the absence of construction or maintenance activities. Table 2 presents an overview of the factors contributing to accidents in work zones and their severity—e.g., congestion, restricted lane width, striking or avoiding construction equipment, material presence on the roadway (such as gravel or oil), and instances of vehicles' merging too late—accounted for the majority of accidents occurring in work zones. The severity index (SI) in Table 2 is defined as the number of equivalent-property-damage-only divided by the total number of accidents. The equivalent-property-damage-only (EPDO) is a metric utilized to evaluate the severity of various accident types by taking into account the number of fatal accidents, possible-injury accidents, and no-injury accidents. It serves as a comparative measure for assessing the severity levels across these accident categories. The EPDO calculation considers the varying levels of harm caused by each accident type, enabling a comprehensive assessment of the overall property-damage impact.

Pigman and Agent (1990) also examined the severity of work-zone accidents in relation to the type of work zone (utility vs. construction), type of accident, vehicle type, and land use. Construction work zones had the most severe accidents, while utility work zones exhibited the least severity, with the difference in traffic speeds among the reasons. Within the work zone, the advance-warning area was identified as the location associated with the most severe accidents. Pedestrian-related accidents were noted as the most severe type, followed by head-on collisions, vehicle-overturning incidents, single-vehicle runoffs, and collisions with fixed objects. Conversely, the most common accident types, such as rear-end and sideswipe collisions, were comparatively less severe, as compared to head-on collisions and vehicle collisions with pedestrians. Accidents involving trucks were more severe than those not involving trucks. Furthermore, accidents occurring at night without adequate lighting were notably more severe than accidents during daylight hours or nighttime with proper roadway lighting. Finally, accidents in rural areas exhibited greater severity, as compared to those in business or residential areas, which was attributed to variation in traffic speed.

Table 1. Variables Influencing Kentucky Work-Zone Accidents and Statewide Accidents (Adapted from Pigman & Agent, 1990)

Variables	Work Zone Accidents (%)	Statewide Accidents (%)
Month		
January	2.3	8.2
February	1.8	7.4
March	4.1	7.4
April	6.1	7.9
May	8.9	8.8
June	12.9	8.2
July	11.8	8
August	14	8.4
September	11	8.1
October	12.6	8.9
November	9.4	8.8
December	5	9.8
Day of Week		
Monday	9.3	10.3
Tuesday	14	14.2
Wednesday	16	13.9
Thursday	16.2	13.8
Friday	15.7	14.2
Saturday	17.1	18.3
Sunday	11.7	15.2
Severity		
Fatal	0.9	0.5
Injury	27.4	21.7
Property Damage Only	71.7	77.8
Land Use		
Rural	54.9	30.1
Business	28.8	41.4
Industrial	1.9	0.9
Residential	13.3	21.6
School	0.7	2.2
Park	0.3	0.4
Private Property	0.2	3.3
Road Characteristics		
Straight, Level	56.3	62.4
Straight, Grade	21.8	17.9
Straight, Hill Crest	2.2	3
Curve, Level	9.9	7.6
Curve, Grade	8.4	8
Curve, Hill Crest	1.3	1.2

Table 2. Factors Contributing to Kentucky Work-Zone Accidents (Pigman & Agent, 1990)

Factor	Percent of Accidents	Severity Index
Congestion	24.0	2.12
Restricted Lane Width	9.3	1.76
Striking or Avoiding Construction Equipment	5.6	1.71
Material such as Gravel or Oil on Roadway	5.4	2.47
Related to Flagger (such as Communication Problem)	5.3	2.23
Vehicle Merging Too Late	5.2	1.64
Uneven Pavement (Including Potholes and Pavement Removal)	3.9	2.58
Vehicle Travelling on Lane Closed to Traffic	2.7	2.19
View Obstructed	2.6	1.74
Pavement Dropoff (Shoulder)	2.6	3.11
Lane Blocked	2.5	1.41
Struck by Construction Vehicle or Equipment	2.2	1.47
Lack of Proper Traffic Control	1. 7	1.74
Ran off Road in Detour	1.5	2.92
No Merge Lane	1.2	2.28
Manhole Cover	0.6	1.62
Water Pooling	0.4	3.61

Raub et al. (2001) analyzed work-zone crash patterns and crash factors from 110 incidents in Illinois. They found that roughly 40% of recorded crashes occurred specifically in the taper and approach sections prior to the work-zone area. Typically, crashes within the work zone involved multiple vehicles; but they were less likely to result in fatal injury. In the approach and taper regions, over 30% of crashes caused injuries and involved two vehicles. Additionally, more than half of all crashes took place when work zones had active workers. Thus, driver distractions from work-zone activities were considered one of the crucial factors in work-zone accidents. Moreover, the crashes outside the work-zone area were primarily caused by a failure to yield to merging traffic and excessive speed. Raub et al. (2001) suggested deployment of enforcement resources in the advance-warning area as one of the measures to mitigate crashes prior to the work-zone area.

Bai and Li (2006) highlighted the primary causes of highway work-zone crashes in Kansas and argued efforts made to reduce work-zone accidents had proven ineffective, as evidenced by the insignificant decline in fatal crash rates nationwide. To address this gap in knowledge, the researchers conducted a comprehensive statistical analysis, examining 157 fatal incidents recorded in the Kansas Department of Transportation (KDOT) database from 1992 to 2004. Table 3 summarizes the most common observations they identified in work zones for Kansas. The study found two high-risk locations: rural two-lane highways with speed limits ranging from 51 to 70 mph and roadways with complex geometric alignments. The researchers also found that multi-vehicle collisions and crashes involving heavy trucks were the most common types of fatal crashes. Driver error was identified as a significant contributing factor, with inattentive driving and misjudgment or disregard of traffic controls being the most prevalent driver errors. The researchers proposed safety-improvement recommendations that could help mitigate fatal crashes: (1) traffic-control enhancements, (2) driver education programs, and (3) improvements to accident-reporting procedures.

Table 3. Most Common Fatal-Crash Observations (Adapted from Bai & Li, 2006)

Variable	Observation	No. of Crash	Percent (%)
Gender	Male	117	75
Age	35–44	38	24
Time (hourly rate)	10:00 a.m.–4:00 p.m.	51	32
Day	Saturday	26	17
Month	June	22	14
Light Condition	Daylight	83	53
Weather Condition	No Adverse Weather	143	91
Surface Condition	Dry	138	88
Vehicle Maneuver	Following Road	116	79
Crash Type	Head-on	37	24
Vehicle Body Type	Truck	53	34
Number of Crash Cars	2	83	53
Road Class	Other Principal Arterial	88	56
Road Character	Straight and Level	80	51
Lane Number	2	99	63
Speed Limit	51–60	74	47
Crash Location	Not at Intersection	105	67
Surface Type	Blacktop	109	69
Road Special Feature	None	134	85
Area Information	Rural	132	84
Traffic Control	None or Inoperative	73	46
Driver Factor	Inattention	83	53

Shehab and Phu (2015) analyzed the accident patterns and their impact on severity of collisions from about ten thousand accident reports in Buena Park, California, from 1999 to 2009. They concluded that 98% of the primary collisions in the work zone are attributable to driver errors and 2% are attributable to the non-driver errors, as presented in Table 4. According to the collision reports, at least four primary factors contribute to more nighttime crashes: driving under the influence (DUI), driving on the wrong side of road, running stop signs, and following another vehicle too closely. Conversely, unsafe speed conditions, including driving at excessive speeds for the given conditions, were a prevalent cause of daytime crashes. Additionally, unsafe lane changes, improper turning maneuvers, and violations of right-of-way rules were also significant factors contributing to collision risk during daylight hours.

Table 4. Primary Collision Factors in Construction Work Zones (Adapted from Shehab & Phu, 2015)

Primary Collision Factor	Daytime Contribution (%)	Nighttime Contribution (%)
Driving under the Influence (DUI)	1	21
Wrong Side of Road	3	4
Ran Red Light/Stop Sign	8	20
Following Too Close	1	4
Unknown	3	6
Unsafe Speed Conditions	32	21
Improper Turning	16	4
Right-of-Way Violations	17	12
Unsafe Lane Change	8	4
Unsafe Starting/Backing	3	0
Other	5	4
Non-driver factor	3	0

By analyzing a total of 453 crash reports from 2008 to 2013 in New Zealand, Sze and Song (2019) conducted an evaluation of the factors influencing injury severity in work-zone crashes. Crash severities occurring in road sections with a temporary reduced-speed limit were significantly influenced by the day of the week; the time of the day; and the involvement of motorcycles, bicycles, and pedestrians.

A study conducted by Gambatese and Jin (2021) discovered that variations in vehicle speed had a significant impact on crash occurrences, with work zones exhibiting greater speed variation, as compared to non-work zones. Consequently, the researchers conducted an evaluation to identify potential strategies for mitigating speed variation within work zones. The proposed interventions included the utilization of a pace car; the implementation of a portable, changeable-message sign (PCMS); the combination of a pace car and PCMS; and the combination of a PCMS and flashing lights on paving equipment in the active work area. The findings revealed that the PCMS intervention proved effective in reducing speed variation, particularly when placed in the advance-warning area and transition area of the work zone. Moreover, the effectiveness of the PCMS intervention was found to be enhanced when combined with other intervention strategies.

The Kansas Department of Transportation (KDOT) recently introduced the Strategic Highway Safety Plan (SHSP) 2020–2024, which has eight areas of attention, such as impaired driving and roadway departures, but does not specifically include work-zone safety. This national initiative is referred to as Vision Zero, which aims to reduce the occurrence of fatal and severe injury collisions on roadways. Mohammed et al. (2023) emphasized that minimizing work-zone crashes is a critical aspect of achieving Vision Zero objectives. He collected collision data from 2016 to 2020 and developed regression models to incorporate 33 variables expected to be correlated with work-zone incidents. The variables statistically significant to work-zone crashes were alcohol involvement, speed limit, vertical curves, number of lanes, speeding, distracted drivers, rural areas, and pedestrian involvement.

The analysis of factors influencing work-zone accidents revealed the significance of both driver errors and non-driver errors in contributing to the occurrence and severity of these incidents. Driver errors, such as alcohol involvement, speeding, distracted driving, and failure to yield right-of-way, play a major role in work-zone accidents. Non-driver errors, such as inadequate signage, improper work-zone design, and lack of proper traffic-control measures, also contribute significantly to these incidents. These findings emphasize strategies that address both driver and non-driver factors to improve work-zone safety.

FATALITIES IN THE WORK ZONE

Work zones pose significant risks to both drivers and workers, leading to severe injuries and numerous fatalities each year. The high-speed nature of roadways, combined with changing traffic patterns and construction activities, creates a potentially hazardous environment that demands careful attention and precautionary measures. Identifying the factors that contribute to fatalities in work zones is crucial for developing effective strategies to enhance safety and prevent such tragic incidents. This section aims to provide an overview of the factors and challenges associated with work-zone fatalities and approaches needed to protect the lives of both road users and construction personnel.

Figure 2 represents the fatal work-zone crashes from all of the states, and including the District of Columbia and Puerto Rico, from ARTBA (2022). The work-zone fatal crashes have climbed continuously over the previous decade. ARTBA (2022) found that around 80% of work-zone fatalities involve a driver or passenger of a vehicle. Figure 3 indicates that the number of fatalities has increased from 600 in 2012 to nearly 1,000 in 2021, with approximately 2% of all fatal crashes occurring in work zones. During the same period, the estimated injuries in work zones have risen from 31,000 to 42,000, which translates to 112 injuries per day in work-zone areas. Rural areas were found to be more susceptible than urban areas to fatal crashes in work zones. As presented in Figure 4, fatal crashes in work zones, particularly on rural roadways, are attributed to rear-end collisions, driver distraction, and involvement of commercial vehicles. These factors contribute significantly to a higher percentage of fatal crashes in work-zone areas, as compared to non-work-zone areas. In fact, ARTBA highlighted that commercial trucks and buses with a gross weight of more than 10,000 lb were responsible for more than half of all fatal work-zone crashes that took place on rural interstates highways. Finally, the Bureau of Labor Statistics reported almost half of the highway-worker fatalities were struck by a vehicle while working on foot; and one-third of fatalities involved workers who were driving or riding in a motor vehicle.

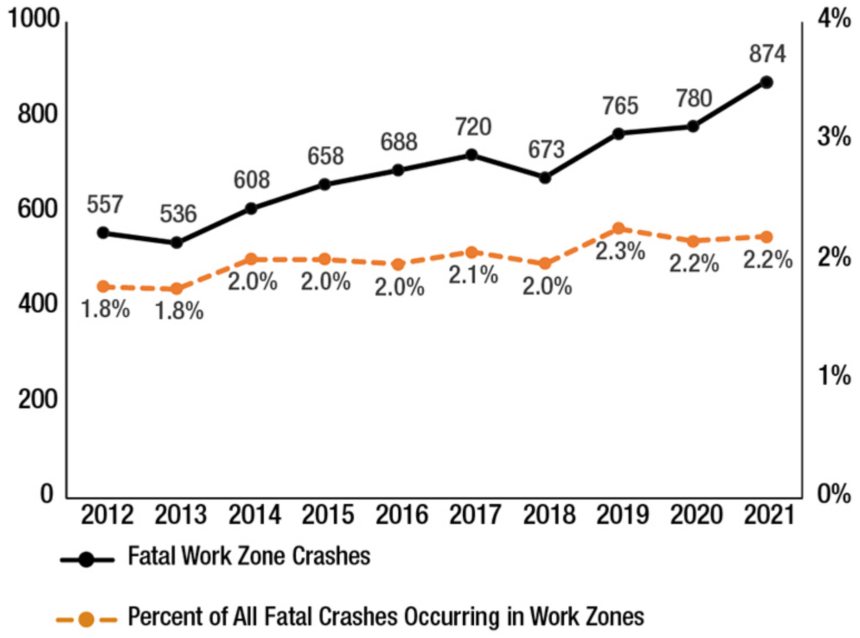


Figure 2. Graph. Work-zone fatal crashes in the United States from 2012 to 2021.

Source: ARTBA, 2022

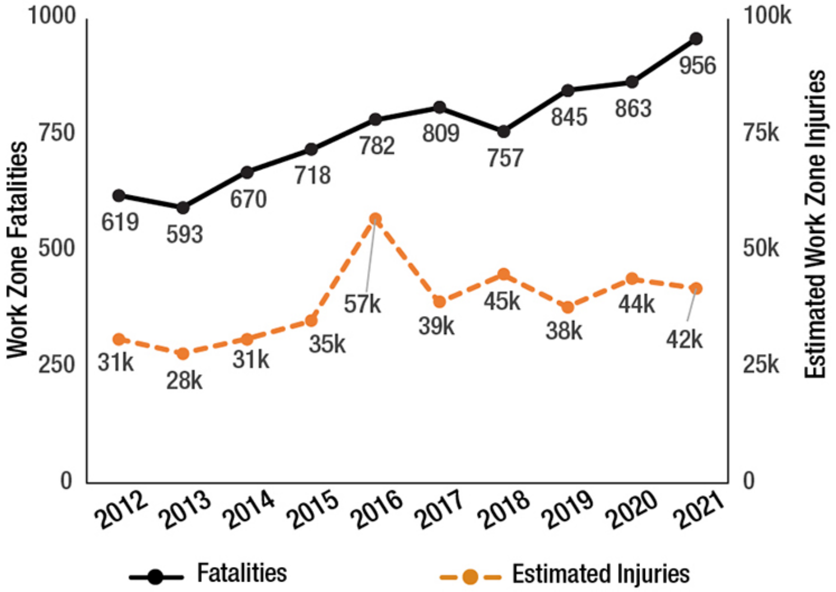
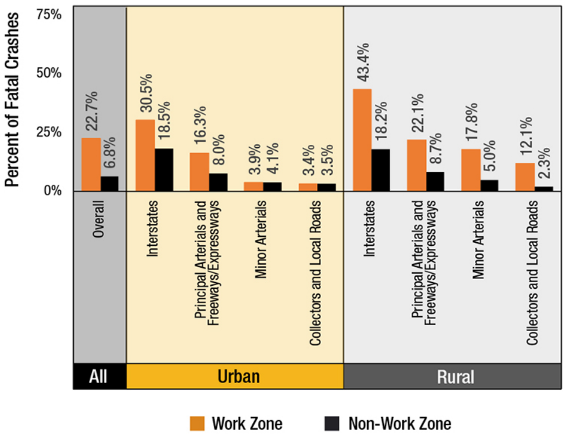
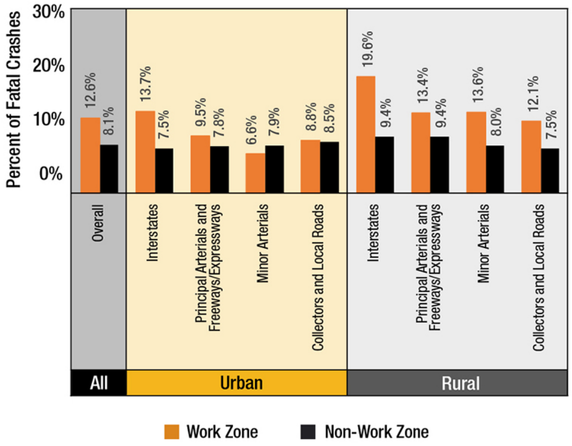


Figure 3. Graph. Work-zone fatalities and estimated injuries in the United States from 2012 to 2021.

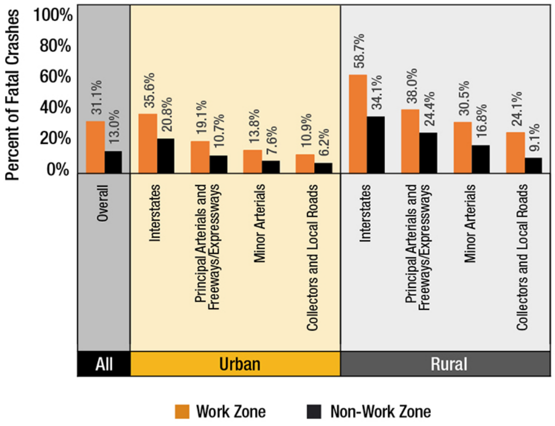
Source: ARTBA, 2022



A. Rear-end, fatal-collision involvement in work zone and non-work zone.



B. Driver-distraction involvement in work zone and non-work zone.



C. Commercial vehicle involvement in work zone and non-work zone.

Figure 4. Three graphs. Major involvements in work-zone and non-work-zone fatal crashes from 2019 to 2021.

Source: ARTBA, 2022

SMART-WORK-ZONE SYSTEMS

Smart-work-zone (SWZ) systems are specifically designed to provide real-time and accurate information to motorists, ensuring they are well-informed about road conditions. These systems encompass various components, including variable-message signs, queue-warning systems, dynamic lane-merge systems, speed-feedback signs (El-Rayes et al., forthcoming). By utilizing these technologies, SWZ systems enable drivers to receive timely updates regarding traffic flow, lane closures, detours, and potential hazards, thereby improving their awareness and enhancing overall safety for both drivers and road workers. The ability to access instantaneous and precise updates empowers drivers to plan their routes more effectively, consider alternative paths when necessary, and adapt to changing conditions within work zones. This approach not only reduces congestion but also contributes to smoother traffic management, minimal user delays, and increased driver awareness of the upcoming hazards. With their potential to optimize work-zone operations and improve the overall transportation experience, SWZ systems serve as a crucial tool in enhancing road safety.

Significant efforts have been made over the years to improve work-zone safety for drivers and construction workers, while minimizing the risks associated with construction and maintenance activities on roadways. Typical work-zone measures are the use of traffic signages, such as warning and speed limit signs, which visually alert drivers about impending work zones. Portable rumble strips have been widely employed to provide audible and vibratory warnings to drivers to promote driver attentiveness as they enter the work zone. Typically, these strips are 12-ft long, 4-in. wide, and 1/8-in. thick, and colored orange for visibility. The rumble strips are attached to the pavement surface in a six-strip configuration, spaced 18 in. apart, as presented in Figure 5. The introduction of speed displays with radar detection encourages drivers to follow construction-zone speed limits (Fontaine & Carlson, 2001). Speed displays consist of a 24-in. LED display and a Ka-band radar detector, as presented in Figure 6. These displays monitor oncoming vehicles and initiate a flashing strobe lamp or a 130-dB siren when a vehicle exceeds the speed limit. Other technologies such as light detection and ranging (LiDAR) and smart-work-zone systems, e.g., intelligent transportation systems, have emerged as tools for improving work-zone safety through real-time monitoring, data analysis, and dynamic traffic management.

Fontaine and Carlson (2001) evaluated the effectiveness of speed displays and rumble strips in rural maintenance work zones, as compared to the temporary work-zone signages such as “Road Work Ahead” and “Left Lane Closed Ahead” signs. Rumble strips were found to have a greater impact on trucks than cars, leading to a speed reduction of approximately 3 to 4 mph for trucks within the work zone area. The speed reduction in passenger vehicles was less significant. Speed displays were shown to generate speed reductions of 2 to 9 mph in passenger vehicles and 7 to 10 mph in trucks. The presence of speed displays also resulted in a reduction in the percentage of vehicles speeding in the advance-warning area. In general, the specific location of the speed display within the work-zone area influenced the magnitude of speed reductions observed at various sites. Although speed displays have a relatively short installation time of under 10 minutes, the high initial cost of these devices may limit their widespread application. Rumble-strip installations can take up to 40 minutes to install but cost less.

Figure 5. Photo. Rumble strips in work zone.

Source: Fontaine & Carlson, 2001

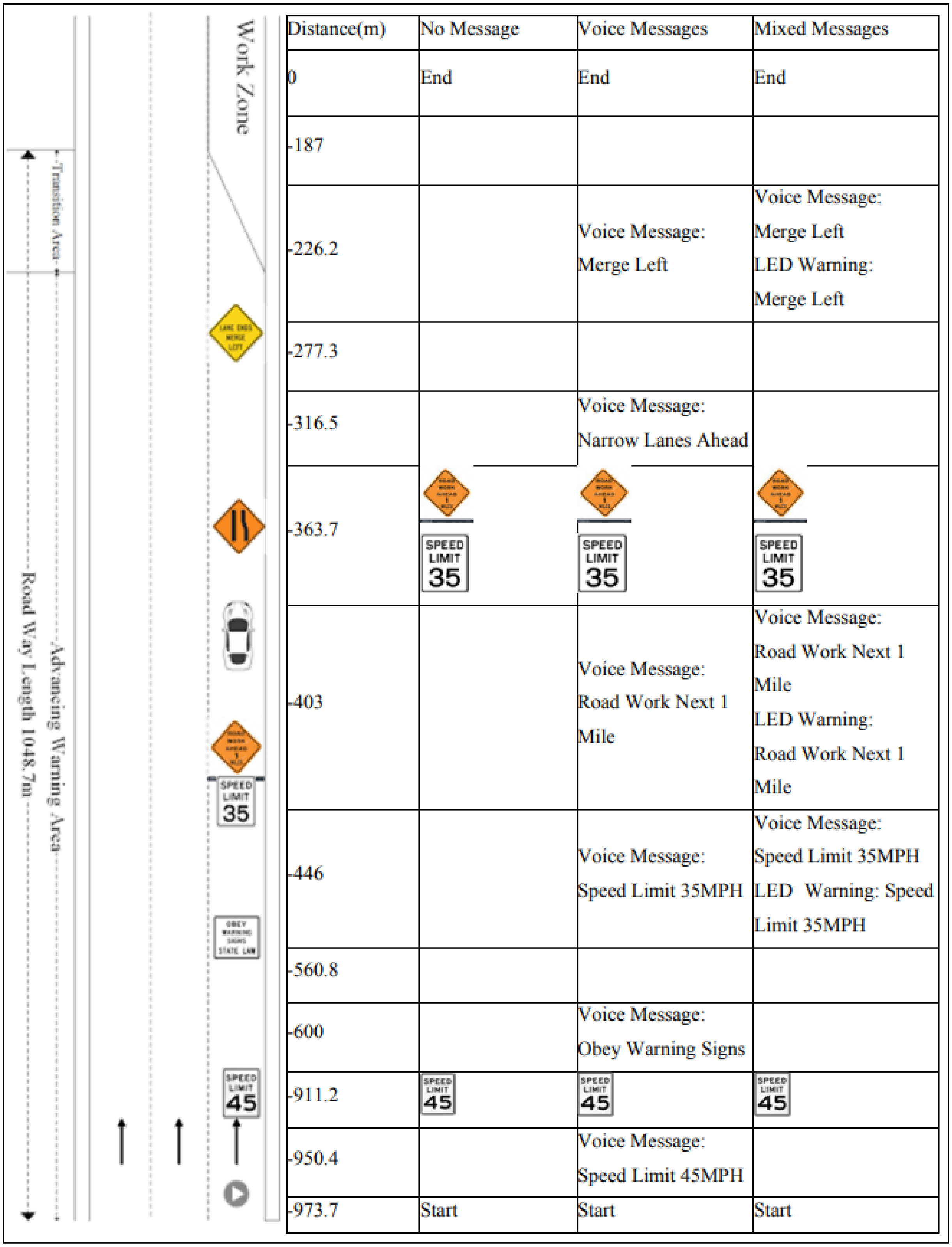
Figure 6. Photo. Speed displays in work zone.

Source: FHWA, 2017

Driver inattention has been one of the most common factors that cause fatal accidents in work zones, and this limits the impact of speed displays and rumble strips. One alternative to external speed displays or rumble strips is an in-vehicle warning-message system. This candidate solution is able to warn the drivers directly in both an audio and visual form inside the vehicle, which may significantly increase driver attentiveness to work-zone warnings.

Craig et al. (2017) conducted a study on the effectiveness of the in-vehicle warning-system messages through smartphones. The simulated-driving study assessed drivers' performance in two different work-zone scenarios: (1) shoulder-work route and (2) lane-closure route. Participants performed three drives through these work zones, each time encountering different hazardous events and using different messaging interfaces to communicate these events. The messaging interfaces included a roadside, portable, changeable-message sign (PCMS); a smartphone providing auditory messages only; and a smartphone displaying audiovisual messages. The work-zone events simulated during the drives encompassed common scenarios such as traffic slowdowns, lane closures, presence of heavy machinery, and workers ahead. The in-vehicle-messaging smartphone was positioned either on the dashboard or in the passenger seat. Driving performance and subjective measures such as event recall, mental workload, user-friendliness, and eye-tracking metrics were evaluated throughout the experiments. The analysis of the driving-simulation study data revealed that both in-vehicle message conditions outperformed the roadside signs in terms of key driving metrics such as speed deviation between work-zone vehicles and the standard deviation in lane changing. Additionally, drivers reported experiencing significantly lower mental workload, better usability, and higher recall of work-zone events when using the in-vehicle messaging systems, as compared to the roadside-sign condition. The eye-tracking data showed that drivers were less likely to divert their gaze from the road when using the in-vehicle messaging systems, as they had to look away from the road to read the messages displayed on the roadside signs. The positive effects of in-vehicle messaging appeared to be more pronounced in the more challenging lane-closure route, suggesting that in-vehicle messages were particularly beneficial in demanding roadway conditions.

Another simulation study by Li et al. (2018) examined the effectiveness of an in-vehicle-messages warning system in the advance-warning area of a work zone. The study used three simulated scenarios, as depicted in Figure 7. The first scenario served as the reference condition, simulating the absence of an in-vehicle warning system. In the second scenario, an audio in-vehicle warning system was incorporated. The third scenario involved the combination of both audio and visual in-vehicle warning systems. The velocity profiles of the three scenarios are depicted in Figure 8 as a function of position in the advance-warning area. The first stage encompassed the area preceding the deceleration point, ranging from the starting point to -492 m. During this stage, a voice message was introduced, suggesting a speed limit of 45 mph or 72 km/h. Consequently, it is evident that the second and third scenarios exhibited lower speeds, as compared to the first scenario. As the vehicles progressed into stage 2, drivers across all scenarios received a warning for a speed limit of 35 mph or 56 km/h. Notably, drivers in the second scenario demonstrated a prompt response in reducing vehicle speed, as compared to drivers in the third and first scenarios, respectively. Moving into stage 3, which commenced 166 m before the transition area, drivers in scenarios two and three maintained a relatively lower and consistent speed after hearing or seeing the warning messages. Conversely, drivers in scenario one were more inclined to approach the transition area at speeds exceeding 35 mph.



Distance(m)	No Message	Voice Messages	Mixed Messages
0	End	End	End
-187			
-226.2		Voice Message: Merge Left	Voice Message: Merge Left LED Warning: Merge Left
-277.3			
-316.5		Voice Message: Narrow Lanes Ahead	
-363.7	ROAD WORK AHEAD 1 MILE SPEED LIMIT 35	ROAD WORK AHEAD 1 MILE SPEED LIMIT 35	ROAD WORK AHEAD 1 MILE SPEED LIMIT 35
-403		Voice Message: Road Work Next 1 Mile	Voice Message: Road Work Next 1 Mile LED Warning: Road Work Next 1 Mile
-446		Voice Message: Speed Limit 35MPH	Voice Message: Speed Limit 35MPH LED Warning: Speed Limit 35MPH
-560.8			
-600		Voice Message: Obey Warning Signs	
-911.2	SPEED LIMIT 45	SPEED LIMIT 45	SPEED LIMIT 45
-950.4		Voice Message: Speed Limit 45MPH	
-973.7	Start	Start	Start

Figure 7. Chart. Simulated scenarios for the in-vehicle-warning system assessment.

Source: Li et al., 2018

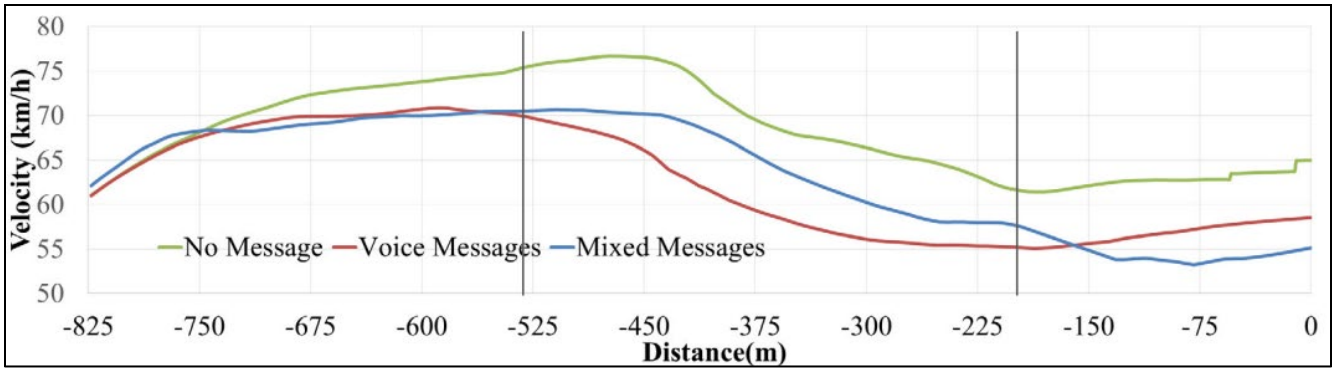


Figure 8. Graph. Speed profiles of simulated scenarios for the in-vehicle warning-system assessment.

Source: Li et al., 2018

Figure 9 provides the interpretation of lane-changing positions for the three scenarios. Participants for the mixed-message scenario demonstrated lane changes at more concentrated positions (less deviation from the mean), indicating the effectiveness of combining auditory and visual cues. In contrast, the no-voice scenario exhibited greater variability in lane-changing positions, as presented in Figure 9 with some drivers failing to merge before the end of the transition area. This study's findings highlighted the importance of incorporating both in-vehicle auditory and visual alerts, especially in work zones, to improve lane-changing behavior and to a degree reduce vehicle speed.

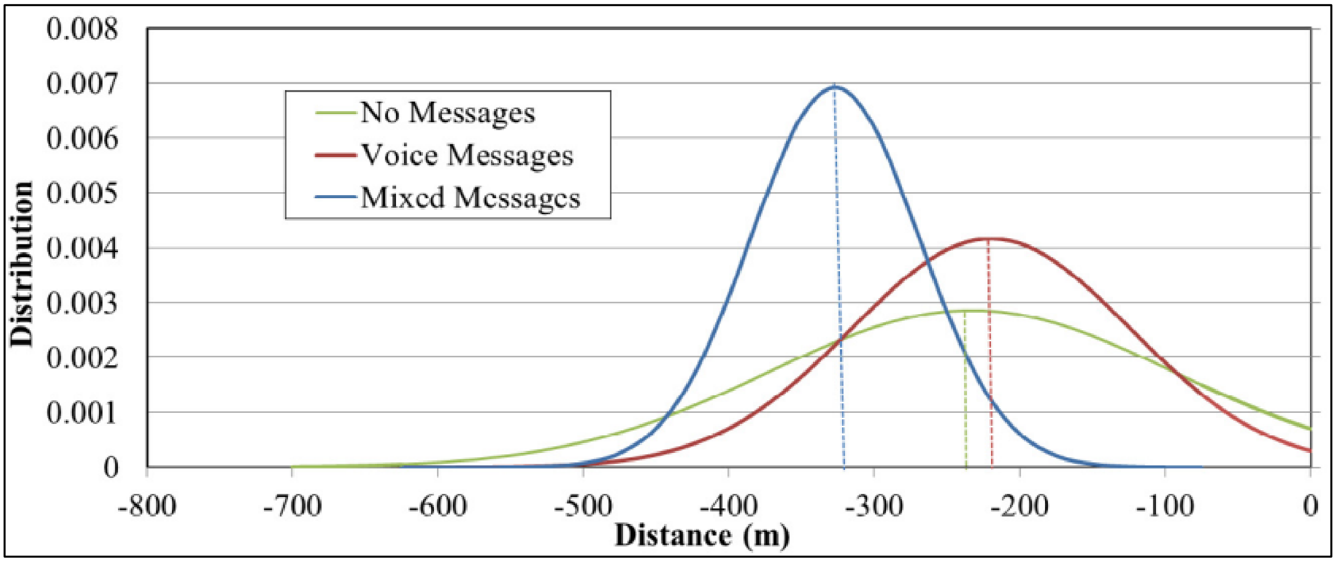


Figure 9. Graph. Distribution of lane-changing position of simulated scenarios for the in-vehicle warning-system assessment.

Source: Li et al., 2018

The exploration of the effectiveness and potential benefits of dynamic lane-merge systems, speed-feedback sign systems, and hazard-intrusion warning systems is essential for the development of future SWZ systems. Dynamic lane-merge systems provide real-time information and guidance to drivers approaching lane closures with technology similar to variable message signs (VMS) and sensors. These systems promote efficient and orderly merging by dynamically adjusting the merging process based on real-time traffic conditions. By reducing congestion and improving traffic management, dynamic lane-merge systems result in greater traffic flow, reduced travel times, and enhanced overall safety within work zones. Figure 10 presents a sample layout for right-lane closure with dynamic lane merge from MnDOT. The activation and deactivation of the “Stopped or Slow Traffic Ahead” sign on the portable, changeable-message signs (PCMS) can be automated. When the downstream sensor detects an average traffic speed drop of 20 to 25 mph below the posted speed limit, the “Slow Traffic Ahead” sign is automatically activated. Conversely, when the average speed recovers and reaches within 10 mph of the posted speed limit or higher, the warning sign is deactivated automatically.

Speed-feedback signs are placed in work zones to display a driver's current speed and provide feedback on whether it exceeds the posted speed limit. These signs encourage motorists to maintain appropriate speeds and comply with posted speed limits. Figure 11 illustrates the MnDOT work-zone layout incorporating speed-feedback signs. There has been a growing interest and motivation in the development of SWZ that can effectively predict and warn construction workers about potential vehicle-intrusion threats. The implementation of LiDAR systems is a viable option for real-time detection and tracking of intruding vehicles within work zones. LiDAR systems offer improved accuracy and provide workers with greater lead times to take necessary safety precautions (Darwesh et al., 2021).

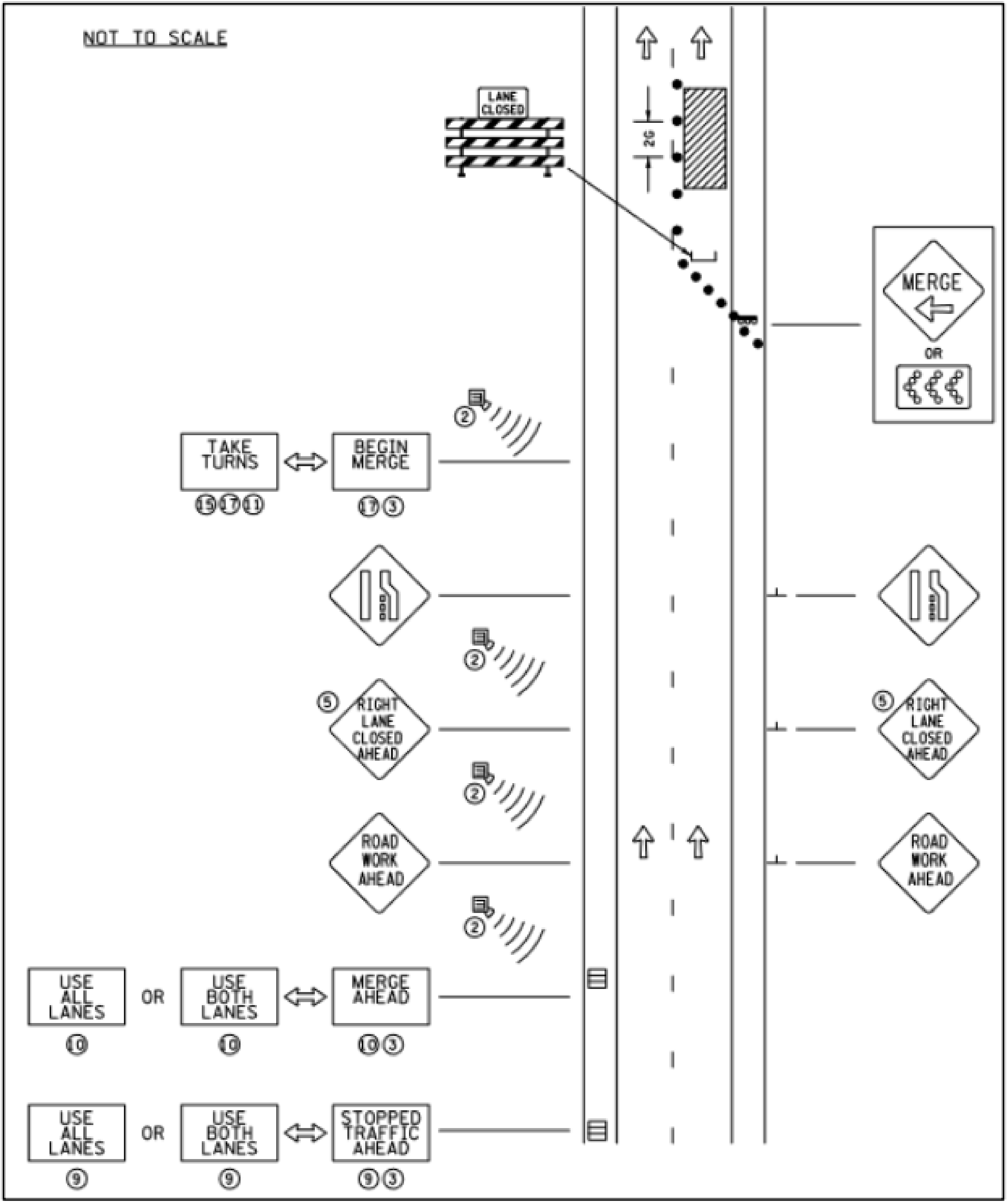
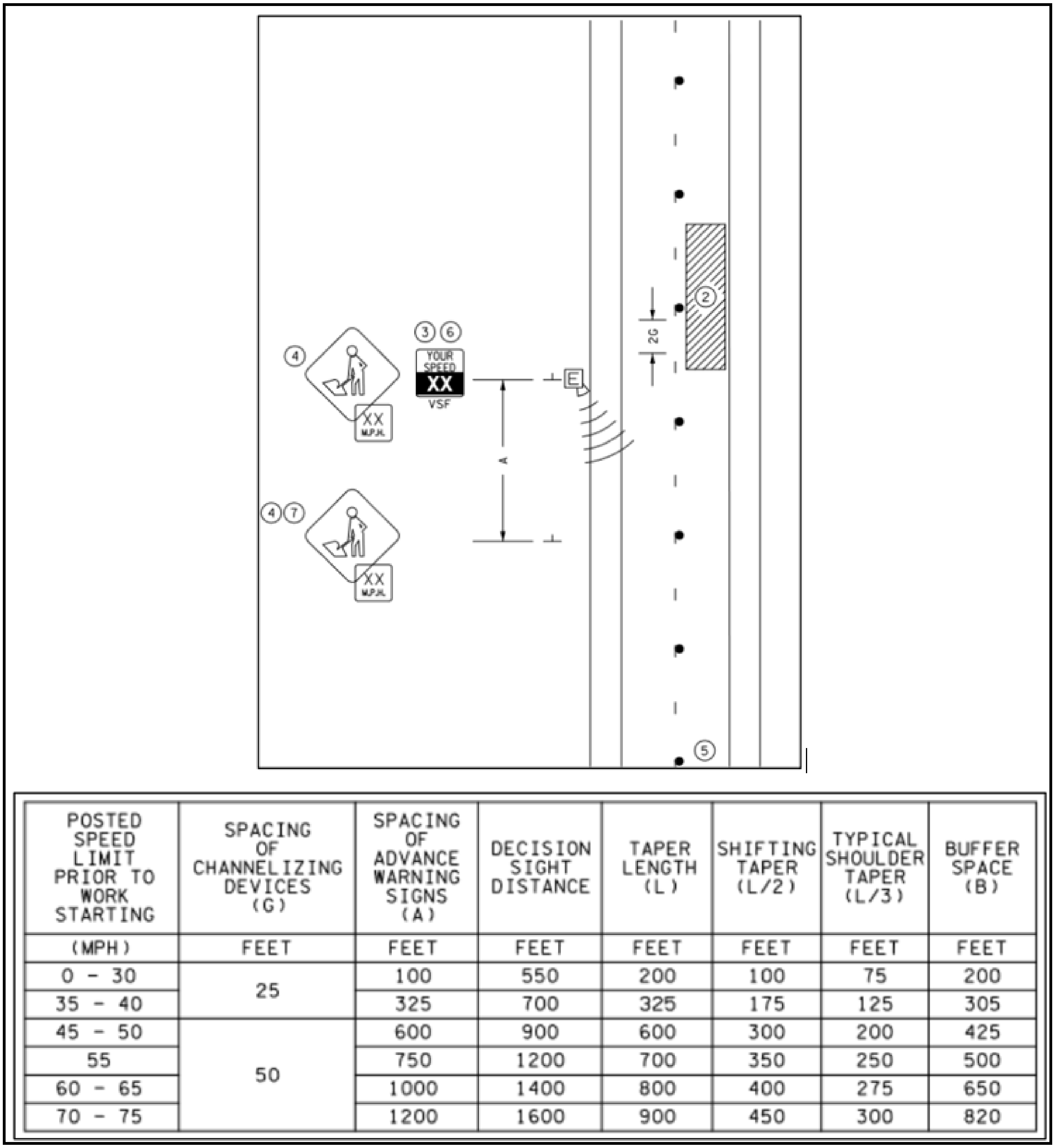


Figure 10. Diagram. Example applications of dynamic lane-merge systems (right-lane closure) recommended by MnDOT.

Source: MnDOT, 2022



POSTED SPEED LIMIT PRIOR TO WORK STARTING	SPACING OF CHANNELIZING DEVICES (G)	SPACING OF ADVANCE WARNING SIGNS (A)	DECISION SIGHT DISTANCE	TAPER LENGTH (L)	SHIFTING TAPER (L/2)	TYPICAL SHOULDER TAPER (L/3)	BUFFER SPACE (B)
(MPH)	FEET	FEET	FEET	FEET	FEET	FEET	FEET
0 - 30	25	100	550	200	100	75	200
35 - 40		325	700	325	175	125	305
45 - 50	50	600	900	600	300	200	425
55		750	1200	700	350	250	500
60 - 65		1000	1400	800	400	275	650
70 - 75		1200	1600	900	450	300	820

Figure 11. Diagram. MnDOT's right-lane-closure layout recommendation on work-zone speed-feedback systems.

Source: MnDOT, 2022

A recent review by El-Rayes et al. (forthcoming) examined the standardization and deployment of SWZ by analyzing current practices, the latest research studies on SWZ, and implementation across different types of roadway projects. Additionally, the researchers gathered feedback from 22 state DOTs about their experiences using SWZ systems. To assess the impact of SWZ systems on reducing the frequency and severity of roadway crashes, the state DOT respondents provided survey feedback. As presented in Figure 12, the average impact of each SWZ system in reducing crash severity and frequency was assessed by assigning a numerical value from 1 to 5, with 1 indicating a negative impact and 5 indicating a very positive impact. One item missing in the SWZ is use of in-vehicle messaging, which has shown promising safety improvements above and beyond current SWZ technologies.

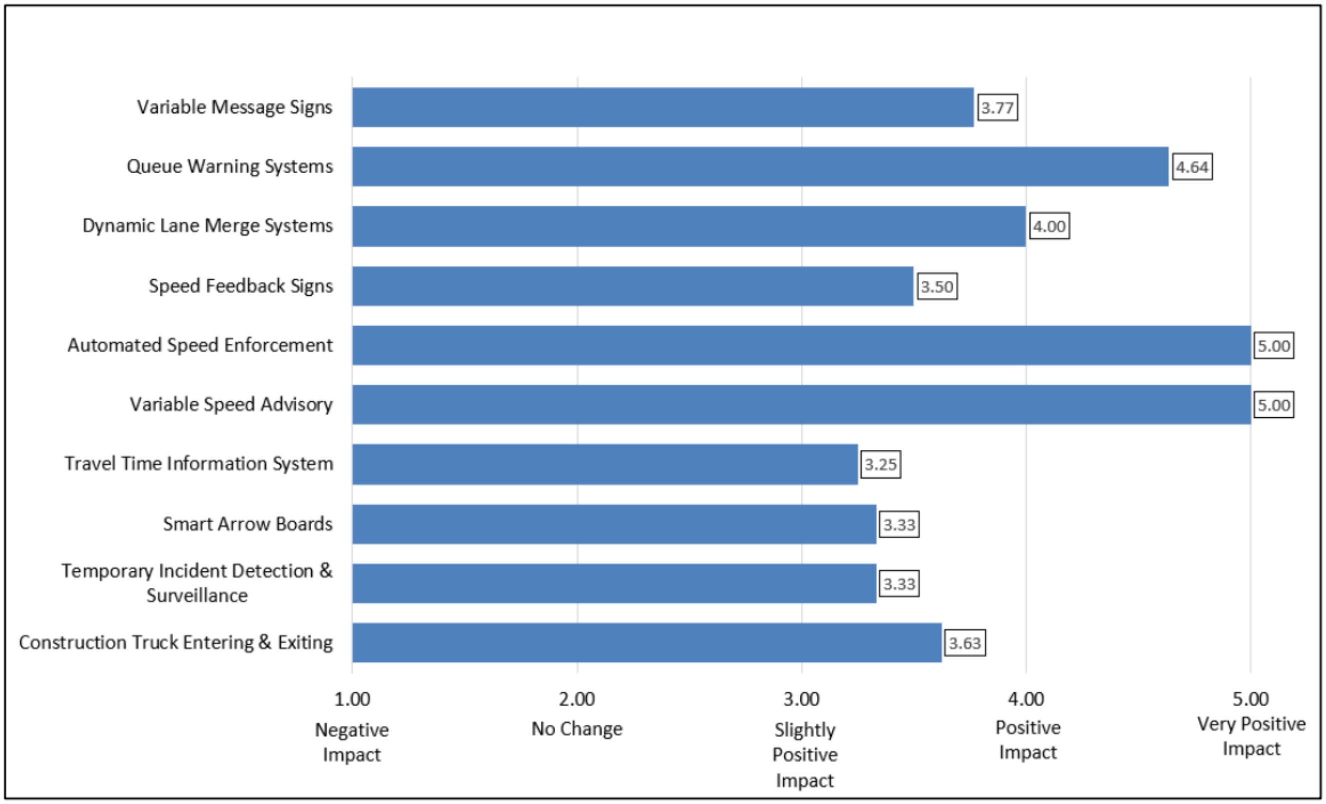


Figure 12. Chart. Average impact of SWZ systems on mitigating crash severity and frequency.

Source: El-Rayes et al., forthcoming

CHAPTER 3: PAVEMENT-ASSISTED PASSIVE SENSING

Advancements continue in vehicle technology, particularly advanced driver-assisted systems (ADAS) and autonomous vehicles (AV), which is focused on improving driver/passenger safety. Research also continues to broaden vehicle technology to V2V and V2I communication to improve roadway safety. Camera-based, lane-departure warning systems in vehicles have significantly increased, with a growth of 30% in the United States between 2013 and 2018 (Wang, 2019). The effectiveness of these systems is limited under adverse weather conditions, as highlighted by Dahal (2022). The National Highway Traffic Safety Administration (NHSTA) reported that a majority of fatal crashes occurring in adverse weather conditions was attributed to the failure of lane departures (NHSTA, 2021). To address the issue of vehicle lane departure, a pavement-assisted, passive-sensing system that enables V2I communication has been developed by Dahal and Roesler (2022). This passive sensing approach modifies the electromagnetic properties of the roadway to create a unique, detectable signature, enabling passive V2I communication and overcoming the challenges faced by camera-based lane-departure warning systems in severe weather conditions.

The pavement-assisted, passive-sensing technology proposed by Roesler and Dahal (2021) creates a continuous electromagnetic (EM) signature, as presented in Figure 13. The lateral position of the vehicle in the lane is tracked by the array of magnetometers, as presented in Figure 14. The EM-signature system outperformed conventional camera-based ADAS systems in vehicle lateral positioning under severe weather conditions. Experimental results in Figure 15 acquired with less than 1 in. of snow on the lane demonstrated that the camera-based ADAS had a significant increase in lateral-positioning error (4.1 in.), whereas the EM-based system maintained a relatively low error (1.2 in.). When the lane had over 2 in. of snow, the camera system failed to perceive lane markings, while the magnetometer exhibited an overall error of 1.8 in., similar to normal weather and visibility conditions. These field findings demonstrate the reliability of the proposed EM method to determine accurately the vehicle's lateral position in the lane, even in adverse weather conditions.

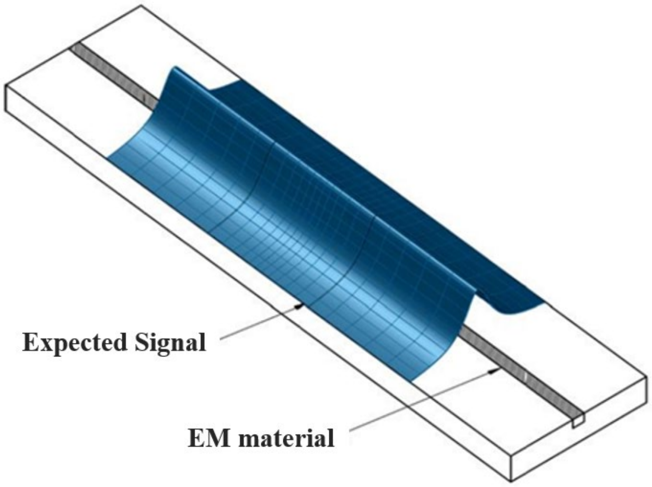


Figure 13. Diagram. Electromagnetic signature generated by embedding EM material.

Source: Dahal, 2022

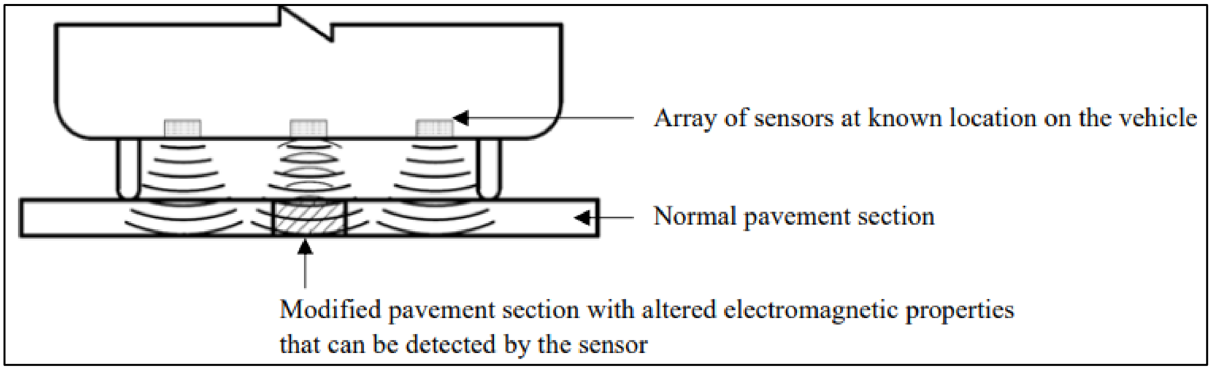
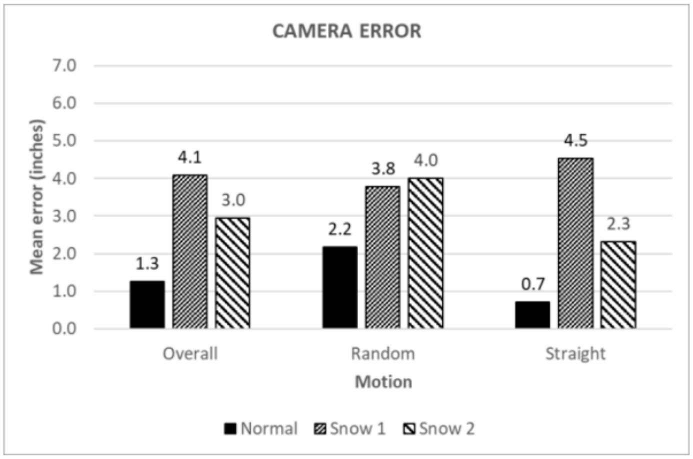
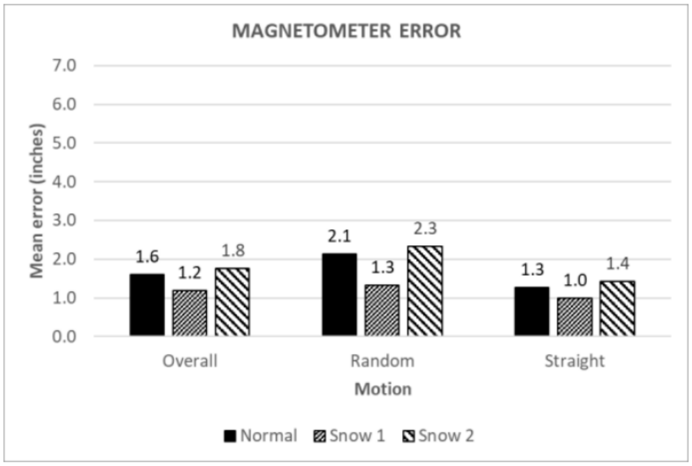


Figure 14. Diagram. Representation of EM signatures captured by array of EM sensors.

Source: Dahal, 2022



A. Vehicle lateral-position error for camera-based ADAS



B. Vehicle lateral-position error for EM-based, passive-sensing system

Figure 15. Two charts. Vehicle lateral position error under different weather conditions.

Source: Dahal, 2022

CAPABILITIES OF PAVEMENT-ASSISTED PASSIVE SENSING IN WORK-ZONE AREAS

Based on conversations with DOT safety engineers and the desire to enhance the safety of workers and drivers on roadway construction sites, the use of designable electromagnetic pavement signatures was explored to provide a temporary in-pavement passive sensor that enables in-vehicle communication (audio and visual cue) to the driver. According to the Chapter 2 literature, unsafe speeds and a failure to enter a merge at the appropriate time are major causes of work-zone accidents, injuries, and fatalities. Pavement-embedded electromagnetic signatures have the potential to warn drivers about upcoming work-zone areas, particularly through the implementation of in-vehicle speed and lane-merge warning systems. These in-vehicle warning systems have a distinct advantage over existing warning systems such as posting roadside message signs, especially in adverse weather conditions. In-vehicle communication can directly warn drivers through vehicle dashboard displays and audio messaging. With these alerts, drivers can receive real-time information about approaching work zones, which enables them to adjust their speed and safely merge into the appropriate lane. The integration of pavement-assisted passive sensing into existing work-zone safety measures will ensure drivers are well-informed and prepared for approaching maneuvers. V2I communication with passive pavement sensing in work zones should lead to fewer accidents, injuries, and fatalities and also improve traffic flow.

THEORETICAL OPTIONS FOR SENSING IN WORK ZONES

Multiple options for passive pavement sensing in work zones can be configured due to the ease with which EM signatures can be created in various positions and patterns. The first option explored with the EM signature is to enable vehicles to be warned of their speed without any external signage, i.e., vehicle-detected and in-vehicle audiovisual warning. The second option for SWZ is application of passive EM-pavement sensing to provide an in-vehicle, lane-merge warning system.

Figures 16 and 17 are a SWZ schematic and process for the in-vehicle speed-warning system, which utilizes EM strips uniformly spaced (X distance), perpendicular to the direction of travel. The electronic control unit (ECU) of the vehicle serves as the main processing unit and activates the system when the EM sensors detect EM roadway signatures above the minimum response threshold. The time interval between the EM peak responses, as presented in Figures 16 and 17 are compared to a predefined, universal period of time constant between the strips (ΔTlimit). By varying the EM strips' spacing (X) as a function of the work-zone speed limit (Vs), the measured time between strips is compared to the universal time constant, as presented in Figure 17. Subsequently, the vehicle system can alert the driver through the vehicle dashboard when the driver exceeds the enforced speed limit.

Figures 18 and 19 present the schematic and process for the in-vehicle lane-merge warning system with the passive EM pavement sensors. Similar to the speed-warning system, the ECU serves as the main processing unit and activates this system when all EM sensors detect EM responses above the minimum threshold. The in-vehicle lane-merge warning system utilizes different EM signatures, as compared to the in-vehicle speed-warning system. The EM strips in the lane-merge system are oriented diagonally to the direction of the vehicle movement versus perpendicularly. The passive sensors for the in-vehicle speed-warning system and the in-vehicle lane-merge warning system function alongside each other. As illustrated in Figures 18 and 19, the in-vehicle lane-merge warning system can provide merging directions on the vehicle's dashboard through calculations involving the absolute time at the peak when all sensors have triggered by exceeding threshold EM intensity.

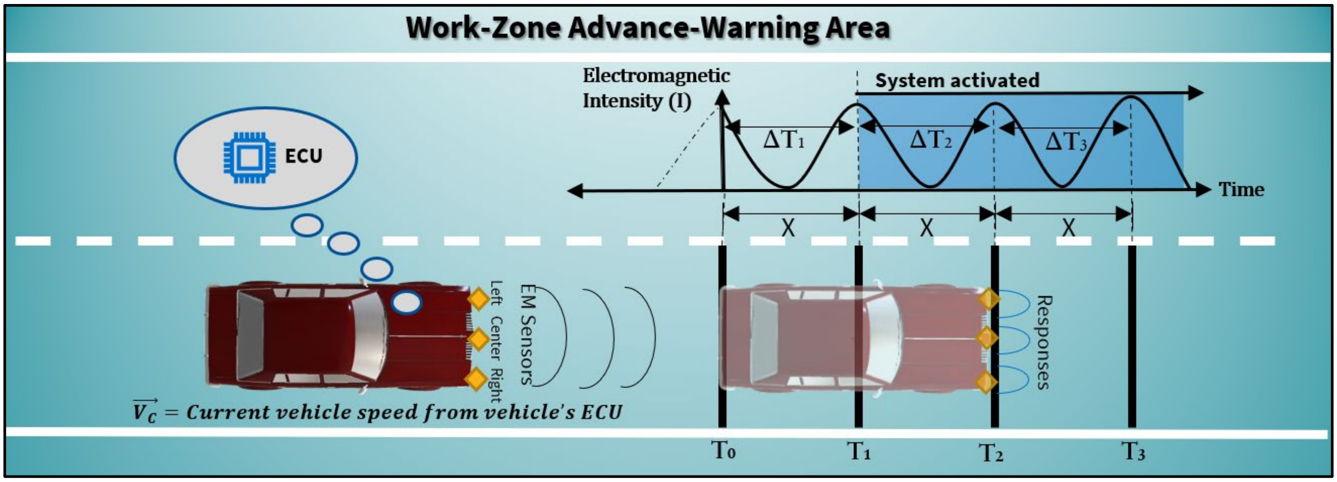


Figure 16. Diagram. Schematic of the proposed in-vehicle speed-warning system for smart construction work zones.

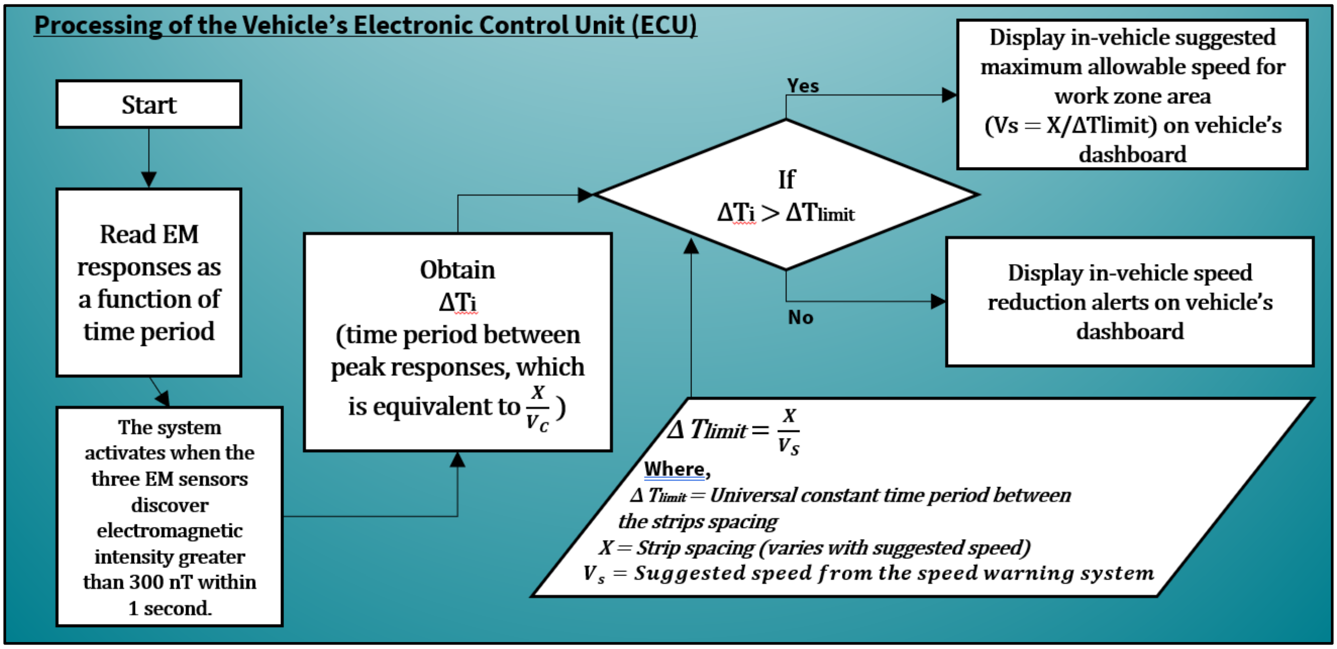


Figure 17. Diagram. Flowchart of the proposed in-vehicle speed-warning system for smart construction work zones.

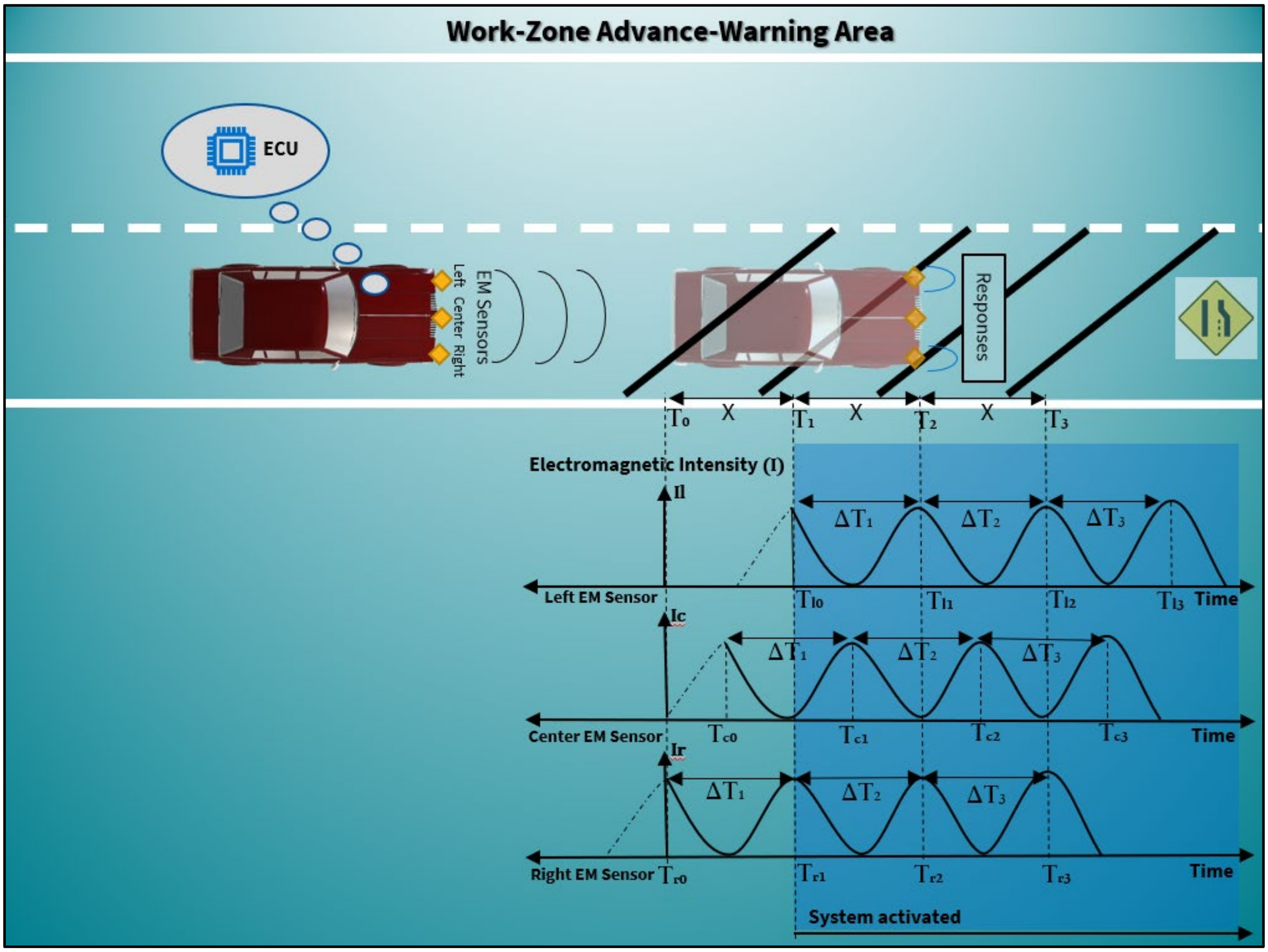


Figure 18. Diagram. Schematic of the proposed lane-merge warning system for smart construction work zone.

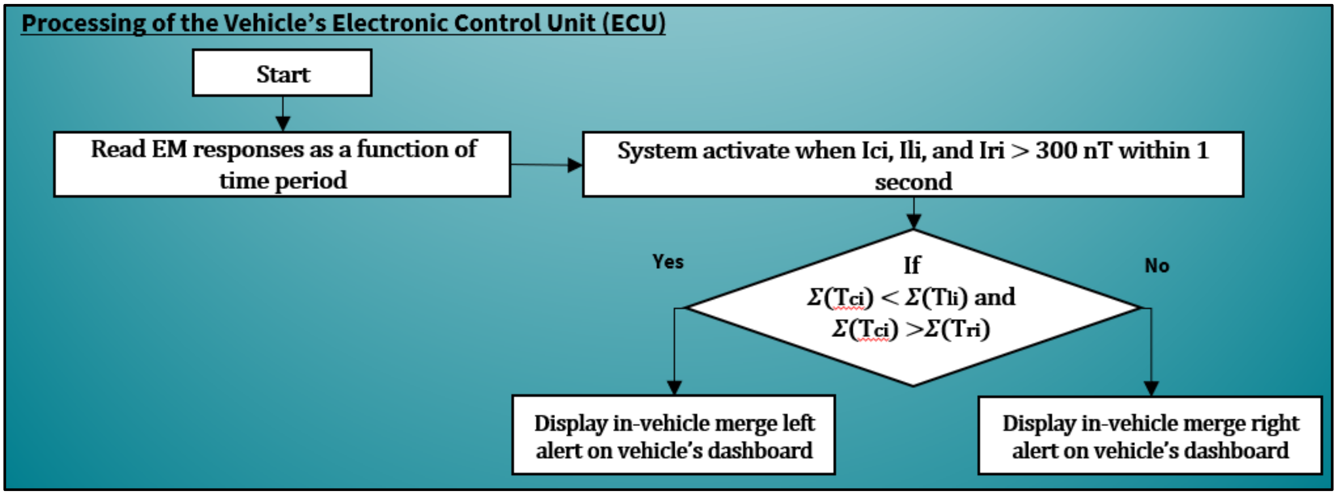


Figure 19. Diagram. Flowchart of the proposed lane-merge warning system for smart construction work zone.

EXPERIMENTAL SETUP FOR PASSIVE EM-SENSING SIGNATURES

To optimize the strip configurations for the proposed in-vehicle speed and lane-merge warning systems in work zones, an experimental design in the laboratory was tested. The objective of the lab testing was to verify the theoretical SWZ configurations with EM-based strips and to determine the suitable spacings and inclination angles for the EM strips for the speed and lane-merge warning systems, respectively. The experiment involved varying the strip spacings and inclination angles, while assessing the impact on the EM intensity at the magnetometer and the calculated times between EM peaks.

Sensing-Strip Configurations

The experimental setup schematic for the EM-strip configuration for both longitudinal spacing and inclination-angle variations is presented in Figure 20. The reference number of each magnetometer sensor is listed in Figure 21. The corresponding testing factorials are summarized in Table 5. The example of the experimental setup when the sensing strips were placed perpendicularly to the sensor arrays is presented in Figure 22, the setup with diagonal placement of the sensing strips in Figure 20. The setups in Figures 22 and 23 provide visual representations of the configurations used during experimentation.

As presented in Table 5, the spacing (X) of the electromagnetic (EM) strips for the speed-warning system varied from 1 to 2 ft. During this variation, the inclination angle (α) of the strips was fixed, i.e., the strips were oriented 45°, 60°, 90°, and 120° from the longitudinal direction. By exploring different strip spacings within this range, the performance of the speed-warning system with the EM-based sensor system can be assessed, and the optimal spacing that enhances the system's effectiveness in speed warnings to drivers can be determined. Likewise, the inclination angles of the EM strips for the lane-merge warning system were varied between 60° and 120° while keeping the strip spacing fixed. This procedure allowed for determining the optimal inclination angle to provide accurate lane-merge warnings to drivers.

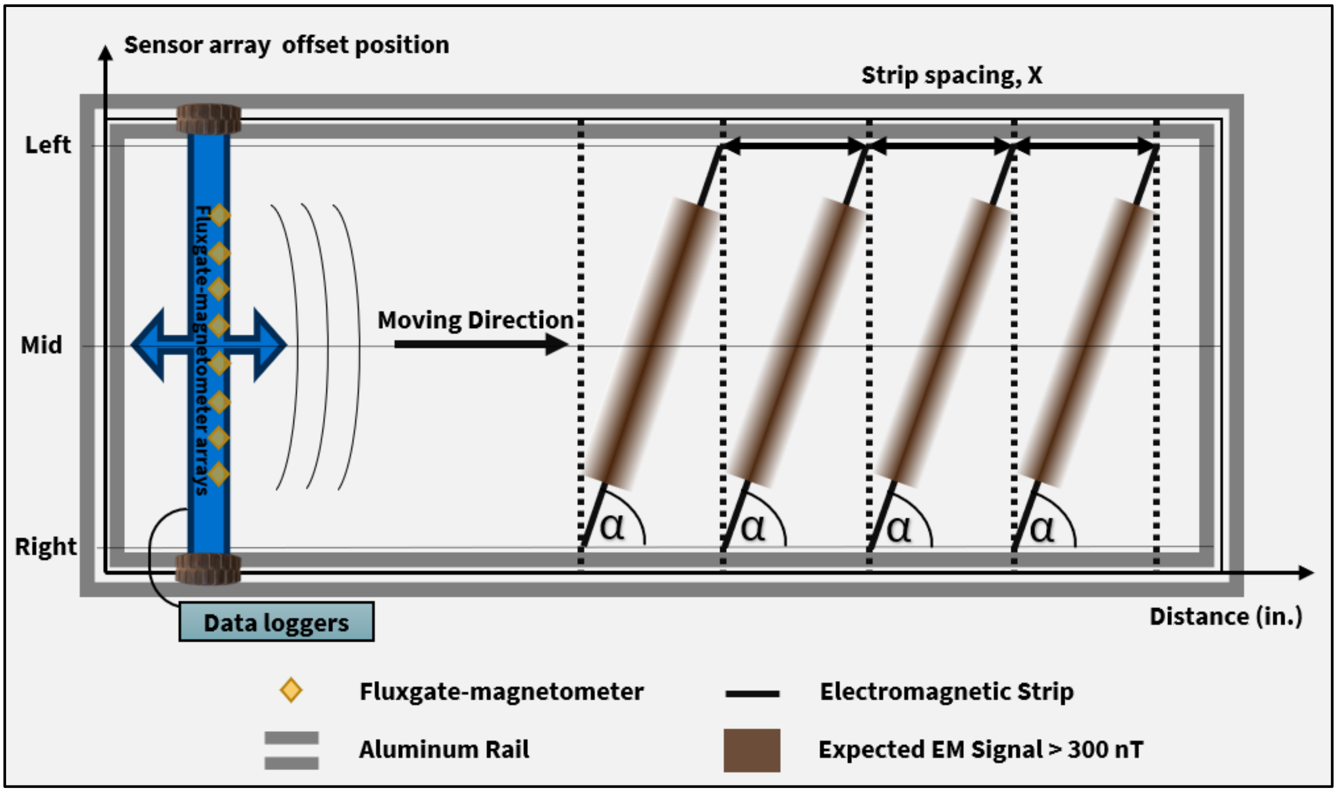


Figure 20. Diagram. Schematic of experimental setup for EM passive-sensing warning system for construction SWZ.

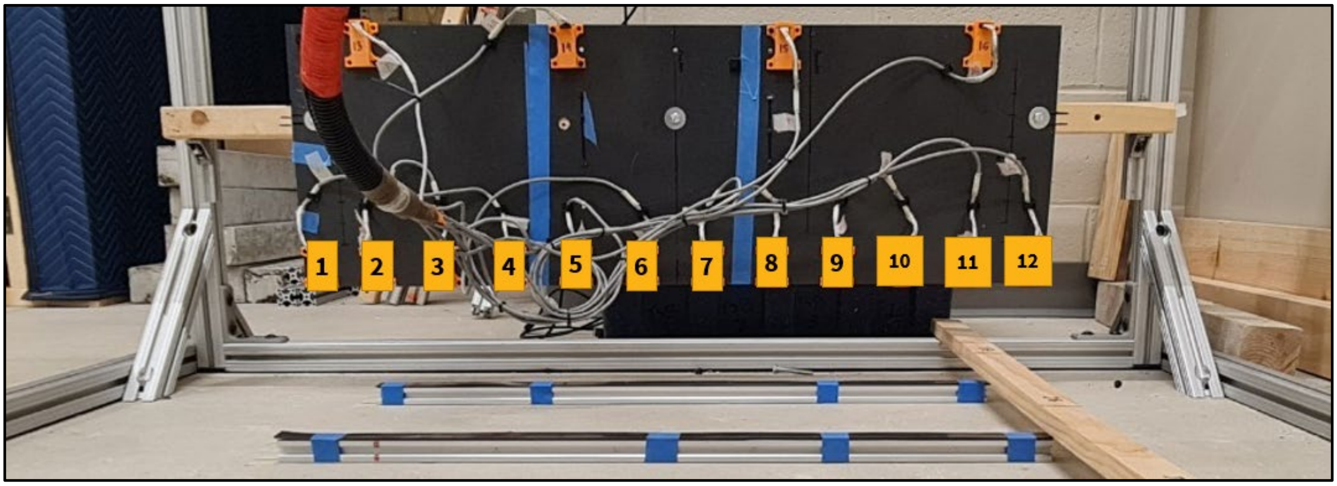


Figure 21. Photo. Reference numbers for the magnetometer sensor arrays.

Table 5. Testing Factorial and Scenarios for EM Passive Sensing for SWZ Warning System.

Test Scenario No.	EM-Strip Spacing (X), ft	Inclination Angle (α), Degrees
1	1.0	90
2	2.0	90
3	1.0	45
4	2.0	45
5	1.0	60
6	2.0	60
7	2.0	120
8	2.0	60 and 90

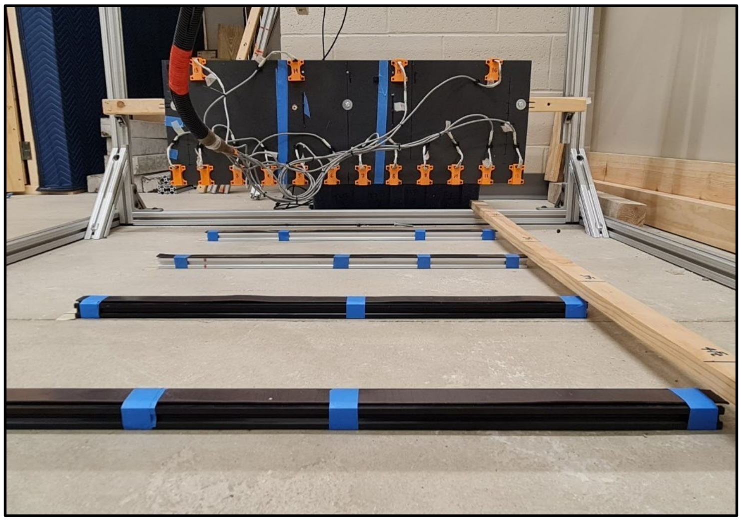


Figure 22. Photo. Experimental setup for EM-sensing strips placed perpendicularly to sensor arrays.

Figure 23. Photo. Experimental setup for EM-sensing strips placed at an angle to sensor arrays.

Experimental Results

The experimental results for the lab testing are presented in Figures 24 to 31. The normalized EM signatures, after eliminating background noise, exhibited similar trends to the theoretical diagrams presented from Figures 16 to 19. The clarity of the EM signals was influenced by the longitudinal strip spacing. The sensing signatures for the 2-ft spacing (Figure 25) demonstrated superior clarity, as compared to the sensing signatures of the 1-ft spacing (Figure 24). As the EM-sensor spacings were reduced, the electromagnetic field affected the next strip. As presented in Figure 25, the two EM-sensor strips can be clearly identified. The experimental results also showed that the passive-sensing signatures could be used to estimate the moving speed of each "vehicle." For example, in Figure 25, the "vehicle" or magnetometer sensor array is moving at 0.32 mph (mean 2 ft / (12.24–8.02) seconds).

In the testing of the inclined strips at 45° and 60°, as presented in Figures 26 to 29, the experimental results exhibited the expected responses from each magnetometer. The sensor arrays successfully captured the EM-signal peak responses at different time steps in the correct order, aligning with the theoretical diagram illustrated in Figures 18 and 19. Figures 26 and 28 had some interference between consecutive EM-sensor strips, and thus a sensor spacing of 1 ft is too close for any speed. Based on the 2-ft sensor spacing and 45° and 60° inclination, the "vehicle" speed is 0.31 mph and 0.24 mph for the 45° and 60° inclination, respectively (Figures 29 and 31).

The performance of the system was examined by inclining the sensing strip to 120°. The output of the sensors, as presented in Figure 30, exhibited trends similar to +60° but with sensors ordered in the opposite rank. The calculated speed for the 120°was 0.35 mph. The responses were also tested for when the placement patterns of the sensing strips were mixed. In this test configuration, the first strip was inclined at 60°; and the second strip was placed 2ft away from the right boundary of the first strip, perpendicular to the moving direction of the sensor arrays. The experimental results are presented in Figure 31. This finding highlights the robustness and adaptability of the system, indicating its effectiveness in detecting and interpreting EM signals regardless of the specific arrangement of the sensing strips, and this small lab trial has shown that EM sensors can be used to detect vehicle speeds and to communicate maneuvers such as merge right or left with in-vehicle messaging.

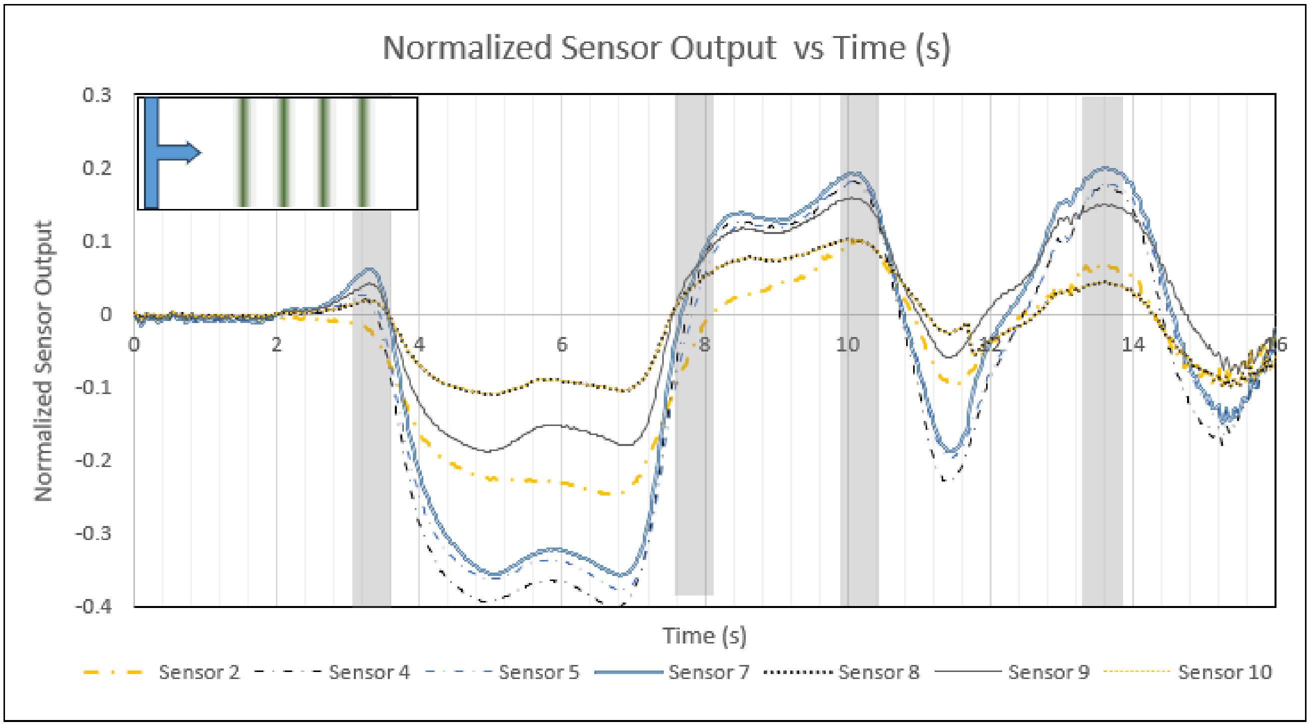


Figure 24. Graph. EM passive-sensing response placed perpendicular to traveling direction for 1-ft strip spacing. EM sensor placed at shaded areas.

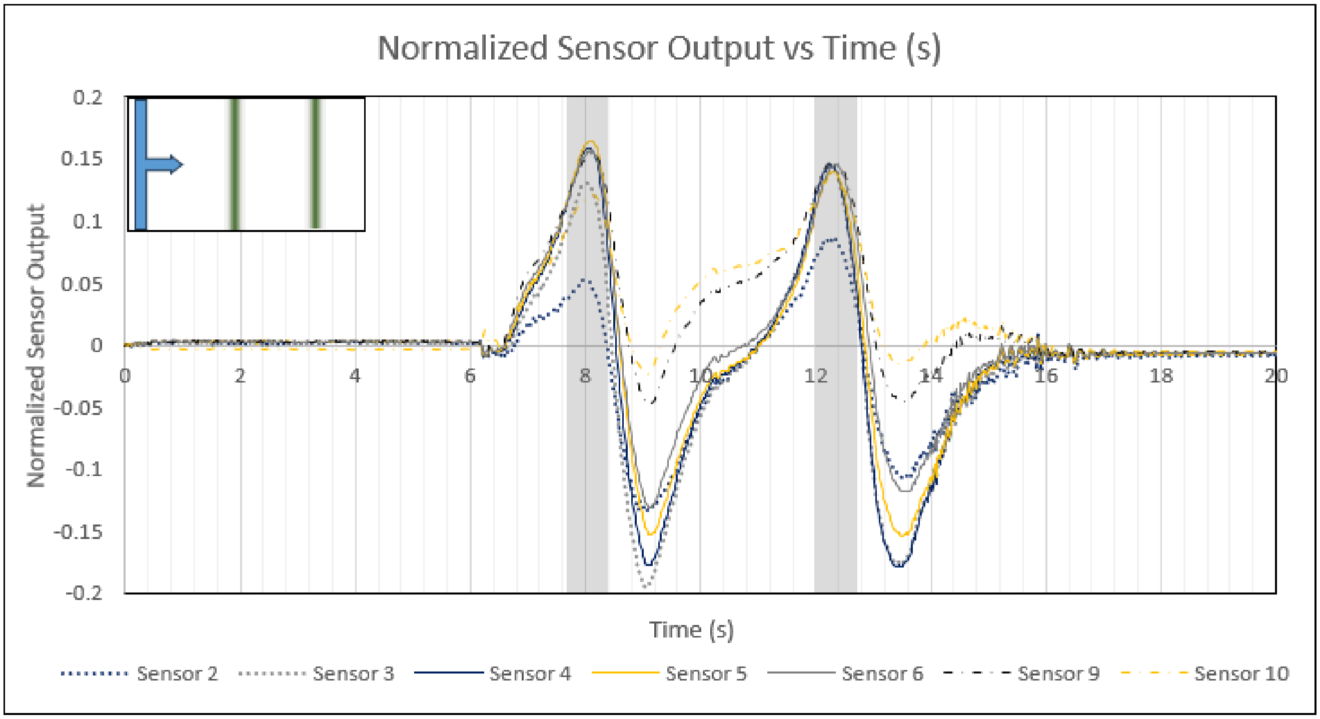


Figure 25. Graph. EM passive-sensing response placed perpendicular to traveling direction for 2-ft strip spacing. EM sensor placed at shaded areas.

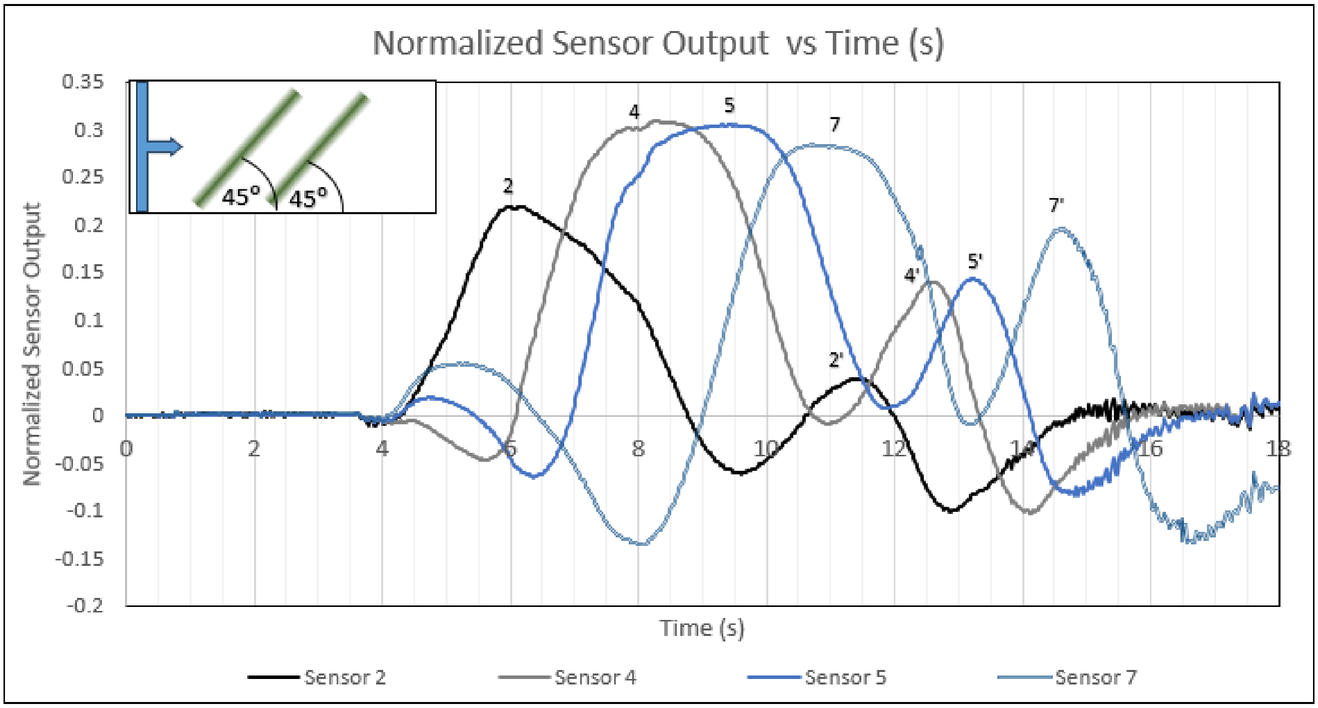


Figure 26. Graph. EM passive-sensing response placed at 45° angle to traveling direction for 1-ft strip spacing.

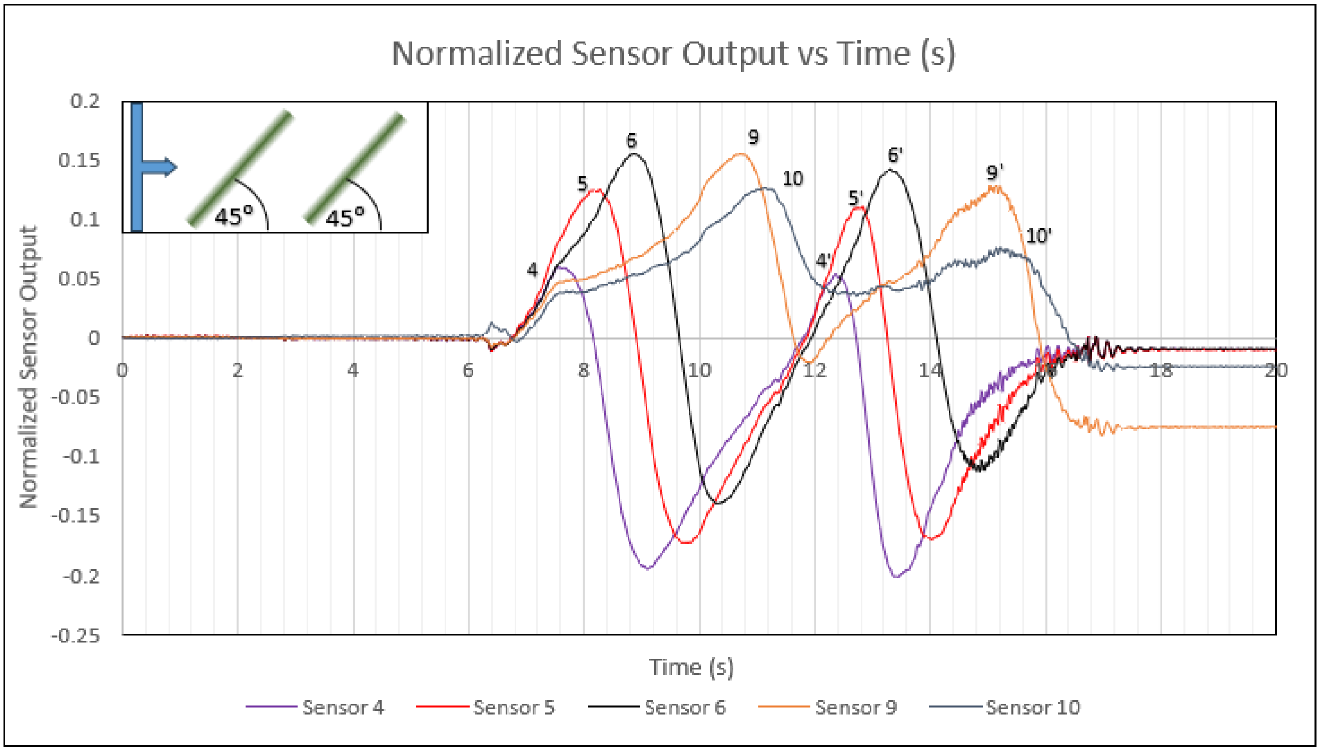


Figure 27. Graph. EM passive-sensing response placed at 45° angle to traveling direction for 2-ft strip spacing.

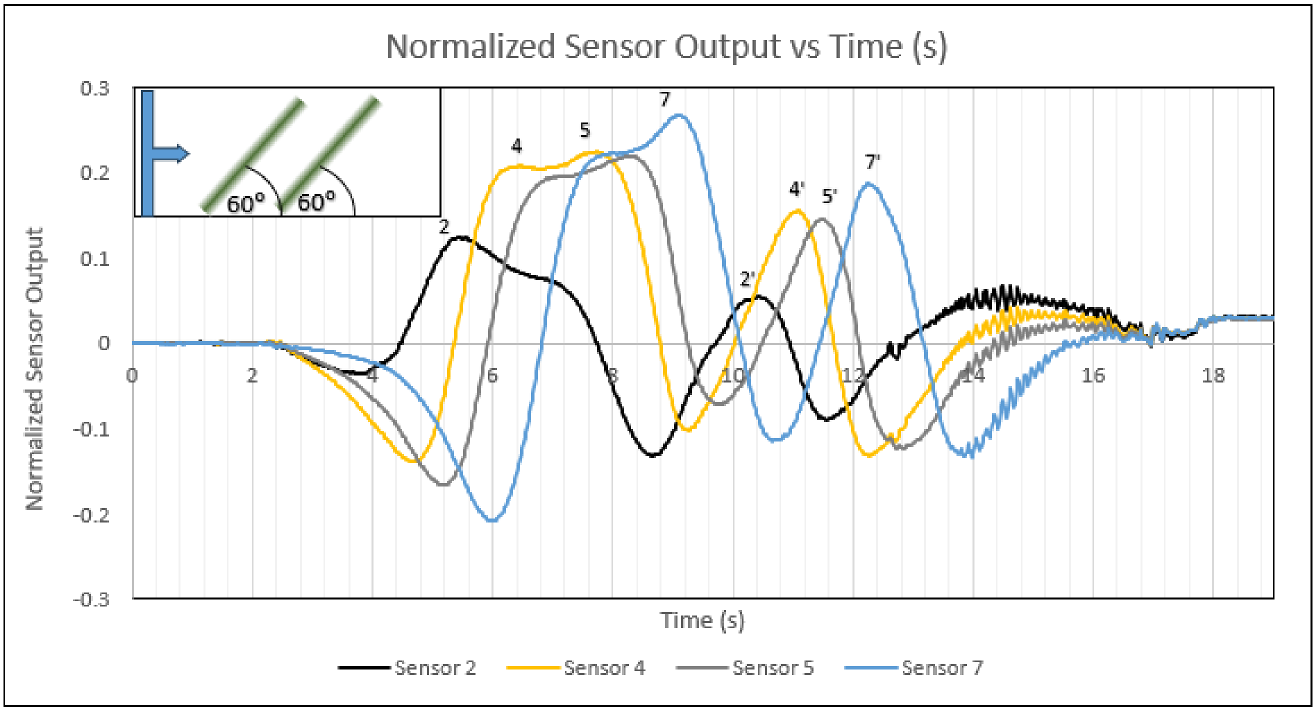


Figure 28. Graph. EM passive-sensing response placed at 60° angle to traveling direction for 1-ft strip spacing.

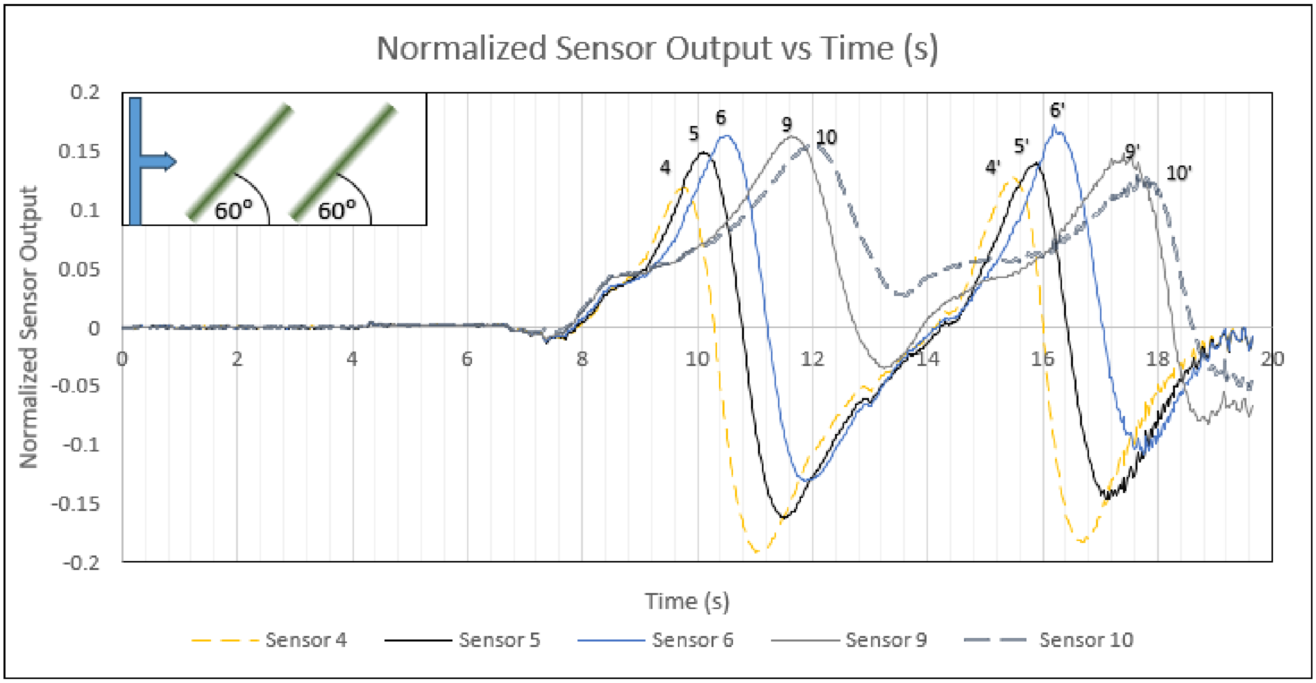


Figure 29. Graph. EM passive-sensing response placed at 60° angle to traveling direction for 2-ft strip spacing.

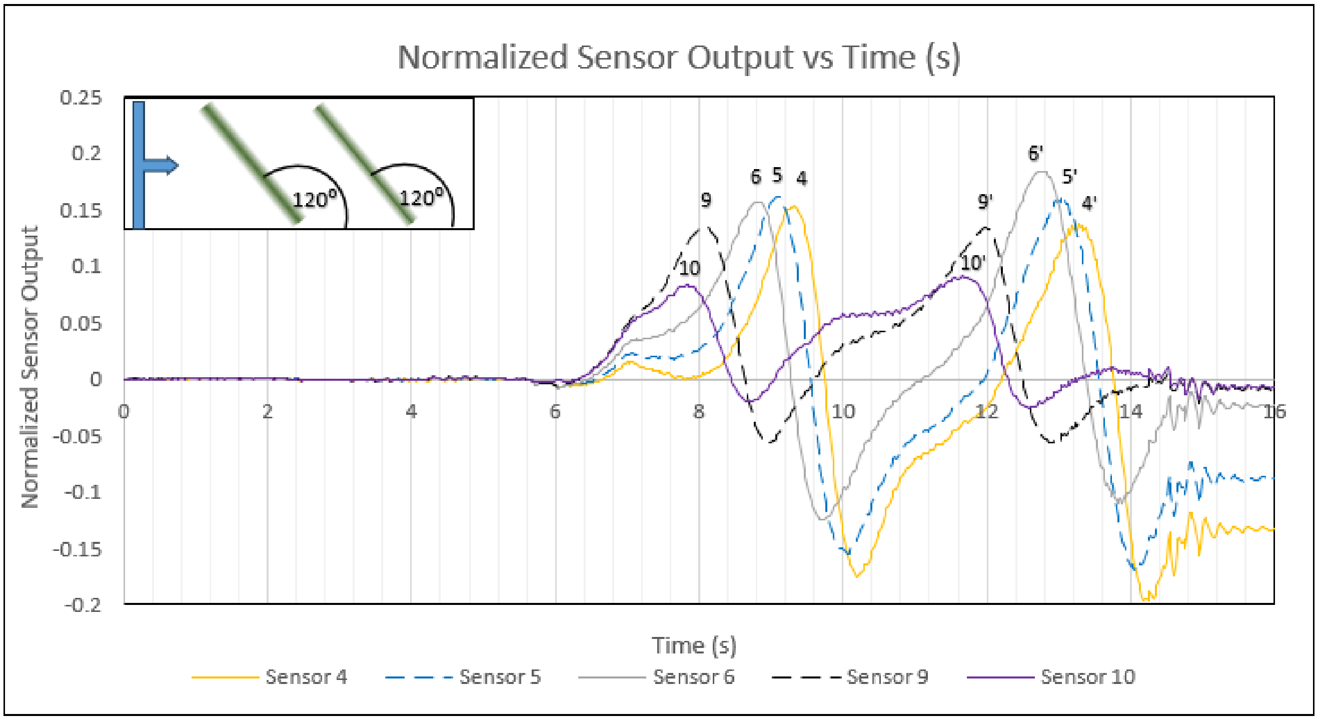


Figure 30. Graph. EM passive-sensing response placed at 120° angle to traveling direction for 2-ft strip spacing.

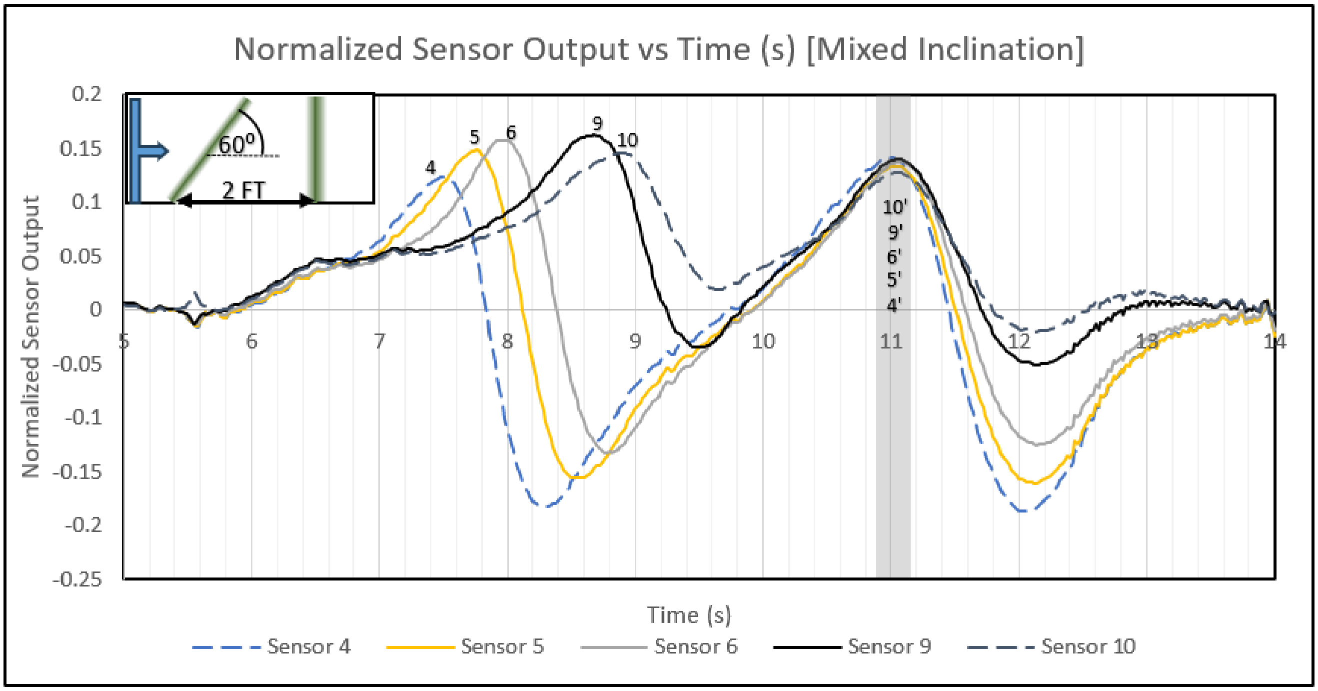


Figure 31. Chart. EM passive-sensing response placed at 60° angle to traveling direction and the perpendicular EM-sensor strip.

CHAPTER 4: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The purpose of this research was to evaluate whether pavement-assisted, passive-sensing technology could offer improvements to construction work-zone safety for roadways. The project's research activities incorporated a review of work-zone safety studies, including collisions, fatalities, and smart work zones (SWZ). Additionally, an experimental plan was developed and executed to test a pavement-assisted sensing system for integration into in-vehicle speed and lane-merge warning systems for roadway construction work zones.

Past studies found accidents, injuries, and fatalities in work-zone areas were influenced by factors such as unsafe speed conditions, improper lane changes, and driver distractions. The implementation of SWZ communication systems in vehicles has shown promising results in reducing traffic speeds and facilitating smoother merging in work-zone transition areas. Pavement-assisted passive sensing with electromagnetic (EM) materials, which enables V2I communication, offers the potential to deliver advanced in-vehicle speed and lane-merge warnings, enhance driver awareness, reduce vehicle speeds, and ultimately improve safety within construction work zones.

Eight test scenarios were conducted in the laboratory to incorporate variations in EM strip spacings and inclination angles. The outcome of the study showed the passive pavement-sensing system could be detected repeatable at a minimum strip spacing, e.g., 2 ft for slower speeds. Additionally, as the EM passive material strips were inclined to the direction of travel, the setup was able to determine repeatedly if the vehicle should perform a left- or right-merge maneuver. The successful lab pilot study showed that it is possible to use V2I passive-sensing technology to determine and communicate speed inside the vehicle and provide a lane-merge warning in the construction-zone transition areas.

Future research efforts should focus on the exploration of suitable and pavement-compatible EM materials that can be embedded, coated, or made programmable. Additionally, a comprehensive, full-scale test should be conducted, utilizing vehicles equipped with EM-sensor arrays, to evaluate the effectiveness of pavement-assisted passive sensing over a wide range of speeds, strip spacings. and inclination angles. The ultimate goal is to develop an in-vehicle visual or audio warning system that can efficiently detect and interpret the EM passive-sensing system in the pavement.

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