Towards Smart Work Zones: Creating Safe and Efficient Work Zones in the Technology Era

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Abstract
Introduction: Work Zones (WZs) have long been identified as a source of traffic fatalities and delays. Despite considerable technological advances that have alleviated many operational challenges associated with a WZ, social concerns about safety and mobility near WZs remain. Notably, the concept of a Smart Work Zone (SWZ) emerged from the compelling need to improve the safety and mobility of traffic and other WZ participants. This study reviewed the literature to assimilate studies related to SWZ Systems (SWZSs), report their findings, and ascertain a future path forward.
Method: To accomplish this, the existing WZ-related literature base was clustered into safety and traffic mobility topics using Latent Dirichlet Allocation (LDA) modeling. A thorough investigation of the pivotal inferences for the research topics was undertaken to comprehend current SWZ technologies and the need for further research.
Results: The review uncovered the prominent features of SWZSs reported in the literature and the hindrances to their adoption. The most reported hindrances are the cost and effort associated with development, installation, and relocation. We uncover that Connected Autonomous Vehicles, vehicle-to-vehicle, and vehicle-to-infrastructure communication, along with technology-based worker training are the most promising next frontier for SWZ.
Conclusion: Significant research gaps exist in the literature regarding developing and implementing SWZS. Additionally, little effort has been directed toward developing workers' skills and competency. Practical approaches such as Virtual Reality (VR)-based training are necessary to bring workers up to pace with the developing SWZ technologies.
Practical Applications: Future research should be directed towards interconnecting and implementing available safety technologies to automate WZ safety and management. Workers should be trained using more practical techniques. In this context, using VR will enable the simulation of hazardous events in a safe environment while also improving workers' skill retention.

Keywords: intelligent transportation system; highway safety technologies; Latent Dirichlet Allocation; literature review study; worker adaptation

1. Introduction

Highway construction/maintenance work zones (WZs) are hazardous working environments owing to the coexistence of moving automobiles and pedestrian laborers (Almallah et al., 2021; Duan et al., 2020; Marks et al., 2017; Nasrollahzadeh et al., 2021). The WZ crash statistics show a definite need for more effective and efficient WZ safety mechanisms and practices (Leder et al., 2019; Y. Li et al., 2018; Nnaji, Gambatese, et al., 2020; Ozan, 2019). National statistics indicate that the annual average growth rate of fatal WZ crashes in the United States is nearly 4%, and WZ crashes are expected to be more severe than non-WZ crashes (Oregon Department of Transportation, 2017). Additionally, WZ is the main reason for non-recurring congestion on freeways, causing more than 10% of congestion (Jagarlamudi, 2018) and 24% of unexpected freeway delays (Rahim & Hassan, 2021). Researchers, policymakers, and WZ managers are actively exploring intelligent technologies and new methodologies to ease these challenges, thereby achieving nearly normal traffic operations and safety (Thapa et al., 2022). This desire spawned the concept of Smart Work Zones (SWZs). The term SWZ is also called a Work Zone Intelligent Transportation System (WZITS), which targets implementing ITS technologies to enhance the mobility, safety, and efficiency of WZs (Ozan, 2020). SWZ Systems (SWZSs) are characterized by a combination of automated detection and communication technologies designed to inform road users of the traffic, road, or environmental conditions, particularly during lane closures (Ozan, 2020). According to (Pant, 2022), a system can be called an SWZS if it is (i) capable of detecting and communicating in real-time, (ii) portable and easy to deploy, (iii) capable of operating automatically with minimal supervision, and (iv) can provide accurate and reliable information to road users. Additionally, when used effectively, SWZSs at the very least are expected to provide solutions to the aforementioned problems by performing one or more of the following tasks: (i) informing road users, particularly motorists, of the downstream conditions (e.g., adverse road or weather conditions, reduced speed limit, lane closures, merge actions, etc.) so they can better prepare, (ii) recommending alternate route to ease congestion and travel delays, or (iii) making WZs safer by enforcing safety measure (e.g., displaying warning and regulatory information).

Numerous initiatives taken at the state, regional and federal levels have sought to proliferate the use of SWZSs to make WZs smarter in the US. Some notable examples are the Work Zone Data Initiative and the Smart Work Zone Deployment Initiative (SWZDI) funded by the Federal Highway Administration (FHWA). SWZDI has been funded since 1999 and currently comprises participant states Iowa, Kansas, Missouri, Nebraska, Wisconsin, Illinois, Michigan, and Texas. The initiative has funded and produced numerous WZ safety-related studies and products. Notably, federal acts such as the IIJA act of 2021, FAST Act of 2015, MAP-21 of 2012, and SAFETEA-LU of 2005 have funded WZ safety-related research in the US over the years. These initiatives have produced a large body of research on WZ, SWZs, and SWZSs. While it is a daunting task to assemble and review all the literature on all these topics, we believe that a review of the "smart" components of WZ is practical and necessary for a path toward SWZs. A thorough review of SWZSs can be helpful to researchers and policy makers. First, it will serve as a one-stop-shop for all "smart" WZ studies. Second, a synthesis of studies will make identifying deficiencies easier and hopefully pave the path toward smarter WZs.

This study clusters WZ-related studies into major topics using a Natural Language Processing (NLP) method called Latent Dirichlet Allocation (LDA) modeling to gain an overall outlook of WZ studies and performs an extensive review of the two main topics that are the foundational components of WZs, safety, and mobility. The literature search using NLP has been widely used in recent years, considering their potential to minimize the human effort required for identifying the relevant literature. Some recent studies using NLP for literature search are (Sun & Yin, 2017; Xiong et al., 2019; Zulkarnain & Putri, 2021). LDA is particularly useful as it does not require advance knowledge of the underlying topics and can be tuned to fit and explore different topic formations (Y. Zhao & Cen, 2014). In this study, as we focus on the "smart" component of WZs, the LDA model was trained to identify the related literature, thereafter, review all research works related to SWZSs. Based on our findings, we present conclusions on current challenges in creating a smart WZ and the means to address them.

1.1. Study contributions

This review seeks to provide a comprehensive synthesis of the literature on WZ-related technologies, with a particular emphasis on SWZSs, to gather knowledge of their state-of-the-art, capabilities, and limitations. This study provides a concise overview of current knowledge on (i) potential SWZSs in the literature and their effectiveness in improving WZ safety and mobility, and (ii) research and development needs for the proliferation of current and future SWZSs. To our knowledge, no studies have studied SWZSs to this end. The findings from the review are reported to provide clear guidance to researchers and practitioners on applying WZ safety systems that can potentially make WZs smarter. Additionally, based on the findings, future research avenues are identified and discussed in detail to provide researchers and policymakers with a clear path forward.

This paper is structured as follows: Section 2 presents an overview of the methodological approach and literature search criteria to identify major aspects of WZs. The findings from our literature review are presented in Section 3. Section 4 discusses the findings and recommends the path forward for future research and development. The study concludes with a summary and limitations in Section 5.

2. Methodology

The methodological approach adopted to review the literature for the current study comprised of three major steps; (i) selection and clustering of WZ-related studies to identify major topics and their subclasses, (ii) review and analysis of SWZ aspects related to the topics, and (iii) conclusions and recommendations on future directions. These steps are detailed in the following sections.

Fig. 1 shows the research methodology followed to select the relevant publications and the review method adopted. The literature on WZ is quite extensive, which makes selecting relevant papers a monumental endeavor in and of itself. This study uses the LDA model to minimize the burden of choosing the appropriate articles to review. Next, we introduce the LDA model followed by the research methodology used to identify the major topics. We only provide a brief discussion of LDA for brevity and suggest the readers consult (Blei et al., 2003) for a more detailed explanation.

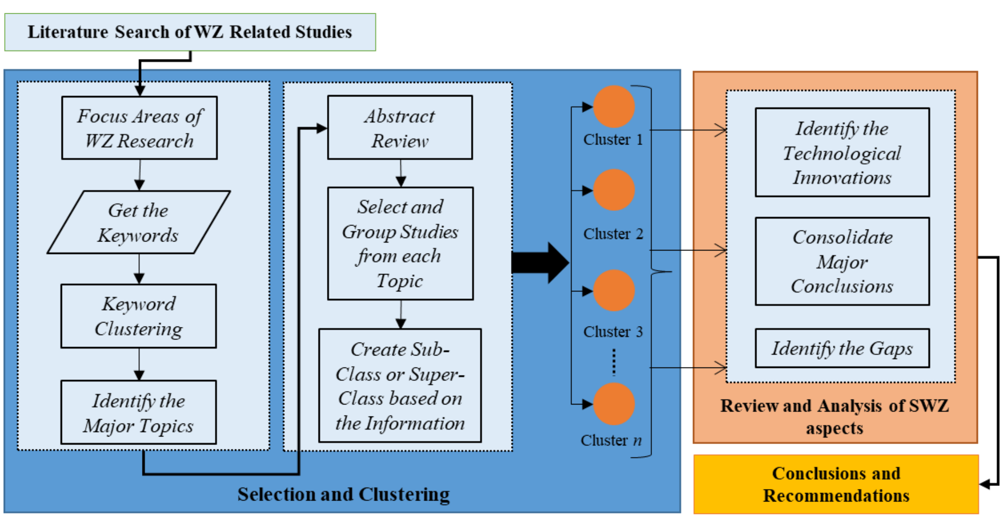

Fig. 1. Review methodology

2.1. Latent Dirichlet Allocation modeling

2.1.1. Introduction

In LDA, it is assumed that each document is a mixture of several topics, each of which can be represented as a probability distribution over words. Provided we have a collection of documents, often called a corpus, the goal of LDA is to learn (i) how the topics are distributed for each document, and (ii) how the words are distributed for each topic. The entire process can be broadly divided into five steps.

i. Initialization: LDA begins with allocating random topics to each word in a document. Thus, we get documents as a mixture of topics, and topics are a mixture of words.
ii. Iteration: In this step, for each word in each document, class membership probability is calculated. This is the probability that a word belongs to a certain topic based on the current topic and word distribution. For a certain topic, the lower-class membership probability of a word indicates they are less likely to be associated. On the other hand, upper-class membership probabilities are indicative of a higher likelihood of topic-word association. For each word, LDA assigns the topic which has upper-class membership or the highest probability. This iteration is repeated until there is no notable change in word-topic assignment between iterations.
iii. Topic distribution: After word-topic assignments are complete, LDA derives the topic distribution for each document which describes the probability of each document being associated with each topic. Similar to the previous step, documents are assigned topics with higher probability.
iv. Word distribution: LDA estimates word distribution for each topic and calculates the probability of each word appearing in a document assigned to a topic.
v. Validation: Consequently, the goodness of the fitted LDA can be evaluated using validation perplexity which evaluates the predictive ability of the model. More specifically, validation perplexity quantifies how well the LDA can predict topic distribution for documents that are not part of the training sample. A lower value of validation perplexity indicates a better LDA model (Blei et al., 2003).

The LDA model can be visualized using a probabilistic graphical model shown in Fig 2. where the outermost "plate" shaded in blue represents documents. The inner plate shaded in orange represents words. The plate in green represents topics. Since LDA is an iterative process, these plates represent repeated entities (documents, words, and topics). The dependencies between the variables in the model are presented by arrows. Considering corpus with documents $i \in \{1,2,3 \dots . I\}$, words $j \in \{1,2,3 \dots . J\}$, and topics $k \in \{1,2,3 \dots . K\}$. Then the variables are as follows.

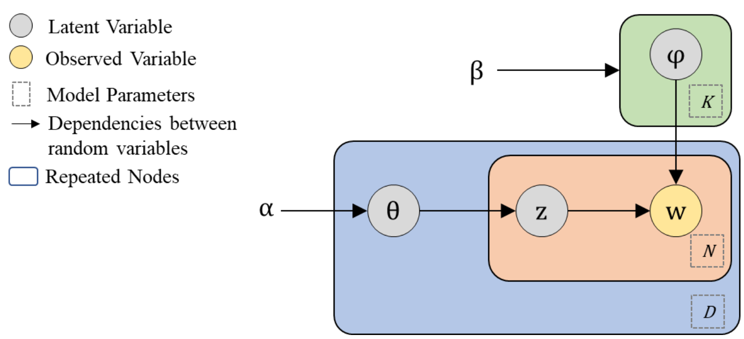

Fig 2. Probabilistic graphical model representing LDA

$D = Number\ of\ documents$
$K = Number\ of\ topics$
$N = Number\ of\ words\ in\ a\ document$ (For example, a document i has N_i words)
$\alpha = \ Parameter\ of\ the\ Dirichlet\ prior\ on\ document\ topic\ distribution$
$\beta = \ Parameter\ of\ the\ Dirichlet\ prior\ on\ topic\ word\ distribution$
$\theta_i = \ Topic\ distribution\ for\ document\ i$
$z_{ij} = Topic\ for\ j^{th}\ word\ in\ i^{th}\ document$
$\Psi_k = Word\ distribution\ for\ topic\ k$
$w_{ij} = \ Specific\ word$

It is worth noting that θ, Ψ, and z are not directly observed and are latent variables. On the contrary, w is the only observed variable in the model.

2.1.2. Data preprocessing

Since LDA is the process of modeling text data, data preprocessing is needed before it is trained. The preprocessing step includes the following.

i. Converting the text data to lowercase
ii. Tokenizing the text
iii. Punctuation removal
iv. Stop words removal (such as "and", "of", and "the")
v. Removing words with two or fewer characters
vi. Removing words with 15 or more characters
vii. Lemmatizing words
viii. Removing general keywords to avoid bias (e.g., in our case traffic, transportation, work, zone, etc.)

2.1.3. Hyperparameter tuning

Hyperparameter tuning is the process of optimizing the performance of the LDA model based on measures such as validation perplexity and model run time. The objective is to find the optimal set of hyperparameters that maximizes model performance. For instance, hyperparameter tuning can be used to find the number of topics, K in the model shown in Fig. 2 that gives the minimum value of validation perplexity.

2.2. Research methodology

The research methodology adopted for this study can be divided into two steps. In the first step, all relevant articles were identified using keywords. Since the number of articles was considerably large, an iterative LDA-based algorithm was developed and implemented to select the most pertinent articles for review. In the next step, after a feasible number of articles were identified, standard LDA model was used to identify most relevant topics from the articles. The two steps are described in greater detail as follows.

2.2.1. Article selection

From a basic keyword querying of online databases (Scopus, Google Scholar, CiteSeerX, Mendeley, Medline/Pubmed, IEEEXplore, ArXiv, and ACM Portal) using the keywords ((*work?zone* OR *construction?site* AND (*traffic* OR *transportation*)), a total of 15,035 articles were obtained. After applying several essential inclusion/exclusion criteria such as language, author information, article type, etc., a total of 12,722 articles were shortlisted. Further, an automated keyword search within the title of the article, author keywords, and abstract was performed to see whether the terms such as work zone, construction zone, or construction site are mentioned along with any of the terms such as traffic, transportation, vehicle, road, highway, freeway. This stage resulted in 2,641 articles for the topic modeling.

To further reduce the number of articles and obtain the most relevant pick, we developed and implemented an LDA-based semi-supervised deletion criterion. An iterative LDA modeling approach was implemented that removed the articles with lower-class membership across the major classes. The algorithm automatically reads the membership probability of the article with different topics and chooses the topic with a higher probability. The inclusion/exclusion criteria were set to at least the 85th percentile of the overall membership probabilities for the topic. Fig. 3 shows the number of articles retained after each iteration step. It is to be noted that at every stage of the iteration, the model evaluates the number of articles retained, validation perplexity, and the time elapsed. The iteration was stopped when there was no change in the number of articles. At the end of this process, 404 articles were selected for the final topic modeling.

2.2.2. Topic modeling

Topic modeling is a word clustering approach, which partitions a set of words into subsets of semantically similar words. In this step, the keywords from each article were fed into LDA, which included the keywords reported by the author as well as those derived from the abstract and title of the publication. After extracting the keywords, they were preprocessed to prepare for LDA as mentioned in Section 2.1.2 (e.g., converting data to lowercase, text tokenization, and so on).

The number of topics is an essential hyperparameter in LDA. The selection of the number of topics should be such that it minimizes validation perplexity and fitting time. There should be a trade-off between them for an optimal clustering of the documents with a minimal convergence time. We implement hyperparameter tuning to find the optimal number of topics as follows:

i. Fit LDA models for a range of the number of topics.
ii. Assess the computational time and the perplexity of each model on the set of test documents.
iii. Choose the value where the perplexity and time-elapsed are minimum.

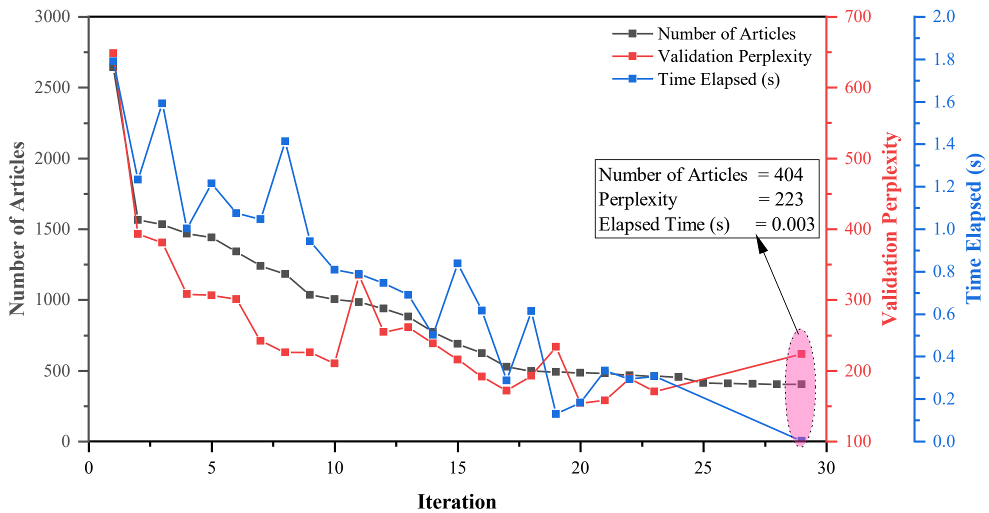

Fig. 3. Optimal selection of the final list of articles for review

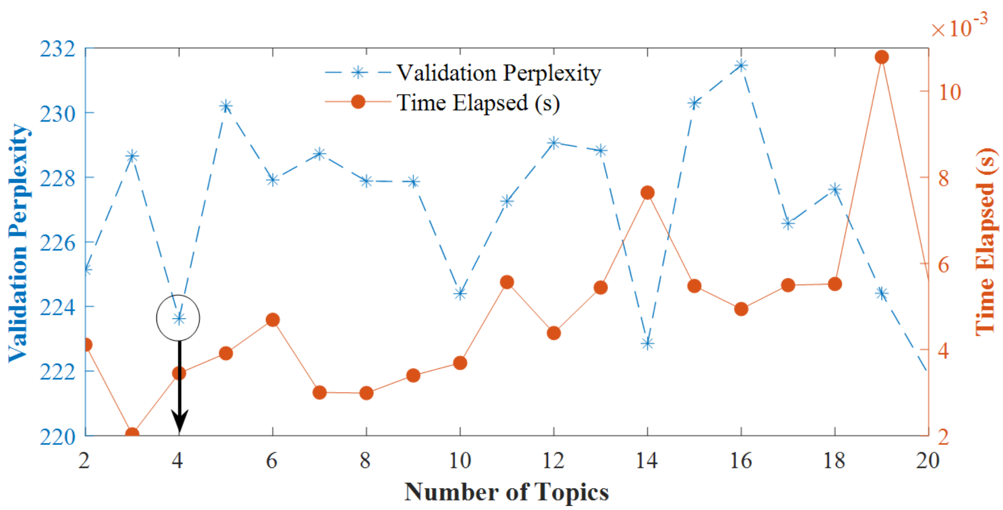

Fig. 4. Selection of the optimal number of topics for LDA

Fig. 4 shows the variation of perplexity and time-elapsed for different topic numbers. An acceptable choice of the number of topics was found to be four, as presented in the figure. Next, LDA topic modeling was performed for all the documents using the keyword list and clustered into four topics, as shown in Fig. 5. Once the important topics of WZ studies are identified, further screening of the selected manuscript was performed based on cluster membership. We also searched for relevant articles online that might be important based on the topic-specific keyword search. Finally, a total of 250 papers were identified for detailed review. The subsequent sections will present a detailed review of the first two foundational topics (i.e., safety and mobility). We chose to limit the current assessment to two topics due to the extensive literature which warrants a comprehensive review and cannot be accommodated in a single article. Furthermore, the chosen topics are often the most prioritized aspects of WZs from a safety and economic point of view.

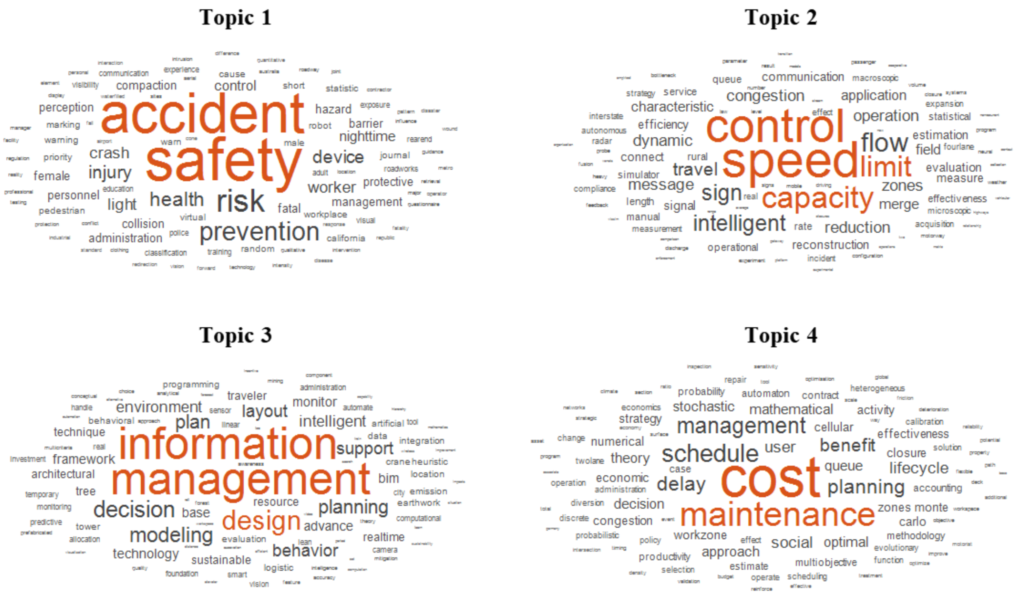

Fig. 5. Word clouds obtained from LDA

3. Review and analysis of SWZ aspects

3.1. Topic 1: Work Zone safety

Highway WZ crashes fall into two categories: those involving construction workers (30%) and those involving vehicles passing through the WZ (70%) (S. B. Mohan & Gautam, 2002). Various transportation organizations have recognized WZ safety as a high-priority concern, and there is a solid requirement for more effective and efficient safety devices and methods (Ozan, 2019). Every year, roughly twelve billion vehicle miles will pass through active WZs, and vehicles are expected to encounter an active WZ at once every hundred miles driven (Federal Highway Administration, 2014). To guarantee the safety of workers and road users in and around WZ, the FHWA emphasized the necessity of safety monitoring throughout the design, planning, and construction stages (Federal Highway Administration, 2009). Nevertheless, between 2018 and 2019, fatal collisions in WZs increased by 11%, whereas fatal collisions elsewhere fell by 2%. The 11% increase in WZ fatalities surpassed the modest increase of 0.3% in overall highway construction spending and 0.8% in total vehicle miles driven countrywide (Fatality Analysis Reporting System (FARS), 2019). In WZs, particularly those with periodic congestion, back-of-queue crashes are a serious safety threat and fatal front-to-rear collisions occurred at an average annual rate of 150, in US WZs between 2014 and 2018, accounting for 22.5% of WZ fatalities (Fatality Analysis Reporting System (FARS), 2019).

Fig. 6 shows the WZ fatal crashes and fatalities for the past ten years in the US. The figure shows that the number of fatalities and fatal crashes consistently increased over the year at an average rate of 30 fatalities/year and 27 fatal crashes/year, respectively. The truck-involved fatalities and fatal crashes also show a positive trend (Benekohal & Shim, 1999) found in their study that about 90% of truck drivers regard the WZ as more unsafe than regular sections. Additionally, when compared to non-WZ locations, trucks are 44.6% more prone to single-vehicle incidents in WZs. Though worker-related crashes are not showing any statistical trend, the situation is not improving. WZ safety is still a threat despite extensive academic research and policy changes. It is to be noted that improving safety in WZs is a key challenge since approximately 20% of the US highway system is under maintenance or construction during the peak construction season each year, with more than 3,000 WZs at a time (Construction Safety Council, 2008). On average, statewide, there occur 7.3 work zone crashes per day each year.

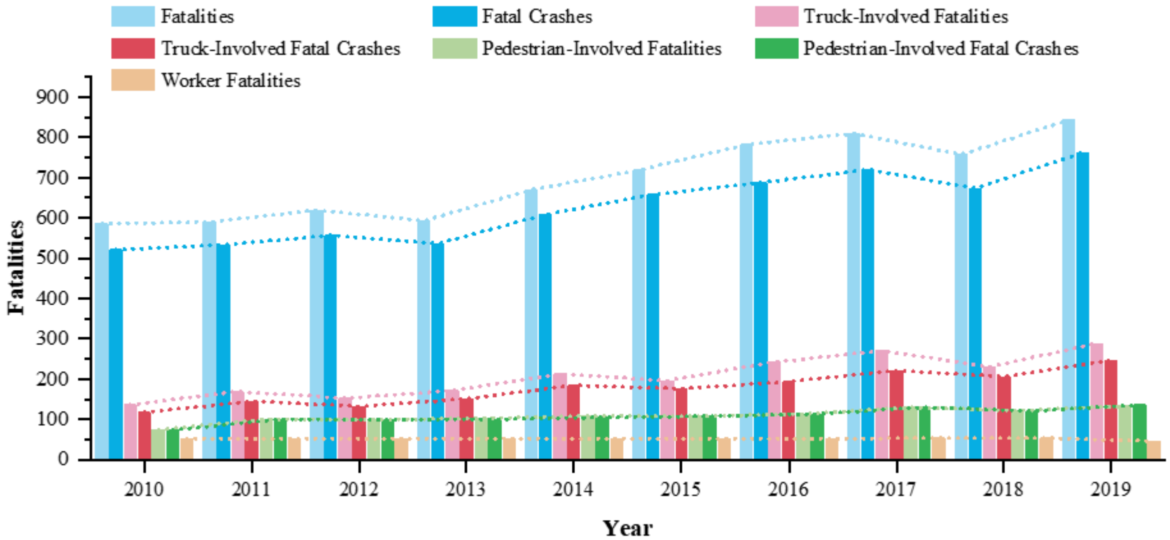

Fig. 6. Work zone fatal crashes and fatalities in the United States

Effective traffic control plans for WZs, together with sufficient training and supervision of workers, are critical for resolving challenges associated with WZs (Atahan et al., 2019; Bryden et al., 1998). Moreover, a better comprehension of the potential risk factors for WZ crashes is vital to make informed decisions and devising proper safety strategies and interventions (Yang et al., 2015). However, the factors contributing to worker and vehicle safety near WZs are distinct, as discussed in the following subsections.

3.1.1. Work zone risk factors and driver behavior

According to the literature, the primary risk factors for WZ crashes are roadway and work zone attributes, and weather/lighting circumstances. Interestingly, these factors can influence another significant risk factor, which is driver behavior.

Based on the literature, driver behavior in WZs is characterized by their willingness to (i) maintain a uniform traffic flow by maintaining a constant speed and speed variance, and (ii) execute safe merge operations. WZs cause sudden interruptions in traffic flow resulting in queues, slowdowns, maneuvers (lane change and overtake), and conflicts thus affecting driver behavior (Flannagan et al., 2019). Driver actions such as overspeeding and large speed variances in WZs are the major contributors to WZ crashes. Therefore, most WZ treatment focuses on improving WZ safety and traffic efficiency by maintaining a uniform traffic flow and enforcing safe merge behavior.

Driver behavior across the literature has been studied alongside WZ, vehicle, environmental, and driver characteristics. (Hamdar et al., 2016) studied driver behavior for various WZ scenarios related to length, barrier type, and level of activity and reported higher average vehicle speeds along longer WZs. This could be attributed to drivers' growing impatience when navigating through longer lane closures. The authors also observed a difference in time and mean space headways when using different barriers. Similarly, it has been observed that drums and channelizers in WZs affect driving performance differently than concrete barriers, and the speed variance of vehicles increases with the level of work zone activity (Reyes & Khan, 2008). Furthermore, with the increase in activity level, the authors observed an overall decrease in speed. He, et al. 2016 investigated drivers' lane change maneuvers and found vehicle type, lane speed, and volumes to be significant determinants of lane change behavior in WZs (He et al., 2016). Weng and Meng 2012 investigated the effects of environment, vehicle, and driver characteristics on risky driving behavior at WZs (Weng & Meng, 2012). The authors reported that adverse weather and lighting conditions, the absence of traffic control devices, and old vehicles were associated with risky driving behavior. The authors also found risky driving behavior was observed on single and multilane roads when the lighting conditions were unfavorable and favorable, respectively. Middle-aged male drivers were most likely to exhibit risky driving behavior.

Debnath et al., 2015 surveyed highway workers to identify WZ risk factors and countermeasures (Debnath et al., 2015). They identified adverse weather and lighting conditions, distracted driving, roadway type, and alignment as the major risks in WZs. According to the workers, the most hazardous conditions were working in wet weather (skid resistance, reduced visibility), driver frustration and aggression toward traffic controllers, and distracted driving from mobile phone use (Debnath et al., 2015). In terms of the time of day, peak hours, and non-daylight hours (dawn, dusk, and night) are considered the most hazardous conditions by workers. Reasons cited for non-daylight hours being the most hazardous were the higher number of drunk drivers and reduced visibility. Similarly, working on freeways and hilly/curved roads was considered risky by workers. Finally, according to the workers the most effective countermeasures for speed compliance were police enforcement, the presence of police cars regardless of the presence of an officer, installation of speed bumps, and WZ-oriented driver education.

Looking at work zone crash data from multiple states, (Dissanayake & Akepati, 2009) reported that most work zone crashes occur in clear weather and daylight conditions. Their study showed only a small difference in the number of crashes observed in dark lighting conditions with and without streetlights. They reported that almost half of all WZ crashes occurred within or adjacent to work activity. Notably, about 42% of all WZ crashes were rear-ended crashes. The primary factors resulting in crashes were taking improper action (32.1%), inattentive driving (19%), and following closely (9.7%). Similarly, when investigating the factors contributing to work zone crashes during adverse weather conditions, (Ghasemzadeh & Ahmed, 2019) reported adverse weather and lighting conditions like rain and fog were important factors influencing crash severity. Their analysis showed that while these weather conditions resulted in less severe work zone crashes on their own, their interaction with other contributing factors increased the likelihood of more severe crashes. They also found that Driving Under the Influence (DUI) was a statistically significant predictor of work zone crash severity.

3.1.2. Worker safety

Highway construction/maintenance job is one of the most unsafe occupations in the United States. According to the latest statistics from the US Bureau of Labor Statistics, approximately 31% (1,590 out of 5,190) of all deadly job-related accidents that occurred in 2021 were caused by collisions with vehicles on roads or pedestrian walkways (US Bureau of Labor Statistics, 2021). According to researchers, traffic crashes in WZs result in around 2,400 worker injury incidents every year (Awolusi & Marks, 2019). In the US alone, roadside WZs account for hundreds of human fatalities and thousands of non-fatal injuries annually due to errant vehicle intrusions (Osman et al., 2016, 2018, 2019a, 2019b). The WZ crashes reported during the last five years in the US account for about 3% of all occupational fatalities, which translates to a worker fatality every 15 hours and an injury every 14 minutes (VDOT, 2019). Since the work situation on the highway is often noisy and chaotic, spotting an errant vehicle and taking appropriate action becomes challenging for WZ personnel (Fyhrie, 2016), owing to the limited period available for reacting. The absence of predictive safety systems that alert workers to impending threats is a major source of contention in the highway maintenance and operation sector (Sabeti et al., 2021).

According to highway workers, driver distraction, excessive vehicle speeds, hostility toward roadworkers, and operating at night, inclement weather, or close to traffic were among the most often cited hazard in the field (Debnath et al., 2015). (Mokhtarimousavi et al., 2020) have shown that construction/maintenance work on the shoulder or median, or advanced warning area, working during daytime non-peak hours, and the presence of multi-occupants have heterogeneous effects on injury severity.

Further, it was reported that inattentive or speeding drivers, careless workers, misplaced traffic control devices, and hazardous roadway conditions can also contribute to crashes, resulting in WZ injuries and fatalities (Arslan et al., 2018; Gambatese et al., 2017; K. Kang & Ryu, 2019). Notably, worker safety during night-time construction has been a key concern as it generates hazardous working circumstances (Arditi et al., 2007). Active strategies, such as deploying intrusion sensing and alert technologies in WZs, can effectively mitigate these unforeseen conditions (Awolusi & Marks, 2019). Studies have shown that wearable technology, such as wearable lighting systems (WLSs), can increase worker safety in various construction industries (Nnaji, Jafarnejad, et al., 2020). (Sayer & Mefford, 2004) emphasized the significance of retroreflective trim on workers' safety garments, especially when the trim is positioned on the garment's sleeves. Recent studies have demonstrated that closely monitoring the status of moving objects in real-time and providing quick feedback to workers may significantly increase the effectiveness of any safety strategy (Andolfo & Sadeghpour, 2015). Several active technologies have been developed to support workers and equipment operators with proximity sensing and alerts. However, most of these systems ignore the differences in WZ settings and environmental conditions, such as equipment types and approaching speeds, resulting in inconsistency and delays (Park, Yang, et al., 2017).

According to (McAvoy et al., 2007), WZ safety can be achieved by providing precise and positive guidance to workers and road users. Unfortunately, workers often misidentified many potential safety threats at construction sites (Albert et al., 2014; Bahn, 2013; Carter & Smith, 2006). Many states in the US have used intelligent transportation system technologies such as queue warning systems, vehicle intrusion alert systems, and sequential warning lights on tapers for alerting workers and road users about approaching hazards. Despite these technologies, little attention has been paid to training workers involved in the WZ system operation, administration, and inspection (Chang et al., 2020).

3.1.3. Safety of passing traffic

Due to traffic complexity in WZs, the typical crash prevention procedures frequently fail to work in a WZ setting (Qiao et al., 2016). According to the Federal Highway Administration's facts and statistics, there were 762 fatal WZ crashes in 2019, resulting in 842 fatalities (Federal Highway Administration, 2021). (McAvoy et al., 2011) have shown that the primary causes of WZ crashes are driver inattention, speed differential, failure to yield, hazardous speed, and one vehicle following another too closely. Daniel et al. (2000) have shown that WZ fatal crashes are more prone to cause multiple vehicles fatal crashes than non-WZ. According to (Silverstein et al., 2016), rear-end and sideswipe crashes are highly likely to result in fatalities in WZ than in non-WZ. (Weng & Meng, 2013) mentioned that the likelihood of merging vehicles crashing diminishes as the remaining distance to the WZ increases. Additionally, there is a 4% chance of a rear-end collision if the merging vehicle fails to complete the merge at the end of the WZ merging area. In contrast, early merging reduces the likelihood of a rear-end collision by 1.2 percent (Weng & Meng, 2013). One notable finding is that there is a heightened danger of rear-end collisions in WZs on weekends and at night (K. Zhang & Hassan, 2019). It is to be emphasized that the classification of crash types within the WZ will assist highway contractors, and owner agencies determine the most cost-effective safety precautions (S. Mohan & Zech, 2005). According to (Jin et al., 2008), the mean crash rates during the construction and non-construction periods were not statistically different, implying that previous WZ safety-related studies' findings of higher crash rates during construction time were not statistically supported by Utah's WZ crash records. Though it contradicts the common belief about WZ safety, this could be possible for well-planned and technologically equipped WZs. Another significant finding is that fatal crashes in WZs are less impacted by horizontal and vertical alignments than fatal crashes in non-WZs (Daniel et al., 2000).

High speed and speed variation, project duration, presence of traffic control devices, peak hours, traffic volumes, work/taper length, and adverse lighting/weather conditions are the most consistently reported contributors to WZ crashes (Garber & Zhao, 2002; Yang et al., 2014). Identifying such risk factors is important for decision-makers to reduce WZ crash risks by rescheduling a specific maintenance or construction activity or altering the operation's characteristics (Nasrollahzadeh et al., 2021). On the contrary, (Silverstein et al., 2016) argued that the ITS solutions (e.g., vehicle-to-vehicle communications, speed harmonization) are more appropriate for WZ safety since some conditions that are considered non-adverse are also correlated with crashes (e.g., clear daylight conditions increase the likelihood of read-end and sideswipe collisions).

3.2. Topic 2: Speed, capacity, congestion, and control

Road renovation is imminent, and it is vital and necessary to minimize the impact of the WZ on traffic flow (Shao et al., 2020). Proper traffic control and delineation are crucial for improving WZ safety and efficiency (Bligh et al., 1998). It has been reported that highway WZ causes over a fifth of the non-recurring congestion, resulting in severe delays, and in 2014, the reported delay was 888 million vehicle hours (Awolusi & Marks, 2019). It is worth noting that temporary traffic control solutions have been created and implemented in WZs over the years (Y. Li & Bai, 2009b), and these technologies have the potential to aid in avoiding some usual human mistakes, such as disregard for traffic control, inattentive driving, following too closely, and exceeding the speed limit or driving too fast for the conditions (Y. Li & Bai, 2009a).

Notably, most traffic-related issues near WZs can be attributed to the associated lane closure. Lane closures are indispensable as most WZ activities cannot be carried out without disrupting traffic, otherwise arising from the workers' safety obligations. It is well known that lane reductions may disrupt regular traffic flow and cause speed drops, resulting in a decline in road capacity and an increase in traffic delays. It is to be noted that the capacity reduction near WZs reduces traffic efficiency and increases traffic crashes (Han et al., 2020; Memarian et al., 2019; Zheng, 2014; Zheng et al., 2010; Zhou & Ahn, 2019). According to existing research, WZs account for a significant portion of highway congestion due to reduced operational lanes (Chung & Recker, 2012). Studies have reported that various types of lane closures can have varying effects on traffic flow, such as speed and capacity. (Gladson et al., 2020) found that near-side lane closure has a minimal impact on capacity (15%), whereas run-around type closure has the maximum (46%). Increased crashes due to lane closure were found because of the need for lane merge. Because the vehicles present in closed lanes must merge into neighboring open lanes, the likelihood of traffic conflicts and traffic safety issues may increase (Weng & Meng, 2013). However, the conventional early merge behavior limits leveraging the available capacity in the closed lane; therefore, typical traffic operations and control at WZ are ineffective in relieving the WZ bottlenecks (Algomaiah & Li, 2021).

Numerous studies have been undertaken on the speed characteristics of motorway WZs (Z. Wang et al., 2021). These studies have reported that speeding is the key factor in unsafe situations in a WZ (Cheng & Cheng, 2020). Any countermeasures to minimize speed variance will certainly enhance safety (Salem et al., 2006). The preponderance of rear-end collisions across all WZ locations suggests a substantial speed variance. Several countermeasures have been practiced in WZs to control the speed within the limits, minimize speed variability, and speed enforcement. Regarding roadwork features, speed increased by 11 km/h when road markings were present, reduced by 9 km/h when road delineators were present, and increased by 5 km/h when barriers were present (Steinbakk et al., 2019).

As mentioned, WZs cause nonrecurring congestion on highways, resulting in a significant reduction in capacity, travel delays, and pollution (Mashhadi et al., 2021; Yu et al., 2019). The reduced roadway capacity is caused by WZ speed limits, fewer traffic lanes, and narrower lanes. Generally, congestion occurs once the inbound traffic flow goes beyond the downstream capacity, and the outflow is lowered due to the congestion-induced capacity reduction (Papageorgiou et al., 2008). A proactive, citywide strategy to manage all WZs can reduce congestion and give agencies superior control over planning and approving projects and budgets (Dickerson et al., 2016). As transportation agencies ought to routinely plan WZ activities for the duration of the construction season, breakdown probability models could have a very immediate influence on WZ planning. Additionally, the models for predictive relationships based on construction scenario capacity and demand have strong correlation coefficients, indicating the possibility of developing such relationships for roadway construction projects. (Du & Razavi, 2019) have found that incorporating a non-linear traffic flow model and a discrete-time sliding mode control in the Variable Speed Limit (VSL) control improved by nearly cutting 90% of the crash risk, 17% of the average travel time, and 6% of NOx, CO_2 emissions, and fuel consumption. However, there is a scarcity of data related to the stochastic capacity of WZs (Kianfar & Abdoli, 2021). While the current methodology for determining the capacity of freeway construction zones in the sixth edition of the Highway Capacity Manual is a significant advance over previous guidelines, it addresses the issue of assuming the mean queue discharge rate as deterministic and ignores the stochastic character of traffic flow and breakdown (Jehn & Turochy, 2020). As we can see, considering speed limits is critical to reduce WZ crashes and their severity. However, speed limits have been shown to reduce capacity.

3.3. Smart Work Zone Systems

Identifying future research and development requirements heavily relies on comprehending the state-of-the-art of SWZS. In this context, according to (Pant, 2022), all SWZSs should be capable of accomplishing the following tasks.

i. Detect and communicate in real-time.
ii. Be portable and easy to deploy.
iii. Operate automatically with minimal supervision.
iv. Provide accurate and reliable information to road users.

However, the literature review suggests there are very few systems that meet all these requirements. Moreover, it is often the case that most SWZSs meet some of these requirements. Based on the literature review, prominent SWZSs were identified which are presented in Table 1. Note that primary use cases for the systems are divided into three categories (WS=Worker safety, TS=Safety of passing traffic, TF=Traffic flow) and presented. A review of the literature on these systems is as follows. It should be noted here that some of these systems fall in the category of Advanced Traveler Information Systems (ATIS) since they acquire and deliver real-time updates to motorists, allowing them to make more efficient and safe use of existing transportation systems (Ermagun, Kelarestaghi, Finney, et al., 2021; Pesti et al., 2004).

Table 1. Prominent Smart Work Zone Systems in the literature

SWZS	Description	Primary use case
Automated Speed Enforcement	Uses sensors to measure vehicle speed, and a camera to identify drivers violating the speed limit and issues citations.	WS
Work Zone Intrusion Alert Systems	Systems designed to detect unauthorized WZ intrusions and warn workers using warning lights, sounds, or haptic feedback devices	WS+TS
Worker tracking	System for tracking worker location	
Queue Warning Systems	Uses roadway sensors to detect queue length and end-of-queue and relays the information to drivers upstream.	TF
Variable Message Sign	A system that detects roadway, traffic, and environment conditions downstream and displays warning or regulatory messages to motorists	WS+TS+TF
Speed Limit Advisory Signs	Displays advisory messages regarding the speed limit on a highway segment	WS+TS+TF
Dynamic Lane Merge Systems	A system that uses sensors to identify safe merging areas based on traffic flow and speed harmonization displays it to motorists.	WS+TS+TF

Note: WS=Worker safety, TS=Safety of passing traffic, TF=Traffic flow

3.3.1 Automated Speed Enforcement Systems

WZ lane closures create bottlenecks for traffic flow. An abrupt reduction in traffic throughput results in a road segment resulting in traffic delays which is often frustrating and annoying to motorists. This elicits aggressive and risky driving behavior from motorists. Further, the speed reduction and differentials make

WZs a prime location for rear-end crashes. Therefore, proper speed enforcement is crucial to ensure the safety of motorists and workers alike.

Automatic Speed Enforcement (ASE) systems can be divided into two types based on detection technology which are either Lidar or Radar-based. These systems are effective in increasing speed compliance. For example, a radar-based ASE system deployed in Maryland was found to reduce speeding violations by 80% and related fatalities by 50% (Adenaiya, 2017). Radar-based ASE, also called Speed Photo-radar Enforcement (SPE) is more popular in the US. SPE for work zones was first investigated in the US by the Illinois Department of Transportation (Benekohal et al., 2008). Several states have since adopted it. In most cases, ASE is operated and monitored by law enforcement agencies and is quite effective in reducing car speeds by as much as 8 mi/h (12.8 km/h) with some halo effects (Benekohal et al., 2008). It should be noted that a similar system called Automatic Section Speed Control (ASSC) is employed in Europe. However, unlike ASE, ASSC calculates speed over a section of a road rather than at a single point (Lahrmann et al., 2016). Regardless, ASSC has also been found to be very effective in reducing speeding violations and crashes. Table 2 presents a summary of findings from investigations on ASE and ASSC.

Table 2. Effect of Automated Speed Enforcement Systems on driving behavior

Study	Findings
(N. L. Morris et al., 2016)	• No improvement in driver attention when using ASE + Dynamic Speed Message Sigs
(Benekohal et al., 2008, 2009, 2010)	• Up to 7.3 mi/h (11.75 km/h) reductions in the free-flowing speed of vehicles • Considerable reduction in vehicles exceeding the speed limit (as much as 8.3% from an initial 39.8%) • Excessive speeding >10 mi/h (11.74 km/h) was eliminated
(Adenaiya, 2017)	• Reduction in the number of violators driving over 6-10 mi/h (9.65-16 km/h) threshold from 20% to 10% over 30 months • Reduction in the number of violators driving over the 11-20 mi/h (17.7-32 km/h) threshold from about 8% to 1%.
(Joerger, 2010; Oregon Department of Transportation, 2015)	• Speeding was reduced by 27.3% in a location with ASE installed over 6 months
(Washington Department of Transportation, 2009; Washington Traffic Safety Commission, 2013)	• A slight decrease in traffic speed violations was observed • Initially, a decrease in average speed values from the baseline was observed but it increased back to the baseline value over the next two years
(Retting et al., 2008)	• Considerable reduction in speeding over 6 months period • As much as a 20% reduction in speed limit violations exceeding 10 mi/h (16 km/h) • Spillover and distance halo effect observed in places without ASE
(Ilgaz & Saltan, 2018)	• The average speed reduced from 38.73 km/h to 35.13 km/h when ASSC was implemented on a university campus
(Montella et al., 2012)	• A 31.2% reduction in crashes after implementing ASSC • Most reductions were observed in crashes at curves and severe crashes
(Lahrmann et al., 2016)	• A 7.5% decrease in the mean speed of vehicles in segments where ASSC was used • Statistically significant reduction in crashes in some test sites
(Ambros et al., 2020)	• A reduction in WZ speed and variance by 3km/h and 2 km/h, respectively after implementing ASSC • Decrease in crash rates by 17% • Decrease in speeding by 10%

3.3.2 Work Zone Intrusion Alert Systems

Work Zone Intrusion Alert Systems (WZIASs) are designed to warn workers of an unauthorized intrusion of a WZ perimeter. Although WZIAS are primarily developed to alert workers, some WZIASs are designed to alert motorists as well (Mishra et al., 2021). Most WZIASs comprise two components, a sensor unit designed to detect intruder vehicles and an alarm/alert unit that produces visual, audio, or vibratory alerts to warn the worker of the intrusion. Numerous WZIASs have been developed over the years since their inception under the Strategic Highway Research Program (Agent & Hibbs, 1996). However, most WZIAS face issues such as lengthy set-up time, false alarms, misfires, and alignment difficulties (Awolusi & Marks, 2019). Some notable WZIASs that have been tested several times over the years are Traffic Guard Worker Alert System (WAS), Intellicone, and Advanced Warning And Risk Evasion (AWARE) (see Table 3). WAS uses a pneumatic sensor that is activated when a vehicle runs over it. Alerts are transmitted to the workers via site alarms and personal safety devices. Intellicone is an impact-activated system that traffic cone mountable sensors to detect intruder vehicles upon impact. It uses wireless technology to transmit signals from the sensors to site alarm. AWARE is an advanced warning system that uses radar to detect intruding vehicles based on a threshold speed value. The system produces warning sounds and lights to warn the drivers and workers. Workers can also use a personal safety device that provides a haptic and auditory alert. Intellicone and AWARE also have several features such as inventory management and active status tracking that enable real-time monitoring of WZs and the systems. However, it should be noted that these systems are not integrated with existing transportation structures such as ITS.

Other technologies have also been developed and tested such as the Intelligent Drum Line (IDL) and a Wireless Sensor Network (WSN) based system but not as widely as those mentioned earlier. IDL was developed and tested by the Minnesota Department of Transportation (Hourdos, 2012). It used a series of modified drums to detect the speed of passing vehicles and activate warning alerts when the prespecified threshold speed was detected. The WSN-based system used a barrier-mountable sensor to detect intrusions and a modified wristwatch to alert workers of the intrusion (Martin et al., 2016). Table 3 presents some notable WZIAS in the literature and results from their evaluation. WZIASs are used in some countries (e.g., Intellicone in the UK), but the literature offered no evidence of such systems currently being used in the US.

Table 3. Findings and recommendations for Work Zone Intrusion Alert Systems

System(s)	Study	Major findings	Recommendations
Intelligent Drum Line (IDL)	(Hourdos, 2012)	• Successful in detecting high-speed vehicles and producing alerts • The cost of manufacturing the system is <$2,000	Improvement in IDL design is needed to make it meet FHWA crash worthiness standards
Intellicone	(Novosel, 2014)	• Condition of channelizers affects mounting of sensors • Risk of the sensor being runover	• Louder alarms desired by workers
Wireless Sensor Network	(Martin et al., 2016)	• The system is not 100% accurate in detecting intrusions (a 3.5% false positive rate)	• Further research of the technology needed to improve accuracy
Intellicone, WAS	(Gambatese et al., 2017)	• Useless when there is no impact (Intellicone) • Poor range (WAS) • Costly (WAS)	• Improve the range of the systems • Provide haptic feedback in addition to sound and light alerts • Visual alarms for equipment operators • Non-impact-activated systems are better

System(s)	Study	Major findings	Recommendations
Intellicone, AWARE, WAS	(Awolusi & Marks, 2019; Marks et al., 2017)	• Personal alerts are delayed by up to 2.5seconds (WAS) • Driver reaction quicker for Intellicone vs WAS	• Use Intellicone on longer tapers and longer duration WZs (> 1 day) • Use AWARE on longer tapers (>1,500 ft) and mobile operations • Use WAS on short tapers and short-duration WZs • Educating and training personnel regarding system use and maintenance
AWARE	(Theiss et al., 2018; G. L. Ullman, Trout, et al., 2016)	• The alert sound might be confused with an emergency response vehicle siren • 100% accurate in detecting speeding vehicles	• Change alarm sound to be different from emergency response vehicle siren • Use white flashing lights rather than amber/red
Intellicone, and WAS	(Khan et al., 2019)	• Low alarm sound but good transmission range (WAS) • Louder alarm desired (Intellicone) • A large number of sensors are needed (Intellicone)	• The site alarm should be mountable on traffic channelizers (WAS) • The incorporate belt clip-on personal alarm (WAS) • Alerts should incorporate flashing lights and sound
Intellicone, WAS, AWARE	(Mishra et al., 2021)	• Workers generally accept WZIAS but are unsure of their effectiveness • Costly (AWARE) • Connectivity issues (Intellicone) • Delay alert on a personal device (WAS)	• Implement systems based on speed limit/taper length and duration of work • Incorporate WZIAS technologies into MUTCD guidelines by specifying use cases and buffer space requirements
Intellicone, WAS, AWARE	(Thapa & Mishra, 2021)	• WZ crashes are associated with intrusion speed, spacing of WZIAS sensor and worker, and worker reaction times	
Intellicone, WAS	(Nnaji et al., 2018; Nnaji, Karakhan, et al., 2020)	• Intellicone is more cost-effective than WAS per unit mile	• Incorporate more factors for Choosing by alternatives (CBA) method before selecting WZIAS for implementation
LiDAR (Light Detection And Ranging) based system	(Darwesh et al., 2021)	• LiDAR-based intrusion detection system showed a high precision of 100% in detecting vehicles	• Future development should study the efficacy of the LiDAR-based system with an alarm system

3.3.3 Queue Warning Systems

Queue Warning Systems (QWSs) are used to detect the formation of queues downstream and warn incoming drivers. The system uses Variable Message Signs (VMSs) to display information to the drivers. This allows drivers enough time to slow down or take alternate routes allowing greater time for the queue to dissipate. Such a system has proven effective in reducing end-of-queue crashes which are mostly real-end crashes (G. L. Ullman, Iragavarapu, et al., 2016), and also improving traffic flow (Hourdos et al., 2017). Since QWS uses sensors and VMS, it is often difficult and expensive to install and relocate. To reduce the cost associate with QWS implementation, researchers have sought to develop and test portable and low-cost QWS which have been proven effective in reducing crash and crash severities (T. Morris et al., 2011;

G. L. Ullman, Iragavarapu, et al., 2016). Table 4 presents findings from studies investigating the effects of QWSs.

Table 4. Effect of Queue Warning Systems on driver behavior

Study	Findings
(Hsieh et al., 2017; G. L. Ullman, Iragavarapu, et al., 2016)	• A 44% reduction in crashes was observed when the system was installed in nighttime WZ • Crashes that occurred were less severe with fewer high-speed crashes • Considering benefits from reduced crashes, the system was break-even after 95-195 nights of use
(Khazraeian et al., 2017)	• Even at low penetration rates of 3%, Connected Vehicles (CVs) can estimate end-of-queue and queue lengths more accurately than detectors • 6% CV penetration can estimate end-of-queue locations with a 4% average error • QWS reduces rear-end collisions considerably • More than a 15% compliance rate is required for safety effects to be significant
(Hourdos et al., 2017)	• 22% reduction in crashes after QWS was installed • Reduced speed variations near queue locations and upstream/downstream traffic
(Bashir & Zlatkovic, 2021)	• CV-based QWS can provide considerable safety benefits and operational benefits to freight traffic • With a 25% CV penetration, time to collision increased by up to 4 times • A reduction in travel time and speed variations were observed

3.3.4 Variable Message Signs

VMSs are used to display regulatory or warning messages in and around WZs. These systems are used with sensors and detection systems such as the queue detection system. VMS displays predefined messages based on data collected using dedicated sensors that measure roadway occupancy, travel speed, and weather/roadway conditions. Using VMS to regulate speed near WZs has been proven to provide several benefits such as reduction of travel delays, congestion prevention, and reduced traffic hazards. VMS in the literature is also referred to as Changeable Message Sign (CMS) and Dynamic Message Sign (DMS) due to their ability to change messages based on the conditions. Since VMS need to be relocated from one place to another, researchers have also developed portable VMS (Bai et al., 2011; Huang & Bai, 2019).

VMS has been used along US Highways since the 1960s. The FHWA has sought to make the use of VMS effective through guidelines and a handbook prepared as early as 1986 with the most recent operation handbook published in 2004 to guide personnel using the system (Dudek, 2004). Since the system is designed to display predefined messages, studies have aimed to investigate their effectiveness when various error messages are used (Zech et al., 2008). Additionally, a major focus in VMS research has been to study (i) the placement of VMS and its effect (Strawderman et al., 2013), (ii) the effectiveness of VMS (Bham & Leu, 2018; Harder & Bloomfield, 2008; Huang & Bai, 2019; Ma et al., 2014; W. Zhao et al., 2020), and (iii) motorists' understanding of VMS messages (Dutta et al., 2004; J.-H. Wang et al., 2005; C. Xu et al., 2020). Although previous studies have found VMS to be effective, researchers have reported its effect on drivers has been diminishing over the years (Foo & Abdulhai, 2006). Current research in VMS has shifted from the use of sensors to Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. For example, (Ibrahim et al., 2013) investigated the use of V2V and V2I enabling Dedicated Short-Range Communications (DSRC) infrastructure for improving traffic flow and safety WZs. They reported that at a 50% DSRC penetration rate, only about 10 veh/miles (7 veh/km) were needed for the effective transmission of information. Table 5 summarizes the effects of VMS on driver behavior reported in the literature.

Table 5. Effect of Variable Message Sign on driver behavior

Study	Findings
(Garber & Patel, 1994; Garber & Srinivasan, 1998)	• Effective in reducing speed in WZs • Compliant drivers are more likely to speed back up at the end of a WZ • Multiple VMSs are needed in longer WZs to maintain speed compliance • No difference in speed reduction across vehicle types
(B. R. Ullman et al., 2007; G. L. Ullman et al., 2005)	• Comprehension of messages delivered using Sequential Portable CMS (Sequential PCMS) with four units of information is comparable to a single large DMS displaying all information at once • Using more than five units of information in Sequential PCMS is not advised
(Zech et al., 2008)	• Type of messages (wordings) have different effects on driver compliance • The message “WORK ZONE|MAX SPEED|45 MPH|BE|PREPARED|TO STOP” resulted in most compliance with speeds reduced by up to 6.7 mph (10.78 km/h)
(Messina et al., 2011)	• Drivers prefer text messages over graphic signs in VMS • Driver reactions to graphic signs are faster than text messages
(Strawderman et al., 2013)	• More vehicle slowdowns near VMS placed closest to the WZ area • The further away the VMS is from the WZ, the greater the compliance
(W. Xu et al., 2018)	• VMS instructing the lane change location is useful in influencing traffic flow • The lane change location should be moved closer to WZ with increasing traffic flow to make VMS more effective
(Bai et al., 2011; Huang & Bai, 2019)	• Graphics-aided PCMS are more effective in reducing speed than PCMS with text messages • Drivers preferred graphic-aided PCMS over text messages
(L. Zhao et al., 2022)	• 90% increase in speed compliance when VMS is used to display warning messages (“NONE”, “SLOW”, “STOP”) based on queues detected by a detection system
(Almallah et al., 2021)	• The use of flashing lights and animations in VMS reduced speed in the advanced warning area • VMS encouraged motorists to change lanes early and maintain headway

3.3.5 Speed Limit Advisory Signs

Speed Limit Advisory Signs (SLASs) are used in the WZs to warn drivers of the speed limit along a certain segment. These warnings are communicated to motorists using VMS. Variable Speed Limit (VSL) uses sensors to detect the traffic, roadway, or environmental conditions downstream and uses inbuilt algorithms to determine the appropriate speed limit for highway segment which is then displayed to incoming motorists. The speed limits are revised to improve traffic safety and increase traffic throughput, particularly in highway work zones and segments with recurrent bottlenecks through speed harmonization and regularization. Therefore, a considerable effort has been focused on developing algorithms to control VSL, particularly in highway WZ (e.g. (Du & Razavi, 2019, 2020; K.-P. Kang et al., 2004; Khondaker & Kattan, 2015; Papamichail et al., 2018)). More recently, (Hou et al., 2022) developed a dynamic VSL control using VMS. The system dynamically changes locations where VSL messages were displayed based on changing traffic conditions. Based on simulation results, their system showed up to an 8.4% improvement in travel time. Comparison between VSL and normal speed signs have proven the former to provide considerable benefits by reducing speed variations, improving speed compliance, and increasing traffic throughout. Interestingly, studies have found that the effect of VSL on traffic safety is more pronounced than on traffic flow (Lu & Shladover, 2014).

The Variable Advisory Speed System (VASS) is a technology that is quite similar to VSL but there is a key difference. Unlike VSL which determines the speed limit for a roadway segment based on downstream conditions, VASS warns drivers of the static/dynamic speed limit downstream (Wilson & Saito, 2012). Both VSL and VASS have been shown to provide similar benefits.

Another system used for providing advisory messages is the Dynamic Speed Feedback System (DSFS). DSFS is designed to avoid over speeding near WZs by drawing the driver's attention. The system uses sensors to detect the speed of the approaching vehicle and displays flashing messages if a pre-specified threshold is crossed. The literature suggests that DSFS is very effective in reducing driver speeds (Flynn et al., 2020). The reader can refer to the most recent review of the literature by (Fisher et al., 2021) for more research related to DSFS. Table 6 presents selected studies that have reported findings from the application of SLAS in WZs.

Table 6. Effect of Speed Limit Advisory Signs on driver behavior

Study	Findings
(Pesti & McCoy, 2001) (DSFS)	• Reduction in speed and speed variation was observed over 5 weeks of installing DSFS in a rural interstate • Greater compliance from passenger vehicles • Speed reduction from DSFS can last at least a week after its removal long
(Mattox et al., 2007) (DSFS)	• DSFS is a cheaper alternative to more expensive systems for traffic calming • The average reduction in vehicle speeds was reported to be 4.1 mi/h (6.6 km/h) where 50% of motorists violated the speed limit before system implementation
(Kwon et al., 2007) (VASS)	• Developed a system that reduced traffic speed upstream to match downstream traffic spread increased traffic throughout by up to 7% • The difference in 1-min maximum speed was reduced by 25%-35%
(McMurtry et al., 2008) (VSL)	• VSL signs can successfully lower speed variations near WZs • Developing trust among drivers is necessary
(Fudala & Fontaine, 2010) (VSL)	• VSL significant advantage over static signs during high demand • VSL can delay congestion and improve speed compliance • The location of VSL is important to ensure driver acceleration after passing through a bottleneck
(Radwan et al., 2011) (VSL)	• VSL + Dynamic Lane Merge System provides better speed compliance and throughput compared to them being used individually • In high-traffic volumes, higher speed compliance is associated with reduced throughput
(Wilson & Saito, 2012) (VASS)	• The difference in vehicle speeds is statistically insignificant on Weekdays • An increase in mean speed and a decrease in speed variance was observed
(Roberts & Smaglik, 2012) (DSFS)	• The number of speeders traveling 5-10 mi/h (8-16 km/h) above the speed limit decreased by one-fourth when displaying the monetary value of the fine with the warning message • People driving 15, 20, and 25 mi/h (24.14, 32, and 40.23 km/h) were reduced by 50%
(Edara et al., 2013) (VSL)	• VSL increases speed compliance by 8 folds • Better speed compliance was observed but with less throughput • VSL use is recommended in uncongested WZs for speed compliance and reducing speed variation
(Gambatese & Jafarnejad, 2015) (DSFS)	• Up to 23% decrease in 85th percentile speed of vehicles when using DSFS mounted on a truck • Up to 48% reduction in speeders when using the DSFS
(Mekker et al., 2016) (VSL)	• Better compliance was observed from commercial trucks • About 4% of cars complied with the speed limit • The median reduction in speed was 7.5 mi/h (12.07 km/h)

3.3.6 Dynamic Lane Merge Systems

Lane Merge Systems (LMSs) are technologies that assist drivers in merging at lane closures by identifying safe merge locations. While studies have shown considerable benefits of using LMS (reduced queues, travel delay, and greater throughput), the scale of benefits reported is often overestimated (Beacher et al., 2004, 2005). Therefore, Dynamic LMS (DLMSs) was developed to automate LMS using sensors that collect traffic data. DLMSs detect traffic conditions in real-time and adopts lane merge control strategies which are communicated to motorists using VMS. DLMSs are used to improve traffic flow in congested WZs and reduce travel delays and vehicle queues and are of two types. There are two types of DLMSs, Dynamic Early Merge Systems (DELMS) and Dynamic Late Merge Systems (DLLMS). DELMS instructs drivers to merge in advance before encountering a traffic queue downstream. On the contrary, DLLMS instructs drivers to merge at a "point" that is closer to the lane closure. This reduces traffic queues on travel lanes. Previous research has shown that DLLMS is better than DELMS in increasing traffic throughput and improving travel times compared to DELMS, however, confusion among drivers is also higher when it is employed (McCoy et al., 1999; Tarko et al., 1998). Researchers have also proposed signalized lane merge controls near WZs to improve safety (Qi & Zhao, 2017; Wei & Pavithran, 2006). The approach uses metering to detect traffic demand and flash green/red lights instructing drivers when it is safe to merge. Recently, the CV-enabled Cooperative Late merge System (CLMS) has also gained popularity. In addition to providing lane change assistance CLMS is also capable of reducing ve hicle headways and synchronizing vehicle speed thus providing considerably more benefits compared to the traditional LMS (Algomaiah & Li, 2022). CLMS uses V2V communications to instruct motorists to cooperate with other motorists and merge at the late merge area when it is safe (Algomaiah & Li, 2021).

As with other systems that use sensors and algorithms to provide instructions to motorists, cost and ease of deployment are major concerns with DLMS. Researchers have pointed out that the installation and relocation costs of DLMS are considerably large (Datta et al., 2004). For this reason, researchers have developed and tested DLMS systems that are portable and also cost-efficient although the accuracy of sensors is often an issue (Harb et al., 2011; Radwan et al., 2009). Table 7 presents a summary of the literature on DLMS and similar systems with the findings.

Table 7. Effect of Dynamic Lane Merge Systems on driver behavior

Study	Findings
(Meyer, 2004)	• No notable improvement in traffic flow • Driver compliance and lane change behavior not as intended
(Datta et al., 2004)	• DELMS can improve traffic flow, reduce travel delays and aggressive driving maneuvers near WZs • DELMS provides a benefit-to-cost ratio of up to 1.96 if installed for at least two months at a site
(Wei & Pavithran, 2006)	• Dynamic merge metering in WZ can reduce WZs by discharging queues at a uniform rate • Reduction in side-swipe crashes since there is no need to change lanes only when an adequate vehicle gap is available
(Yulong & Leilei, 2007)	• Intelligent LMS can reduce delays and relieve congestion • Can reduce traffic conflicts near WZs
(Grillo et al., 2008)	• Improved flow and percentage of merging vehicles at the taper • Considerable reduction in travel delays when using DLLMS and DELMS • DELMS use is recommended in rural congested roadways to reduce driving aggression • DLLMS use is recommended in urban roadways to reduce queues • A high benefit-to-cost ratio
(Sperry et al., 2009)	• The use of DMS and DLLMS was problematic due to sensor errors • DMS has no considerable impact on drivers' merging behavior

Study	Findings
(Harb et al., 2011; Radwan et al., 2009)	• Installation and relocation costs for DLMS make them inefficient • A simplified and cost-effective version of DLMS is necessary • Simplified DLLMS and DELMS are effective but should be employed based on demand volumes
(Ren et al., 2020)	• Reinforcement Learning based Cooperative LMS outperforms other lane merge strategies
(Algomaiah & Li, 2021, 2022)	• CLMS offers superior performance compared to LMS in terms of queue length, traffic throughout, and travel delays • High compliance rate in moderate to high traffic demand

3.3.7 Other technologies

Several systems and technologies currently available are either new or sparsely studied in the past. Regardless, these technologies have a promising outlook. A brief introduction to two such systems is presented here is provided here.

Autonomous Truck Mounted Attenuator (ATMA) which is also called autonomous impact protection are TMAs that can autonomously maintain a safety gap between them and the activity area within a WZ. This is achieved by establishing V2V communication between a leader and the follower vehicle of which the latter is the TMA. This allows the follower vehicle to move behind the leader vehicle autonomously while also maintaining a safe buffer space. This is a relatively new technology that reportedly performs consistently as expected in terms of maintaining a safe distance through information exchange (Kohls, 2019; Tang et al., 2021). The technology has so far been tested in the UK and the US (Kohls, 2019; Kratos Defense & Security, 2017).

The Automated Cone Placement and Retrieval System is an automated machine/system that can deploy and retrieve cones from WZs. An example of such a system is the Automated Cone Machine (ACM). The prototype ACM vehicle capable of installing and removing traffic cones was developed and tested in 2004 (Velinsky & White, 2004). Another example is the Automated Cone Truck (ACT) used in Australia. The ACT is a vehicle that can be operated by the driver for the semi-autonomous deployment of and retrieval of traffic cones (ARROWES Roading Safety, 2022).

4. Results and Discussion

Real-time WZ management systems that can integrate with current WZ practices are necessary to create smart WZs. It is also necessary that future workers are skilled and qualified to operate in a 'smart' environment. Therefore, based on the literature review, two main aspects need to be considered for the proliferation of SWZSs. These are (i) developing and implementing 'smarter' systems, and (ii) worker training and adaptation to support their use. These are detailed below.

4.1 Development of systems and technologies

4.1.1 System development and implementation

First, as previously mentioned, an SWZS should be capable of accomplishing the following tasks.

i. Detect and communicate in real-time,
ii. be portable and easy to deploy,
iii. operate automatically with minimal supervision, and
iv. provide accurate and reliable information to road users.

However, no system currently employed in WZs meets all these requirements. Promising SWZSs that can accomplish some, if not all, of these tasks, have been tested but never adopted or integrated with the existing ITS infrastructure (e.g., WZIAS such as AWARE). Moreover, based on the literature review it is safe to assert that the complexity of developing/procuring, installing infrastructure components, and evaluating SWZS almost always makes their deployment an expensive endeavor whose benefits might not always outweigh the investment. For example, most SWZSs today use sensors embedded in the road which makes them difficult to install and relocate. This has continued to hinder the widespread application of these technologies for WZ safety. While this has motivated researchers to develop more portable and cheaper systems that use less invasive sensors such as radar and cameras, they are not manufactured at a commercial scale and are often limited to field testing. Most of these systems, therefore, end up not being adopted despite showing promising results (e.g., (Harb et al., 2011; Radwan et al., 2009)). This cautious attitude toward technology adoption stems from a scarcity of resources to assist construction professionals in determining whether to adopt a particular technology. Even though previous research has proposed stringent protocols for evaluating WZ technologies, many construction professionals are unsure how to put them into practice (Nnaji, Karakhan, et al., 2020). We recommend steps that can be taken during the stages of development, evaluation, and implementation.

It is evident from our discussion that cost, and portability are the greatest hindrances to the wide adoption of SWZS. Therefore, future WZ technologies should be studied and developed from a financial perspective. Manufacturers should implement a review and support process by involving DOTs and researchers in product development to ensure their system is cost-effective and the return on investment is justified.

For system evaluation after their development, transportation agencies need to develop standard procedures and protocols. Based on the review it is evident that several methodological approaches have been implemented to evaluate WZ systems. While varying methodological approaches is not an issue, no "minimum benchmark" has been established to guide the testing process. For example, what should be the least allowable error permitted in detecting speed when using ASE? State and federal transportation agencies should therefore consider setting benchmarks for system evaluation.

There is also a need to investigate system implementation as little research has been conducted in this direction. Most WZ safety systems are costly, and each has its strengths and weaknesses. Therefore, there might be a case where one system, when used with another, can complement one another, and improve overall safety and traffic throughout to justify their high cost. For example, (Thapa & Mishra, 2021) have pointed out that using RADAR and impact-based WZIAS together in a WZ can increase coverage and reduce the possibility of missed detections. Future research should focus on this direction by developing a framework for system selection (e.g., see (Nnaji et al., 2018)).

4.1.2 Development of V2V, V2I, and CAV technology

The advent of wireless V2V and V2I communications, CAVs enabled by the ITS infrastructure has made it possible to develop systems and technologies that do not rely on physical system components such as loop detectors, road-side cameras, and sensors. Particularly, CAVs have the potential to automate all traffic operations with automated cooperative features that control vehicle speed, spacing, and lane change (Z. Wang et al., 2020; Z. Xu et al., 2021). They will be capable of identifying WZs and lane closures automatically using data from multiple sensors and cameras (Shi & Rajkumar, 2021). These features will improve overall traffic safety, and efficiency and alleviate the need to develop SWZSs for specific tasks such as lane merge, speed enforcement, etc. For example, (Algomaiah & Li, 2021) has demonstrated that the CAV-enabled cooperative late merge method outperforms the late merge strategy without a CAV in operational performance due to its ability to maintain optimal spacing. However, CAVs equipped with low to medium-level automation systems that are incapable of effectively addressing WZ situations in all conditions may initiate control transitions and impending minimum-risk maneuvers, causing severe traffic interruption and several safety-critical occurrences (Mintsis et al., 2020). The magnitude of CAV impact will also depend on their penetration rate (e.g., (Abdulsattar et al., 2020; Bashir & Zlatkovic, 2021)). Currently, CAV penetration rates are very low to have any measurable impact. With the impending penetration of CAVs into the highway network, utilizing the highly efficient safety and mobility functions of CAVs in WZs is likely to be an active and significant area of research (Dehman & Farooq, 2021; Wu et al., 2020).

With the gradually growing penetration rates of CAVs and ITS infrastructure, there is also a growing concern with data safety and their acceptance which needs to be addressed first (Thapa et al., 2021). Recent cyber-physical intrusions on DMS across the nation highlight the challenges that current and future ITS infrastructure faces and call attention to security risks. Since the first known DMS hacking twelve years ago, hacked DMS has become more prevalent and problematic (Kelarestaghi et al., 2018). Nevertheless, there is a dearth of information regarding how and to what degree motorists react to a breach of ITS infrastructure and the inaccurate information disseminated by hackers (Bakhsh Kelarestaghi et al., 2020; Ermagun, Kelarestaghi, & Heaslip, 2021; Ermagun, Kelarestaghi, Finney, et al., 2021). In this regard, (Ermagun, Kelarestaghi, Finney, et al., 2021) contended that fabricated messages confuse drivers and influence their speed in WZs, both of which may impair WZ safety. Therefore, cyber-security should be a concern to federal, state, and local authorities as well as researchers. Moreover, a complete understanding of risks arising from an impaired ITS infrastructure can help agencies and the public prepare for an attack. Therefore, future research should focus on the flaws and vulnerabilities of transportation systems, possible implications, and solutions (Ermagun, Kelarestaghi, Finney, et al., 2021).

4.1.3 Implementing worker monitoring and tracking technologies

The literature suggests that the next frontier in WZ safety is the automation of WZ operations. WZs have limited space with vehicles, construction equipment, and personnel operating close to one another. The lack of space creates hazardous conditions which make workers prone mainly to struck-by crashes. To minimize the risk of such crashes, automated systems have been developed that can monitor and track worker location and issue alerts to selected workers based on their proximity to a hazard. Recent research has explored the use of Global Positioning System (GPS), Radio Frequency Identification (RFID), Ultra-Wideband (UWB), and Bluetooth technologies to track the location and proximity of workers, machinery, and vehicles. Among these technologies, UWB has been proven to be more accurate and feasible, offering location within a precision of 2cm-15cm. However, it is difficult to implement on sites without WLAN infrastructure and requires a line of sight for effective signal transmission (Fang et al., 2016). Most recently, (Gnawali & Kim, 2022) developed a UWB-based system called Vehicle Pose Estimation using ultra-wideband Radios (ViPER) which showed very high accuracy, greater than 98%, in detecting workers and equipment successfully. Table 8 highlights some of the findings from various monitoring and tracking technologies.

While there has been considerable research on these technologies, their implementation in WZs is absent. SWZSs of the future should incorporate worker, equipment, and vehicle detection and tracking technologies to automate WZ management and monitor WZ safety in real time. Future research in this direction should focus on implementing sensor and decision systems that can seamlessly integrate with present WZ practices and technologies.

Table 8. Worker monitoring and tracking technologies

Study	Description	Findings
(Park et al., 2016)	Comparison of proximity detection and alert systems based on RFID, Magnetic, and Bluetooth technologies	• Minimal false alerts from RFID and Bluetooth systems, no false alerts from Magnetic system • Alert distance for Magnetic system may not be adequate for avoiding the hazard • Setup time for Bluetooth the least of the three
(Park, Kim, et al., 2017)	Developed a safety monitoring system for construction that uses Bluetooth for location detection, Building Information Model (BIM) for hazard identification, and a cloud for communication	• Successful detection of potentially hazardous situations with reliable detection of 97.5% • The use of sensors might reduce detection and tracking errors
(Park, Yang, et al., 2017)	Developed and tested a Bluetooth-based proximity sensor and alarm system for	• Decrease in the average alert distance when the system is traveling at a higher speed

Study	Description	Findings
	dynamic conditions (when either the worker or the vehicle is moving)	• The signal processing method has a notable impact on the magnitude and consistency of alert distances
(Park, Chen, et al., 2017)	Developed a hybrid system with absolute and relative motion tracking sensors in construction sites based on Bluetooth and inertial measurement unit, respectively along with BIM	• In a scenario where worker movements are more complex (with sharp turns), tracking becomes inaccurate • Integration of the motion sensors and BIM reduces tracking error
(Teizer et al., 2008)	Used UWB in tracking worker location under realistic working in construction operations with	• UWB can measure locations with an accuracy of less than 1 m • Installation time was considerably longer but the system was easy to maintain • UWB systems in construction sites should be rugged in design
(Carbonari et al., 2011)	Tested a prototype UWB-based position tracking system for construction operations with proactive virtual fencing logic to warn workers and inspectors of imminent risk in an area	• False alarms were frequent when workers walked parallel to the fence perimeter • Change in control algorithms was necessary to reduce the likelihood of false alarms • The system was overall accurate in detecting worker location and providing alerts
(Gnawali & Kim, 2022)	Developed and tested a real-time UWB-based location tracking and monitoring system for construction vehicles and equipment	• The system was able to track workers and vehicles with an accuracy of 100% and 98.4%, respectively • More rigorous testing of the system under rare WZ conditions necessary to validate the system • Necessitates many signal readers, resulting in substantial system infrastructure
(Fang et al., 2016)	Employed a BIM and cloud-based RFID localization system to test system accuracy considering practical criteria	• Worker position detected with a 88% accuracy • System components should be closer to the workers to ensure accuracy • System components with a faster refresh rate are desired for improved accuracy
(Arslan et al., 2017)	Developed an application that collects and processes GPS data points to create worker movement and trajectories to monitor construction activity	• The application can be used only for outdoor activities due to GPS interference indoors • Obtaining contextual information needed to interpret worker movements cannot be derived from GPS
(Jiang & Li, 2002)	A vehicle with GPS used to measure vehicle position, traffic flow, travel delay, and queue formation in a work zone in Indiana	• The GPS device was accurate within 1 m and 0.1 mph (0.16 km/h) • Real-time estimation of vehicle acceleration, deceleration, and queues are readily achievable using GPS

4.1.4 Worker wearables for transmitting safety alerts and messages

As mentioned in the previous section, SWZS should facilitate automated intrusion detection and warning. In this context, the use of wearables that are connected to detectors has considerable potential. Such wearables serve two main purposes, (i) detect worker location and activity for WZ management and risk perception, and (ii) provide alerts to workers under hazardous conditions such as vehicle intrusion. Communicating in a WZ is usually difficult due to its confusing and distracting nature which arises from loud operating machinery and its dynamic nature. As a result, a worker might often be unable to perceive an alert, or in case of an alert, be aware of the source and location of the hazard. In this context, wearables with message-encoded sound alerts or haptic feedback are particularly pertinent. Although current worker wearables used in WZs provide warnings, they do not convey messages on safe actions.

Researchers have developed and tested wearable tactile feedback systems with unique tactile languages in controlled settings (Cho & Park, 2018; Sakhakarmi & Park, 2022). The strategy followed by

(Cho & Park, 2018) was to use a modified safety vest embedded with motors to convey different tactile intensities and durations to communicate specific messages (e.g., low-intensity level and duration can correspond to the message "move right"). This system was further improved to communicate information about the zone of intrusion and level of risk to the workers using the relative location of motors within the vest and the vibration pattern, respectively (Sakhakarmi & Park, 2022). However, the authors note that proper worker training is needed to increase the accuracy of worker perception and reaction. While the haptic-based hazard communication system has proven very effective in acquiring desired safety maneuvers from workers in controlled field tests, their implementation in WZs is still lacking (Cho & Park, 2018; Sakhakarmi & Park, 2022). Future developments should incorporate the use of similar wearable alert systems along with other detection and tracking systems, particularly intrusion detection systems. Furthermore, the current issue highlights the need to develop worker training strategies.

4.2 Virtual Reality-based worker training and adaptation

A considerable effort has been expended on SWZ. In contrast, a trivial effect has been put on preparing and training the workforce accordingly. It has been reported that in absence of adequate training and knowledge, workers could render SWZSs ineffective. For example, (Mishra et al., 2021) report that the use of the AWARE WZ intrusion detection system could be less effective when used by technologically conservative individuals since the system can only be configured through a smartphone application. Therefore, perception and ease of use have been central to SWZSs that are deployed by workers in the field (e.g., WZIAS). Moreover, it is crucial that the workforce is competent, well-trained, and adapted to SWZ practices. The current worker training approach largely relies on passive strategies such as demonstrations and information dissemination through reports, presentations, and case studies. Active strategies such as simulation have a lasting impact on skill and memory retention compared to passive approaches (Dale, 1969). Therefore, Virtual Reality-based (VR-based) training will provide realistic and effective training conditions for workers by exposing them to situations that are comparable to those encountered in actual WZs (Chang et al., 2020; Sowndararajan et al., 2008).

VR-based training is upcoming technology and is used in various fields such as education (Matsika & Zhou, 2021; Reeves et al., 2021; Srinivasa et al., 2020), medicine (Mansoory et al., 2021; Mao et al., 2021; Rothlind et al., 2021; Yamazaki et al., 2021), construction (F.-Z. Wang et al., 2021; X. Wang et al., 2021; Z. Zhang & Pan, 2021), and so on. One of the advantages of VR-based training is that the trainer can record the trainee's whole activity throughout the educational process, including any errors made during a particular training period. Additional data collected during the training (such as worker reaction) can be used to correct worker response, rearrange WZ elements and improve overall WZ safety. (Wittenberg, 1995) concludes that VR-based training produces superior results than real-world training, is more cost-efficient, and does not require expensive factory equipment to be used for training purposes. Some of the advantages offered by VR-based safety training include:

i. Presenting trainees with threats directly and realistically without jeopardizing their safety.
ii. Holding trainees' attention was better than traditional classroom teaching.
iii. Giving trainees a degree of control in the environment reinforces learning.
iv. Allowing trainers to repeat learning content for many participants under the same training conditions.

While VR-based training is still new to the WZ literature, we present some studies and findings from similar fields related to occupational safety and health in Table 9. These studies highlight the benefits of VR-based training in different fields.

Table 9. Results from VR-based training on participants

Study	Training Purpose	Benefits
(Seymour et al., 2002)	Technical skills in the Operating Room (OR) environment.	The use of VR surgical simulation to reach specific target criteria significantly improved the OR performance of residents during laparoscopic cholecystectomy.
(Patrão & Menezes, 2013)	Training of tower crane operators, reducing their costs and risks.	The VR simulator is robust, reliable, and provides an experience very similar to reality.
(H. M. Li & Kang, 2014)	Safety Training System for Coal Mining Industry	The system can provide an intuitive approach to studying safety knowledge and provide interactive exercises for learning self-rescue and escape in disasters. Virtual reality training can provide more meaningful and effective training to address the identified safety needs in the coal mining industry.
(Grabowski & Jankowski, 2015)	Coal mine safety training	Trainees consider the used system useful. The miners feel the positive effects of training even after three months.
(Çakiroğlu & Gökoğlu, 2019)	Teach basic behavioral skills for fire safety	The results indicated that students' fire safety behavioral skills significantly improved with virtual reality-based training, and most of the students could transfer their behavioral skills to real environments.
(Reeves et al., 2021)	Undergraduate students learning chemistry in VR laboratories	Improved learning experience
(Fortes et al., 2021)	Training on passing decision-making, visual search behavior, and inhibitory control performance in young soccer athletes	VR leads to more significant improvements in decision-making and visual search behavior
(Liu et al., 2021)	Port Safety Training	Trainees can have a high degree of safety awareness to reduce the accident rate effectively.

Although VR-based training has demonstrated effectiveness in other fields, there are several challenges that users must contend with. Developing various construction simulations in VR will take time and effort. Further, some researchers claim that VR trainees retain the same level of safety information as conventional methods (Burke et al., 2011; Hilfert et al., 2016; Sacks et al., 2013; Zaker & Coloma, 2018). Therefore, there is a need to develop a methodological approach for VR-based training. Simulating all possible safety scenarios in VR will be a challenging task. Based on practices from other fields, we recommend the stages outlined in Fig. 7 for developing a VR-based worker training environment with the worker training strategy in Fig. 8. The proposed strategy is an iterative process that is repeated until a worker shows appropriate action.

5. Conclusion

This study conducted a systematic mapping review of the literature to identify the crucial elements of an SWZ. Using the LDA model, we found that the WZ-related studies can be grouped into four major topics: safety, control, design, and cost. Further, a comprehensive review of the "smart" WZ components for safety and mobility was performed.

Studies have shown that rear-end and side-swipe crashes are the most common type of crashes in a WZ, resulting from the significant speed differential, queue formation, and forced lane change requirements. Therefore, the safety improvement strategies at WZs must focus on speed harmonization, queue warning and dissipation systems, and appropriate lane merge strategies.

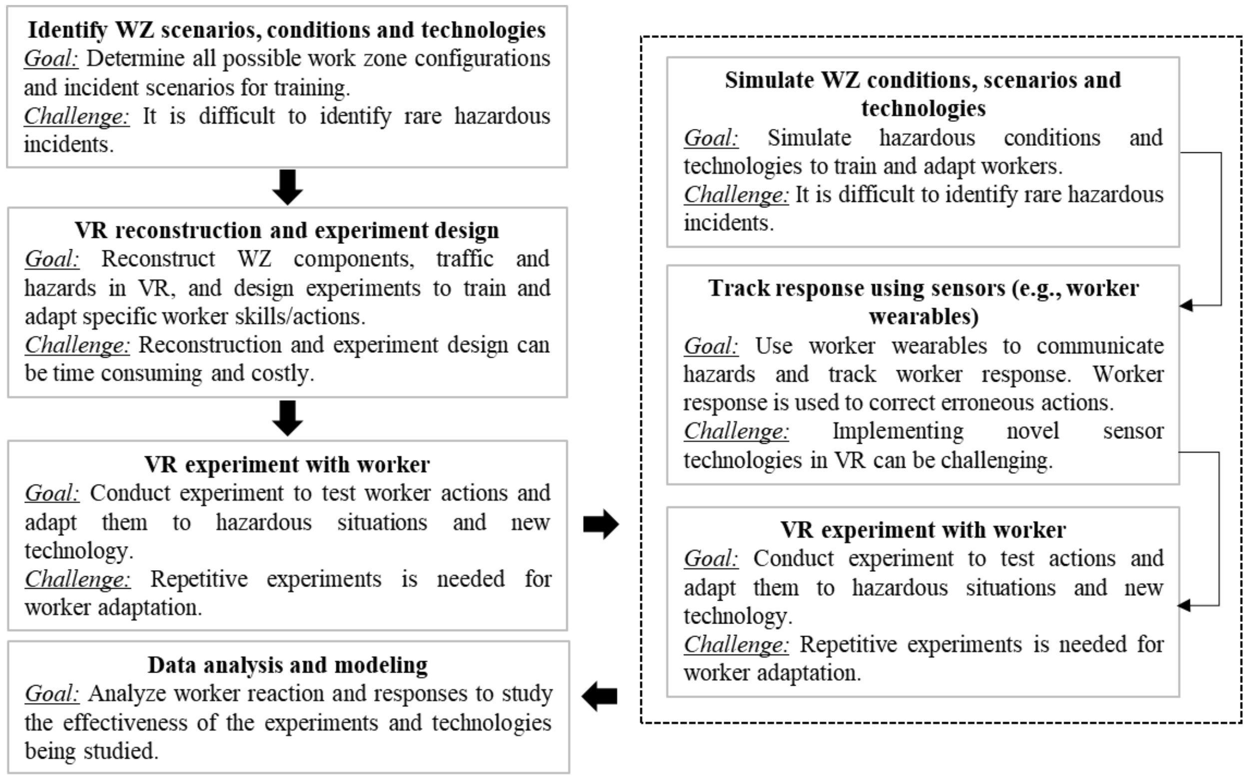

Fig. 7. Stages of VR-based worker training for WZs

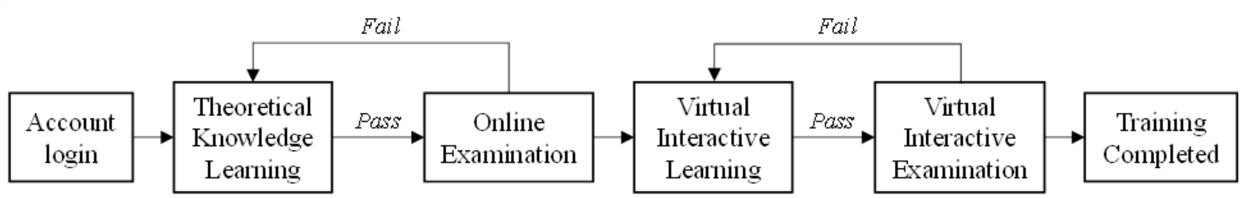

Fig. 8. Worker training strategy using VR-technology

It has been found that the lack of a predictive safety system that alerts the workers about impending danger is a major reason for the increased worker injury at WZs. The use of wearable technology with predictive warning capability was reported to benefit worker safety significantly. Besides, the lack of adequate worker education/training was a major cause of worker injuries. While the technology capable of making WZ smart is still developing, this study highlights the need to implement them in a manner that facilitates the continued application of current policy and practices. To support the implementation of 'smart' systems, there is a need to implement virtual reality as a training and adaptation tool for educating and training workers. An innovative training strategy based on virtual reality may provide more realistic conditions for workers to experience situations comparable to those encountered in actual WZs.

The article finishes by discussing the prospects of an SWZ. It has been found that, though the concept of SWZ is very innovative, its implementation in the real field demands overcoming issues related to the high cost and limited portability. Additionally, several steps can be taken to remove barriers to the proliferation of adoption by agencies and project managers. These steps should address the lack of an appropriate simulation platform to generate and test WZ scenarios, and the possible infiltration of the hackers into the electronic components of SWZ. Indeed, there has been increased research interest in the SWZ recently. Although these efforts are promising, employers, employees, educators, and policymakers need to ensure that more people can pursue these opportunities and that technology improves the way we all work. The following are some future research directions that help to enhance work zone safety:

i. Investigate integration of currently available systems with available ITS infrastructure.
ii. Develop new safety technologies, or improve existing safety technologies, so they can be seamlessly integrated into current infrastructure.
iii. Develop and implement smart technologies that are cost-effective and portable to use.
iv. Develop guidelines and standards for the evaluation and selection of SWZSs.
v. Establish VR-based worker training/education strategy for SWZS systems adaptation.
vi. Investigate the interaction between different SWZSs and various WZ design/control attributes and their impact on safety, mobility, and overall cost must be investigated.

Limitations are inherent in all research, and this study is no exception. First, we limit our analysis to two topics, WZ safety, and mobility, due to the enormous literature covered. Two topics that were excluded from the current study are WZ design/maintenance and its cost. It might not be appropriate to focus on specific topics and an understanding of the interaction between all four components is necessary. This is crucial considering all the WZ topics are interrelated with one another. For example, longer WZ tapers are generally safer as it decreases the likelihood of fatal crashes. However, longer work zones require more man hours to set up and dismantle which increases project duration and associated costs (project and user costs). Further, longer durations have a direct impact on WZ safety as long-duration WZs are more likely to encounter crashes. Tackling these issues requires collectively addressing all facets of WZ, which includes safety, mobility, maintenance, and cost, most optimally. Second, this study does not compare the existing WZ design and operation guidelines with the research finding. We refrained from establishing such a comparison to avoid evaluating the relevance of research findings in terms of pre-existing guidelines. Such consideration could help avoid bias toward various research findings, even if they are contradictory but can be attributed to the WZ project environment. Indeed, the authors believe that existing guidelines require revision, a stance shared by several researchers. Finally, future research can extend beyond literature review and perform a meta-analysis of secondary data or information to validate the reliability of research findings.

References

Abdulsattar, H., Mostafizi, A., Siam, M. R. K., & Wang, H. (2020). Measuring the impacts of connected vehicles on travel time reliability in a work zone environment: an agent-based approach. *Journal of Intelligent Transportation Systems*, *24*(5), 421–436. https://doi.org/10.1080/15472450.2019.1573351

Adenaiya, K. (2017). *Maryland SafeZones: Work Zone Automated Speed Enforcement Program (Powerpoint presentation)*.

Agent, K. R., & Hibbs, J. O. (1996). *Evaluation of SHRP Work Zone Safety Devices*. 24.

Albert, A., Hallowell, M. R., & Kleiner, B. M. (2014). Enhancing Construction Hazard Recognition and Communication with Energy-Based Cognitive Mnemonics and Safety Meeting Maturity Model: Multiple Baseline Study. *Journal of Construction Engineering and Management*, *140*(2), 4013042. https://doi.org/10.1061/(asce)co.1943-7862.0000790

Algomaiah, M., & Li, Z. (2021). Exploring work zone late merge strategies with and without enabling connected vehicles technologies. *Transportation Research Interdisciplinary Perspectives*, *9*, 100316. https://doi.org/10.1016/j.trip.2021.100316

Algomaiah, M., & Li, Z. (2022). Enhancing Work Zone Capacity by a Cooperative Late Merge System Using Decentralized and Centralized Control Strategies. *Journal of Transportation Engineering, Part A: Systems*, *148*(2). https://doi.org/10.1061/JTEPBS.0000632

Almallah, M., Hussain, Q., Alhajyaseen, W. K. M., Pirdavani, A., Brijs, K., Dias, C., & Brijs, T. (2021). Improved traffic safety at work zones through animation-based variable message signs. *Accident Analysis & Prevention*, *159*, 106284. https://doi.org/10.1016/j.aap.2021.106284

Ambros, J., Turek, R., Elgner, J., Křivánková, Z., & Valentová, V. (2020). Effectiveness Evaluation of Section Speed Control in Czech Motorway Work Zones. *Safety*, *6*(3), 38. https://doi.org/10.3390/safety6030038

Andolfo, C., & Sadeghpour, F. (2015). A Probabilistic Accident Prediction Model for Construction Sites. *Procedia Engineering*, *123*, 15–23. https://doi.org/10.1016/j.proeng.2015.10.052

Arditi, D., Lee, D.-E., & Polat, G. (2007). Fatal accidents in nighttime vs. daytime highway construction work zones. *Journal of Safety Research*, *38*(4), 399–405. https://doi.org/10.1016/j.jsr.2007.04.001

ARROWES Roading Safety. (2022). *Automated Cone Truck*. https://arrowes.com.au/product/act-automated-cone-truck/

Arslan, M., Cruz, C., & Ginhac, D. (2018). Semantic Enrichment of Spatio-temporal Trajectories for Worker Safety on Construction Sites. *Procedia Computer Science*, *130*, 271–278. https://doi.org/10.1016/j.procs.2018.04.039

Arslan, M., Cruz, C., Roxin, A.-M., & Ginhac, D. (2017). Using Spatio-Temporal Trajectories to Monitor Construction Sites for Safety Management. *Proceedings of the 9th International Conference on Information Management and Engineering*, 211–216. https://doi.org/10.1145/3149572.3149600

Atahan, A. O., Arslan, T., Ganster, W., & Edl, T. (2019). Development of a precast slim temporary concrete safety barrier STCSB 50 for work zone applications. *Journal of Transportation Safety & Security*, *11*(3), 287–304. https://doi.org/10.1080/19439962.2017.1402837

Awolusi, I., & Marks, E. D. (2019). Active Work Zone Safety: Preventing Accidents Using Intrusion Sensing Technologies. *Frontiers in Built Environment*, *5*. https://doi.org/10.3389/fbuil.2019.00021

Bahn, S. (2013). Workplace hazard identification and management: The case of an underground mining operation. *Safety Science*, *57*, 129–137. https://doi.org/10.1016/j.ssci.2013.01.010

Bai, Y., Huang, Y., Schrock, S. D., & Li, Y. (2011). *Determining the Effectiveness of Graphic-aided Dynamic Message Signs in Work Zone*.

Bakhsh Kelarestaghi, K., Ermagun, A., Heaslip, K., & Rose, J. (2020). Choice of speed under compromised Dynamic Message Signs. *PLOS ONE*, *15*(12), e0243567. https://doi.org/10.1371/journal.pone.0243567

Bashir, S., & Zlatkovic, M. (2021). Assessment of Queue Warning Application on Signalized Intersections for Connected Freight Vehicles. *Transportation Research Record: Journal of the Transportation Research Board*, *2675*(10), 1211–1221. https://doi.org/10.1177/03611981211015247

Beacher, A. G., Fontaine, M. D., & Garber, N. J. (2004). *EVALUATION OF THE LATE MERGE WORK ZONE TRAFFIC CONTROL STRATEGY*.

Beacher, A. G., Fontaine, M. D., & Garber, N. J. (2005). Guidelines for Using Late Merge Traffic Control in Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, *1911*(1), 42–50. https://doi.org/10.1177/0361198105191100105

Benekohal, R. F., Chitturi, M. V., Hajbabaie, A., Wang, M. H., & Medina, J. C. (2008). Automated speed photo enforcement effects on speeds in work zones. *Transportation Research Record*, *2055*, 11–20. https://doi.org/10.3141/2055-02

Benekohal, R. F., Hajbabaie, A., Medina, J. C., Wang, M.-H., & Chitturi, M. V. (2010). *SPEED PHOTO-RADAR ENFORCEMENT EVALUATION IN ILLINOIS WORK ZONES*. Illinois Department of Transportation.

Benekohal, R. F., & Shim, E. (1999). Multivariate analysis of truck drivers' assessment of work zone safety. *Journal of Transportation Engineering*, *125*(5), 398–406. https://doi.org/10.1061/(ASCE)0733-947X(1999)125:5(398)

Benekohal, R. F., Wang, M.-H., Chitturi, M. V., Hajbabaie, A., & Medina, J. C. (2009). Speed Photo–Radar Enforcement and Its Effects on Speed in Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, *2096*(1), 89–97. https://doi.org/10.3141/2096-12

Bham, G. H., & Leu, M. C. (2018). A driving simulator study to analyze the effects of portable changeable message signs on mean speeds of drivers. *Journal of Transportation Safety & Security*, *10*(1–2), 45–71. https://doi.org/10.1080/19439962.2017.1314398

Blei, D. M., Ng, A. Y., & Jordan, M. I. (2003). Latent Dirichlet allocation. *Journal of Machine Learning Research*, *3*(4–5), 993–1022. https://doi.org/10.1016/b978-0-12-411519-4.00006-9

Bligh, R. P., Mak, K. K., & Rhodes, L. R. (1998). Crash Testing and Evaluation of Work Zone Barricades. *Transportation Research Record: Journal of the Transportation Research Board*, *1650*(1), 36–44. https://doi.org/10.3141/1650-05

Bryden, J. E., Andrew, L. B., & Fortuniewicz, J. S. (1998). Work Zone Traffic Accidents Involving Traffic Control Devices, Safety Features, and Construction Operations. *Transportation Research*

Record: Journal of the Transportation Research Board, *1650*(1), 71–81. https://doi.org/10.3141/1650-09

Burke, M. J., Salvador, R. O., Smith-Crowe, K., Chan-Serafin, S., Smith, A., & Sonesh, S. (2011). The dread factor: How hazards and safety training influence learning and performance. *Journal of Applied Psychology*, *96*(1), 46–70. https://doi.org/10.1037/a0021838

Çakiroğlu, Ü., & Gökoğlu, S. (2019). Development of fire safety behavioral skills via virtual reality. *Computers & Education*, *133*, 56–68. https://doi.org/10.1016/j.compedu.2019.01.014

Carbonari, A., Giretti, A., & Naticchia, B. (2011). A proactive system for real-time safety management in construction sites. *Automation in Construction*, *20*(6), 686–698. https://doi.org/10.1016/j.autcon.2011.04.019

Carter, G., & Smith, S. D. (2006). Safety Hazard Identification on Construction Projects. *Journal of Construction Engineering and Management*, *132*(2), 197–205. https://doi.org/10.1061/(asce)0733-9364(2006)132:2(197)

Chang, D., Hopfenblatt, J., Edara, P., & Balakrishnan, B. (2020). Immersive Virtual Reality Training for Inspecting Flagger Work zones. *2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*, 327–330. https://doi.org/10.1109/AIVR50618.2020.00066

Cheng, G., & Cheng, R. (2020). Optimizing Speed Limits Upstream of Freeway Reconstruction and Expansion Work Zones Based on Driver Characteristics. *Journal of Transportation Engineering, Part A: Systems*, *146*(7), 4020066. https://doi.org/10.1061/jtepbs.0000389

Cho, C., & Park, J. (2018). An Embedded Sensory System for Worker Safety: Prototype Development and Evaluation. *Sensors*, *18*(4), 1200. https://doi.org/10.3390/s18041200

Chung, Y., & Recker, W. W. (2012). A Methodological Approach for Estimating Temporal and Spatial Extent of Delays Caused by Freeway Accidents. *IEEE Transactions on Intelligent Transportation Systems*, *13*(3), 1454–1461. https://doi.org/10.1109/TITS.2012.2190282

Construction Safety Council. (2008). *Work Zone Hazards Workbook*. Occupational Safety and Health Administration.

Dale, E. (1969). *Audio-Visual Methods in Teaching* (Third). Dryden.

Daniel, J., Dixon, K., & Jared, D. (2000). Analysis of Fatal Crashes in Georgia Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, *1715*(1), 18–23. https://doi.org/10.3141/1715-03

Darwesh, A., Wu, D., Le, M., & Saripalli, S. (2021). Building a Smart Work Zone Using Roadside LiDAR. *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, *2021-Septe*, 2602–2609. https://doi.org/10.1109/ITSC48978.2021.9564527

Datta, T., Schattler, K., Kar, P., & Guha, A. (2004). *DEVELOPMENT AND EVALUATION OF AN ADVANCED DYNAMIC LANE MERGE TRAFFIC CONTROL SYSTEM FOR 3 TO 2 LANE TRANSITION AREAS IN WORK ZONES.*

Debnath, A. K., Blackman, R., & Haworth, N. (2015). Common hazards and their mitigating measures in work zones: A qualitative study of worker perceptions. *Safety Science*, *72*, 293–301. https://doi.org/10.1016/j.ssci.2014.09.022

Dehman, A., & Farooq, B. (2021). Are work zones and connected automated vehicles ready for a harmonious coexistence? A scoping review and research agenda. *Transportation Research Part C: Emerging Technologies*, *133*, 103422. https://doi.org/https://doi.org/10.1016/j.trc.2021.103422

Dickerson, C. L., Wang, J., Witherspoon, J., & Crumley, S. C. (2016). Work Zone Management in the District of Columbia: Deploying a Citywide Transportation Management Plan and Work Zone Project Management System. *Transportation Research Record: Journal of the Transportation Research Board*, *2554*(1), 37–45. https://doi.org/10.3141/2554-05

Dissanayake, S., & Akepati, S. R. (2009). *Identification of Work Zone Crash Characteristics*. Federal Highway Administration. https://intrans.iastate.edu/app/uploads/2018/08/Dissanayake_WZCrashChar.pdf

Du, S., & Razavi, S. (2019). Variable Speed Limit for Freeway Work Zone with Capacity Drop Using Discrete-Time Sliding Mode Control. *Journal of Computing in Civil Engineering*, *33*(2), 4019001. https://doi.org/10.1061/(asce)cp.1943-5487.0000815

Du, S., & Razavi, S. (2020). Fault-tolerant control of variable speed limits for freeway work zone using likelihood estimation. *Advanced Engineering Informatics*, *45*, 101133. https://doi.org/10.1016/j.aei.2020.101133

Duan, K., Yan, X., Li, X., Hang, J., & Yang, J. (2020). Analysis of driver's decision distance and merging distance in work zone area based on parametric survival models: With the aid of a driving simulator experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*, *71*, 31–48. https://doi.org/10.1016/j.trf.2020.03.017

Dudek, C. L. (2004). *Changeable Message Sign Operation and Messaging Handbook*.

Dutta, A., Fisher, D. L., & Noyce, D. A. (2004). Use of a driving simulator to evaluate and optimize factors affecting understandability of variable message signs. *Transportation Research Part F: Traffic Psychology and Behaviour*, *7*(4–5), 209–227. https://doi.org/10.1016/j.trf.2004.09.001

Edara, P., Sun, C., & Hou, Y. (2013). *Evaluation of Variable Advisory Speed Limits in Work Zones*.

Ermagun, A., Kelarestaghi, K. B., Finney, M., & Heaslip, K. (2021). "Speed Up to Hit the Worker": Impact of hacked road signs on work zone safety. *International Journal of Transportation Science and Technology*, *10*(1), 49–59. https://doi.org/10.1016/j.ijtst.2020.05.006

Ermagun, A., Kelarestaghi, K. B., & Heaslip, K. (2021). Drivers' self-reported responses to a potentially realistic fabricated road sign message. *Transportation Research Part F: Traffic Psychology and Behaviour*, *78*, 103–118. https://doi.org/10.1016/j.trf.2021.02.001

Fang, Y., Cho, Y. K., Zhang, S., & Perez, E. (2016). Case Study of BIM and Cloud–Enabled Real-Time RFID Indoor Localization for Construction Management Applications. *Journal of Construction Engineering and Management*, *142*(7), 05016003. https://doi.org/10.1061/(asce)co.1943-7862.0001125

Fatality Analysis Reporting System (FARS). (2019). *Traffic Fatality Data*.

Federal Highway Administration. (2009). *Manual of Traffic Control Devices for Streets and Highways*.

Federal Highway Administration. (2014). *Work Zone Safety and Mobility FACT Sheet*.

Federal Highway Administration. (2021). *Road User Cost Calculator*. https://highways.dot.gov/federal-lands/design/tools-wfl/road-user-cost-calculator

Fisher, D. L., Breck, A., Gillham, O., & Flynn, D. (2021). *Effectiveness of Dynamic Speed feedback signs, Volume I: Literature review and meta-analysis*.

Flannagan, C. A., Baykas, P. B., Leslie, A., Kovaceva, J., & Thomson, R. (2019). *Analysis of SHRP2 Data to Understand Normal and Abnormal Driving Behavior in Work Zones*. Federal Highway Administration. https://rosap.ntl.bts.gov/view/dot/48835

Flynn, D. F. B., Breck, A., Gillham, O., Atkins, R. G., & Fisher, D. L. (2020). Dynamic Speed Feedback Signs Are Effective in Reducing Driver Speeds: A Meta-Analysis. *Transportation Research Record: Journal of the Transportation Research Board*, *2674*(12), 481–492. https://doi.org/10.1177/0361198120957326

Foo, S., & Abdulhai, B. (2006). Evaluating the impacts of changeable message signs on traffic diversion. *2006 IEEE Intelligent Transportation Systems Conference*, 891–896. https://doi.org/10.1109/ITSC.2006.1706857

Fortes, L. S., Almeida, S. S., Praça, G. M., Nascimento-Júnior, J. R. A., Lima-Junior, D., Barbosa, B. T., & Ferreira, M. E. C. (2021). Virtual reality promotes greater improvements than video-stimulation screen on perceptual-cognitive skills in young soccer athletes. *Human Movement Science*, *79*, 102856. https://doi.org/10.1016/j.humov.2021.102856

Fudala, N. J., & Fontaine, M. D. (2010). Interaction between System Design and Operations of Variable Speed Limit Systems in Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, *2169*(1), 1–10. https://doi.org/10.3141/2169-01

Fyhrie, P. B. (2016). Work Zone Intrusion Alarms for Highway Workers. *Caltrans Division of Research, Innovation and System Information Work*, 1–21.

Gambatese, J. A., & Jafarnejad, A. (2015). *Evaluation of Radar Speed Display for Mobile Maintenance Operations*.

Gambatese, J. A., Lee, H. W., & Nnaji, C. A. (2017). *Work Zone Intrusion Alert Technologies: Assessment and Practical Guidance*. Oregon State University School of Civil and Construction Engineering.

Garber, N. J., & Patel, S. T. (1994). *Effectiveness of Changable Message Signs in Controlling Vehicle speeds in Work Zones*.

Garber, N. J., & Srinivasan, S. (1998). Influence of Exposure Duration on the Effectiveness of Changeable-Message Signs in Controlling Vehicle Speeds at Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, *1650*(1), 62–70. https://doi.org/10.3141/1650-08

Garber, N. J., & Zhao, M. (2002). *CRASH CHARACTERISTICS AT WORK ZONES*.

Ghasemzadeh, A., & Ahmed, M. M. (2019). Exploring factors contributing to injury severity at work zones considering adverse weather conditions. *IATSS Research*, *43*(3), 131–138. https://doi.org/10.1016/j.iatssr.2018.11.002

Gladson, J., Sivagnanasundaram, K., Kasi, K., & Karuppanan, G. (2020). Examining the Characteristics of Heterogeneous Traffic at Various Lane Closures. *Periodica Polytechnica Transportation Engineering*, *48*(4), 384–392. https://doi.org/10.3311/pptr.15232

Gnawali, O., & Kim, K. (2022). *RULE-BASED AUTOMATED SAFETY MONITORING SYSTEM FOR WORK ZONE SAFETY (NCHRP IDEA Project 206)*.

Grabowski, A., & Jankowski, J. (2015). Virtual Reality-based pilot training for underground coal miners. *Safety Science*, *72*, 310–314. https://doi.org/10.1016/j.ssci.2014.09.017

Grillo, L. F., Datta, T. K., & Hartner, C. (2008). Dynamic Late Lane Merge System at Freeway Construction Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, *2055*(1), 3–10. https://doi.org/10.3141/2055-01

Hamdar, S. H., Khoury, H., & Zehtabi, S. (2016). A simulator-based approach for modeling longitudinal driving behavior in construction work zones: Exploration and assessment. *SIMULATION*, *92*(6), 579–594. https://doi.org/10.1177/0037549716644515

Han, Y., Ramezani, M., Hegyi, A., Yuan, Y., & Hoogendoorn, S. (2020). Hierarchical ramp metering in freeways: An aggregated modeling and control approach. *Transportation Research Part C: Emerging Technologies*, *110*, 1–19. https://doi.org/10.1016/j.trc.2019.09.023

Harb, R., Radwan, E., Abdel-Aty, M., & Su, X. (2011). Two Simplified Intelligent Transportation System-Based Lane Management Strategies for Short-Term Work Zones. *Journal of Intelligent Transportation Systems*, *15*(1), 52–61. https://doi.org/10.1080/15472450.2011.544589

Harder, K. A., & Bloomfield, J. (2008). *The Effectiveness and Safety of Traffic and Non-Traffic Related Messages Presented on Changeable Message Signs—Phase II*.

He, Y., Shu, Z., Ge, Y., & Daniel, J. (2016). Drivers' Lane Change Maneuver and Speed Behavior in Freeway Work Zones. In S. of A. E. of C. (SAE-China) (Ed.), *Proceedings of SAE-China Congress 2015: Selected Papers* (Vol. 364, pp. 229–241). Springer Singapore. http://link.springer.com/10.1007/978-981-287-978-3_22

Hilfert, T., Teizer, J., & König, M. (2016, July). First Person Virtual Reality for Evaluation and Learning of Construction Site Safety. *Proceedings of the 33rd International Symposium on Automation and Robotics in Construction ({ISARC})*. https://doi.org/10.22260/isarc2016/0025

Hou, J., Ma, M., & Xiao, J. (2022). Variable Speed Limit Control with Dynamic Location of Message Signs for the Internet-of-Vehicles Environment. *Transportation Research Record: Journal of the Transportation Research Board*, *2676*(6), 756–773. https://doi.org/10.1177/03611981221076127

Hourdos, J. (2012). Portable, Non-Intrusive Advance Warning Devices for Work Zones with or without Flag Operators. *Minnesota Department of Transportation*, *October*.

Hourdos, J., Liu, Z., Dirks, P., Liu, H. X., Huang, S., Sun, W., & Xiao, L. (2017). *Development of a Queue Warning System Utilizing ATM Infrastructure System Development and Field Testing*.

Hsieh, E. Y., Ullman, G. L., Pesti, G., & Brydia, R. E. (2017). Effectiveness of End-of-Queue Warning Systems and Portable Rumble Strips on Lane Closure Crashes. *Journal of Transportation Engineering, Part A: Systems*, *143*(11). https://doi.org/10.1061/JTEPBS.0000084

Huang, Y., & Bai, Y. (2019). Driver responses to graphic-aided portable changeable message signs in highway work zones. *Journal of Transportation Safety & Security*, *11*(6), 661–682. https://doi.org/10.1080/19439962.2018.1463336

Ibrahim, U., Hayee, M. I., & Kwon, E. (2013). Hybrid Work Zone Information System with Portable Changeable Message Signs and Dedicated Short-Range Communication. *Transportation Research Record: Journal of the Transportation Research Board*, *2380*(1), 29–35. https://doi.org/10.3141/2380-04

Ilgaz, A., & Saltan, M. (2018). ANALYSIS OF THE IMPACTS OF AUTOMATIC SECTION SPEED CONTROL ON A SAMPLE GROUP OF COMMUTER DRIVERS IN AN EDUCATIONAL CAMPUS. *Mühendislik Bilimleri ve Tasarım Dergisi*, *6*(4), 707–715. https://doi.org/10.21923/jesd.408670

Jagarlamudi, V. K. (2018). Traffic Congestion Alert System in Work Zone. In *Creative Components*. Iowa State University.

Jehn, N. L., & Turochy, R. E. (2020). Development of Breakdown Probability Models and Heavy Vehicle Passenger Car Equivalents for Rural Freeway Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, *2674*(12), 144–154. https://doi.org/10.1177/0361198120951197

Jiang, Y., & Li, S. (2002). Measuring and analyzing vehicle position and speed data at work zones using global positioning systems. *ITE Journal (Institute of Transportation Engineers)*, *72*(3), 48–53.

Jin, T. G., Saito, M., & Eggett, D. L. (2008). Statistical comparisons of the crash characteristics on highways between construction time and non-construction time. *Accident Analysis & Prevention*, *40*(6), 2015–2023. https://doi.org/10.1016/j.aap.2008.08.024

Joerger, M. (2010). *PHOTO RADAR SPEED ENFORCEMENT IN A STATE HIGHWAY WORK ZONE: DEMONSTRATION PROJECT YEON AVENUE*. Oregon Department of Transportation.

Kang, K., & Ryu, H. (2019). Predicting types of occupational accidents at construction sites in Korea using random forest model. *Safety Science*, *120*, 226–236. https://doi.org/10.1016/j.ssci.2019.06.034

Kang, K.-P., Chang, G.-L., & Zou, N. (2004). Optimal Dynamic Speed-Limit Control for Highway Work Zone Operations. *Transportation Research Record: Journal of the Transportation Research Board*, *1877*(1), 77–84. https://doi.org/10.3141/1877-09

Kelarestaghi, K. B., Heaslip, K., Khalilikhah, M., Fuentes, A., & Fessmann, V. (2018). Intelligent Transportation System Security: Hacked Message Signs. *SAE International Journal of Transportation Cybersecurity and Privacy*, *1*(2), 11-01-02–0004. https://doi.org/10.4271/11-01-02-0004

Khan, G., Sanni, S., Berr, S., & Shafizadeh, K. (2019). *EVALUATION OF WORK ZONE INTRUSION ALARMS*.

Khazraeian, S., Hadi, M., & Xiao, Y. (2017). Safety Impacts of Queue Warning in a Connected Vehicle Environment. *Transportation Research Record: Journal of the Transportation Research Board*, *2621*(1), 31–37. https://doi.org/10.3141/2621-04

Khondaker, B., & Kattan, L. (2015). Variable speed limit: an overview. *Transportation Letters*, *7*(5), 264–278. https://doi.org/10.1179/1942787514Y.0000000053

Kianfar, J., & Abdoli, S. (2021). Deterministic and Stochastic Capacity in Work Zones: Findings from a Long-Term Work Zone. *Journal of Transportation Engineering, Part A: Systems*, *147*(1), 4020141. https://doi.org/10.1061/jtepbs.0000470

Kohls, A. G. (2019). *Autonomous Truck Mounted Attenuator (ATMA) Pilot*.

Kratos Defense & Security. (2017). *Kratos Deploys the World's First Autonomous Vehicle Utilized in Live Operation on Public Roadways (Press release)*.

Kwon, E., Brannan, D., Shouman, K., Isackson, C., & Arseneau, B. (2007). Development and Field Evaluation of Variable Advisory Speed Limit System for Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, *2015*(1), 12–18. https://doi.org/10.3141/2015-02

Lahrmann, H., Brassøe, B., Johansen, J. W., & Madsen, J. C. O. (2016). Safety Impact of Average Speed Control in the UK. *Journal of Transportation Technologies*, *06*(05), 312–326. https://doi.org/10.4236/jtts.2016.65028

Leder, J., Horlitz, T., Puschmann, P., Wittstock, V., & Schütz, A. (2019). Comparing immersive virtual reality and powerpoint as methods for delivering safety training: Impacts on risk perception, learning, and decision making. *Safety Science*, *111*, 271–286. https://doi.org/10.1016/j.ssci.2018.07.021

Li, H. M., & Kang, B. S. (2014). A Virtual Reality Safety Training System for Coal Mining Industry. *Applied Mechanics and Materials*, *687–691*, 2371–2374. https://doi.org/10.4028/www.scientific.net/amm.687-691.2371

Li, Y., & Bai, Y. (2009a). Highway work zone risk factors and their impact on crash severity. *Journal of Transportation Engineering*, *135*(10), 694–701. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000055

Li, Y., & Bai, Y. (2009b). Effectiveness of temporary traffic control measures in highway work zones. *Safety Science*, *47*(3), 453–458. https://doi.org/10.1016/j.ssci.2008.06.006

Li, Y., Mori, J. C. M., & Work, D. B. (2018). Estimating traffic conditions from smart work zone systems. *Journal of Intelligent Transportation Systems*, *22*(6), 490–502. https://doi.org/10.1080/15472450.2018.1438274

Liu, W., Cheng, L., Liu, Z., Yang, Y., & Li, L. (2021). The Development of Port Safety Training Platform Based on Virtual Reality Technology. *2021 IEEE 7th International Conference on Virtual Reality (ICVR)*, 207–214. https://doi.org/10.1109/ICVR51878.2021.9483808

Lu, X.-Y., & Shladover, S. E. (2014). Review of Variable Speed Limits and Advisories. *Transportation Research Record: Journal of the Transportation Research Board*, *2423*(1), 15–23. https://doi.org/10.3141/2423-03

Ma, Z., Shao, C., Song, Y., & Chen, J. (2014). Driver response to information provided by variable message signs in Beijing. *Transportation Research Part F: Traffic Psychology and Behaviour*, *26*, 199–209. https://doi.org/10.1016/j.trf.2014.07.006

Mansoory, M. S., Khazaei, M. R., Azizi, S. M., & Niromand, E. (2021). Comparison of the effectiveness of lecture instruction and virtual reality-based serious gaming instruction on the medical students' learning outcome about approach to coma. *BMC Medical Education*, *21*(1), 347. https://doi.org/10.1186/s12909-021-02771-z

Mao, R. Q., Lan, L., Kay, J., Lohre, R., Ayeni, O. R., Goel, D. P., & de SA, D. (2021). Immersive Virtual Reality for Surgical Training: A Systematic Review. *Journal of Surgical Research*, *268*, 40–58. https://doi.org/10.1016/j.jss.2021.06.045

Marks, E., Vereen, S., & Awolusi, I. (2017). *Active Work Zone Safety Using Emerging Technologies 2017*. University Transportation Center for Alabama The University of Alabama.

Martin, J., Rozas, A., & Araujo, A. (2016). A WSN-Based Intrusion Alarm System to Improve Safety in Road Work Zones. *Journal of Sensors*, *2016*, 1–8. https://doi.org/10.1155/2016/7048141

Mashhadi, A. H., Farhadmanesh, M., Rashidi, A., & Marković, N. (2021). Review of Methods for Estimating Construction Work Zone Capacity. *Transportation Research Record: Journal of the Transportation Research Board*, *2675*(9), 382–397. https://doi.org/10.1177/03611981211002202

Matsika, C., & Zhou, M. (2021). Factors affecting the adoption and use of AVR technology in higher and tertiary education. *Technology in Society*, *67*, 101694. https://doi.org/10.1016/j.techsoc.2021.101694

Mattox, J. H., Sarasua, W. A., Ogle, J. H., Eckenrode, R. T., & Dunning, A. (2007). Development and Evaluation of Speed-Activated Sign to Reduce Speeds in Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, *2015*(1), 3–11. https://doi.org/10.3141/2015-01

McAvoy, D. S., Duffy, S., & Whiting, H. S. (2011). Simulator Study of Primary and Precipitating Factors in Work Zone Crashes. *Transportation Research Record: Journal of the Transportation Research Board*, *2258*(1), 32–39. https://doi.org/10.3141/2258-04

McAvoy, D. S., Schattler, K. L., & Datta, T. K. (2007). Driving Simulator Validation for Nighttime Construction Work Zone Devices. *Transportation Research Record: Journal of the Transportation Research Board*, *2015*(1), 55–63. https://doi.org/10.3141/2015-07

McCoy, P. T., Pesti, G., & Byrd, P. S. (1999). *Alternative Driver Information to Alleviate Work-Zone-Related Delays*.

McMurtry, T., Saito, M., Riffkin, M., & Heath, S. (2008). VARIABLE SPEED LIMITS SIGNS: EFFECTS ON SPEED AND SPEED VARIATION IN WORK ZONES. *Transportation Research Record*. https://doi.org/10.17226/23030

Mekker, M. M., Remias, S. M., Bunnell, W. A., Krohn, D. W., Cox, E. D., & Bullock, D. M. (2016). Variable Speed Limit Study Upstream of an Indiana Work Zone with Vehicle Matching. *Transportation Research Record: Journal of the Transportation Research Board*, *2555*(1), 53–64. https://doi.org/10.3141/2555-07

Memarian, A., Rosenberger, J. M., Mattingly, S. P., Williams, J. C., & Hashemi, H. (2019). An optimization-based traffic diversion model during construction closures. *Computer-Aided Civil and Infrastructure Engineering*, *34*(12), 1087–1099. https://doi.org/10.1111/mice.12491

Messina, J., Song, M., Ortiz-Varela, J. D., & Wang, J. H. (2011). ASSESSING THE MESSAGE DESIGN ON VARIABLE MESSAGE SIGNS IN MITIGATING THE BOTTLENECK ISSUE AT WORK ZONES. *91st Annual Meeting of TheTransportation Research Board*.

Meyer, E. (2004). *Construction Area Late Merge (CALM) System*.

Mintsis, E., Lucken, L., Karagounis, V., Porfyri, K., Rondinone, M., Correa, A., Schindler, J., & Mitsakis, E. (2020). Joint Deployment of Infrastructure-Assisted Traffic Management and Cooperative

Driving around Work Zones. *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*, 1–8. https://doi.org/10.1109/ITSC45102.2020.9294256

Mishra, S., Golias, M. M., & Thapa, D. (2021). *Work Zone Alert Systems*. https://rosap.ntl.bts.gov/view/dot/56274

Mohan, S. B., & Gautam, P. (2002). Cost of Highway Work Zone Injuries. *Practice Periodical on Structural Design and Construction*, *7*(2), 68–73. https://doi.org/10.1061/(asce)1084-0680(2002)7:2(68)

Mohan, S., & Zech, W. C. (2005). Characteristics of worker accidents on NYSDOT construction projects. *Journal of Safety Research*, *36*(4), 353–360. https://doi.org/10.1016/j.jsr.2005.06.012

Mokhtarimousavi, S., Azizinamini, A., & Hadi, M. (2020, August). Severity of Worker-Involved Work Zone Crashes: A Study of Contributing Factors. *International Conference on Transportation and Development 2020*. https://doi.org/10.1061/9780784483145.005

Montella, A., Persaud, B., D'Apuzzo, M., & Imbriani, L. L. (2012). Safety Evaluation of Automated Section Speed Enforcement System. *Transportation Research Record: Journal of the Transportation Research Board*, *2281*(1), 16–25. https://doi.org/10.3141/2281-03

Morris, N. L., Cooper, J. L., Ton, A., Plummer, J. P., & Easterlund, P. (2016). *Examining the Impact of ASE (Automated Speed Enforcement) in Work Zones on Driver Attention*.

Morris, T., Schwach, J. A., & Michalopoulos, P. G. (2011). *Low-Cost Portable Video-Based Queue Detection for Work-Zone Safety*.

Nasrollahzadeh, A. A., Sofi, A. R., & Ravani, B. (2021). Identifying factors associated with roadside work zone collisions using machine learning techniques. *Accident Analysis & Prevention*, *158*, 106203. https://doi.org/10.1016/j.aap.2021.106203

Nnaji, C., Gambatese, J., Lee, H. W., & Zhang, F. (2020). Improving construction work zone safety using technology: A systematic review of applicable technologies. *Journal of Traffic and Transportation Engineering (English Edition)*, *7*(1), 61–75. https://doi.org/10.1016/j.jtte.2019.11.001

Nnaji, C., Jafarnejad, A., & Gambatese, J. (2020). Effects of Wearable Light Systems on Safety of Highway Construction Workers. *Practice Periodical on Structural Design and Construction*, *25*(2), 4020003. https://doi.org/10.1061/(asce)sc.1943-5576.0000469

Nnaji, C., Karakhan, A. A., Gambatese, J., & Lee, H. W. (2020). Case Study to Evaluate Work-Zone Safety Technologies in Highway Construction. *Practice Periodical on Structural Design and Construction*, *25*(3). https://doi.org/10.1061/(ASCE)SC.1943-5576.0000498

Nnaji, C., Lee, H. W., Karakhan, A., & Gambatese, J. (2018). Developing a Decision-Making Framework to Select Safety Technologies for Highway Construction. *Journal of Construction Engineering and Management*, *144*(4), 4018016. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001466

Novosel, C. (2014). Evaluation of Advanced Safety Perimeter Systems for Kansas Temporary Work Zones. In *Civil, Environmental, and Architectural Engineering, University of Kansas*.

Oregon Department of Transportation. (2015). *PHOTO RADAR 2015 ODOT EXECUTIVE SUMMARY*.

Oregon Department of Transportation. (2017). *2017 Facts and Tips: Work Zone Safety in Oregon* (Vol. 2018, Issue November 26).

Osman, M., Mishra, S., Paleti, R., & Golias, M. (2019a). Impacts of Work Zone Component Areas on Driver Injury Severity. *Journal of Transportation Engineering, Part A: Systems*, *145*(8), 04019032. https://doi.org/10.1061/jtepbs.0000253

Osman, M., Mishra, S., Paleti, R., & Golias, M. (2019b). Impacts of Work Zone Component Areas on Driver Injury Severity. *Journal of Transportation Engineering, Part A: Systems*, *145*(8), 4019032. https://doi.org/10.1061/jtepbs.0000253

Osman, M., Paleti, R., & Mishra, S. (2018). Analysis of passenger-car crash injury severity in different work zone configurations. *Accident Analysis and Prevention*, *111*(May 2017), 161–172. https://doi.org/10.1016/j.aap.2017.11.026

Osman, M., Paleti, R., Mishra, S., & Golias, M. M. (2016). Analysis of injury severity of large truck crashes in work zones. *Accident Analysis and Prevention*, *97*, 261–273. https://doi.org/10.1016/j.aap.2016.10.020

Ozan, E. (2019). Requirements Analysis for the System Level Design of Smart Work Zones. *2019 14th Annual Conference System of Systems Engineering (SoSE)*, 313–316. https://doi.org/10.1109/SYSOSE.2019.8753874

Ozan, E. (2020). *Using IoT Technology to Create Smart Work Zones*.

Pant, P. D. (2022). *Smart Work Zone Systems*. https://ops.fhwa.dot.gov/wz/workshops/accessible/pant_paper.htm

Papageorgiou, M., Papamichail, I., Spiliopoulou, A. D., & Lentzakis, A. F. (2008). Real-time merging traffic control with applications to toll plaza and work zone management. *Transportation Research Part C: Emerging Technologies*, *16*(5), 535–553. https://doi.org/10.1016/j.trc.2007.11.002

Papamichail, I., Papageorgiou, M., & Stamatakis, I. (2018). Feedback Traffic Control at Highway Work Zones using Variable Speed Limits. *IFAC-PapersOnLine*, *51*(9), 329–336. https://doi.org/10.1016/j.ifacol.2018.07.054

Park, J., Chen, J., & Cho, Y. K. (2017). Self-corrective knowledge-based hybrid tracking system using BIM and multimodal sensors. *Advanced Engineering Informatics*, *32*, 126–138. https://doi.org/10.1016/j.aei.2017.02.001

Park, J., Kim, K., & Cho, Y. K. (2017). Framework of Automated Construction-Safety Monitoring Using Cloud-Enabled BIM and BLE Mobile Tracking Sensors. *Journal of Construction Engineering and Management*, *143*(2), 05016019. https://doi.org/10.1061/(asce)co.1943-7862.0001223

Park, J., Marks, E., Cho, Y. K., & Suryanto, W. (2016). Performance Test of Wireless Technologies for Personnel and Equipment Proximity Sensing in Work Zones. *Journal of Construction Engineering and Management*, *142*(1), 4015049. https://doi.org/10.1061/(asce)co.1943-7862.0001031

Park, J., Yang, X., Cho, Y. K., & Seo, J. (2017). Improving dynamic proximity sensing and processing for smart work-zone safety. *Automation in Construction*, *84*, 111–120. https://doi.org/10.1016/j.autcon.2017.08.025

Patrão, B., & Menezes, P. (2013). A Virtual Reality System for Training Operators. *International Journal of Online and Biomedical Engineering*, *9*(S8), 53. https://doi.org/10.3991/ijoe.v9is8.3383

Pesti, G., & McCoy, P. T. (2001). Long-Term Effectiveness of Speed Monitoring Displays in Work Zones on Rural Interstate Highways. *Transportation Research Record: Journal of the Transportation Research Board*, *1754*(1), 21–30. https://doi.org/10.3141/1754-03

Pesti, G., McCoy, P. T., Meisinger, M. D., & Kannan, V. (2004). *Evaluation of Work Zone Speed Advisory System*.

Qi, Y., & Zhao, Q. (2017). Safety impacts of signalized lane merge control at highway work zones. *Transportation Planning and Technology*, *40*(5), 577–591. https://doi.org/10.1080/03081060.2017.1314499

Qiao, F., Rahman, R., Li, Q., & Yu, L. (2016). Safe and Environment-Friendly Forward Collision Warning Messages in the Advance Warning Area of a Construction Zone. *International Journal of Intelligent Transportation Systems Research*, *15*(3), 166–179. https://doi.org/10.1007/s13177-016-0130-2

Radwan, E., Harb, R., & Ramasamy, S. (2009). *Evaluation of Safety and Operational Effectiveness of Dynamic Lane Merge System in Florida*.

Radwan, E., Zaidi, Z., & Harb, R. (2011). Operational Evaluation of Dynamic Lane Merging In Work Zones with Variable Speed Limits. *Procedia - Social and Behavioral Sciences*, *16*, 460–469. https://doi.org/10.1016/j.sbspro.2011.04.467

Rahim, M. A., & Hassan, H. M. (2021). A deep learning based traffic crash severity prediction framework. *Accident Analysis & Prevention*, *154*, 106090. https://doi.org/10.1016/j.aap.2021.106090

Reeves, S. M., Crippen, K. J., & McCray, E. D. (2021). The varied experience of undergraduate students learning chemistry in virtual reality laboratories. *Computers & Education Education*, *175*, 104320. https://doi.org/10.1016/j.compedu.2021.104320

Ren, T., Xie, Y., & Jiang, L. (2020). Cooperative Highway Work Zone Merge Control Based on Reinforcement Learning in a Connected and Automated Environment. *Transportation Research Record: Journal of the Transportation Research Board*, *2674*(10), 363–374. https://doi.org/10.1177/0361198120935873

Retting, R. A., Farmer, C. M., & McCartt, A. T. (2008). Evaluation of Automated Speed Enforcement in Montgomery County, Maryland. *Traffic Injury Prevention*, *9*(5), 440–445. https://doi.org/10.1080/15389580802221333

Reyes, M. L., & Khan, S. A. (2008). *Examining Driver Behavior In Response to Work Zone Interventions: A Driving Simulator Study*. https://intrans.iastate.edu/app/uploads/2018/08/SWZDI-2008-1_Reyes_FinalReport3.pdf

Roberts, C. A., & Smaglik, E. J. (2012). Driver Feedback on Monetary Penalty and Its Impact on Work Zone Speed. *Transportation Research Record: Journal of the Transportation Research Board*, *2272*(1), 27–34. https://doi.org/10.3141/2272-04

Rothlind, E., Fors, U., Salminen, H., Wändell, P., & Ekblad, S. (2021). Virtual patients reflecting the clinical reality of primary care – a useful tool to improve cultural competence. *BMC Medical Education*, *21*(1), 270. https://doi.org/10.1186/s12909-021-02701-z

Sabeti, S., Shoghli, O., Baharani, M., & Tabkhi, H. (2021). Toward AI-enabled augmented reality to enhance the safety of highway work zones: Feasibility, requirements, and challenges. *Advanced Engineering Informatics*, *50*, 101429. https://doi.org/10.1016/j.aei.2021.101429

Sacks, R., Perlman, A., & Barak, R. (2013). Construction safety training using immersive virtual reality. *Construction Management and Economics*, *31*(9), 1005–1017. https://doi.org/10.1080/01446193.2013.828844

Sakhakarmi, S., & Park, J. (2022). Improved intrusion accident management using haptic signals in roadway work zone. *Journal of Safety Research*, *80*, 320–329. https://doi.org/10.1016/j.jsr.2021.12.015

Sayer, J. R., & Mefford, M. L. (2004). High visibility safety apparel and nighttime conspicuity of pedestrians in work zones. *Journal of Safety Research*, *35*(5), 537–546. https://doi.org/10.1016/j.jsr.2004.08.007

Seymour, N. E., Gallagher, A. G., Roman, S. A., O'Brien, M. K., Bansal, V. K., Andersen, D. K., & Satava, R. M. (2002). Virtual Reality Training Improves Operating Room Performance. *Annals of Surgery*, *236*(4), 458–464. https://doi.org/10.1097/00000658-200210000-00008

Shao, Y., Luo, Z., Wu, H., Han, X., Pan, B., Liu, S., & Claudel, C. G. (2020). Evaluation of Two Improved Schemes at Non-Aligned Intersections Affected by a Work Zone with an Entropy Method. *Sustainability*, *12*(14), 5494. https://doi.org/10.3390/su12145494

Shi, W., & Rajkumar, R. R. (2021). Work Zone Detection For Autonomous Vehicles. *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)*, 1585–1591. https://doi.org/10.1109/ITSC48978.2021.9565073

Silverstein, C., Schorr, J., & Hamdar, S. H. (2016). Work zones versus nonwork zones: Risk factors leading to rear-end and sideswipe collisions. *Journal of Transportation Safety & Security*, *8*(4), 310–326. https://doi.org/10.1080/19439962.2015.1036332

Sowndararajan, A., Wang, R., & Bowman, D. A. (2008). Quantifying the benefits of immersion for procedural training. *Proceedings of the 2008 Workshop on Immersive Projection Technologies/Emerging Display Technologiges - {IPT}/{EDT} {\textquotesingle}08*. https://doi.org/10.1145/1394669.1394672

Sperry, R., McDonald, T., Nambisan, S., & Pettit, R. (2009). *Effectiveness of Dynamic Messaging on Driver Behavior for Late Merge Lane Road Closures*.

Srinivasa, A. R., Jha, R., Ozkan, T., & Wang, Z. (2020). Virtual reality and its role in improving student knowledge, self-efficacy, and attitude in the materials testing laboratory. *International Journal of Mechanical Engineering Education*, *49*(4), 382–409. https://doi.org/10.1177/0306419019898824

Steinbakk, R. T., Ulleberg, P., Sagberg, F., & Fostervold, K. I. (2019). Effects of roadwork characteristics and drivers' individual differences on speed preferences in a rural work zone. *Accident Analysis & Prevention*, *132*, 105263. https://doi.org/10.1016/j.aap.2019.105263

Strawderman, L., Huang, Y., & Garrison, T. (2013). The Effect of Design and Placement of Work-Zone Warning Signs on Driver Speed Compliance: A Simulator-Based Study. *IIE Transactions on Occupational Ergonomics and Human Factors*, *1*(1), 66–75. https://doi.org/10.1080/21577323.2012.714839

Sun, L., & Yin, Y. (2017). Discovering themes and trends in transportation research using topic modeling. *Transportation Research Part C: Emerging Technologies*, *77*, 49–66. https://doi.org/10.1016/J.TRC.2017.01.013

Tang, Q., Cheng, Y., Hu, X., Chen, C., Song, Y., & Qin, R. (2021). Evaluation Methodology of Leader-Follower Autonomous Vehicle System for Work Zone Maintenance. *Transportation Research Record: Journal of the Transportation Research Board*, *2675*(5), 107–119. https://doi.org/10.1177/0361198120985233

Tarko, A., Kanipakapatnam, S., & Wasson, J. (1998). *Modeling and Optimization of the Indiana Lane Merge Control System on Approaches to Freeway Work Zones, Part I*. https://doi.org/10.5703/1288284313469

Teizer, J., Venugopal, M., & Walia, A. (2008). Ultrawideband for Automated Real-Time Three-Dimensional Location Sensing for Workforce, Equipment, and Material Positioning and Tracking. *Transportation Research Record: Journal of the Transportation Research Board*, *2081*(1), 56–64. https://doi.org/10.3141/2081-06

Thapa, D., Gabrhel, V., & Mishra, S. (2021). What are the factors determining user intentions to use AV while impaired? *Transportation Research Part F: Traffic Psychology and Behaviour*, *82*, 238–255. https://doi.org/10.1016/j.trf.2021.08.008

Thapa, D., & Mishra, S. (2021). Using worker’s naturalistic response to determine and analyze work zone crashes in the presence of work zone intrusion alert systems. *Accident Analysis and Prevention*, *156*, 106125. https://doi.org/10.1016/j.aap.2021.106125

Thapa, D., Paleti, R., & Mishra, S. (2022). Overcoming challenges in crash prediction modeling using discretized duration approach: An investigation of sampling approaches. *Accident Analysis & Prevention*, *169*, 106639. https://doi.org/10.1016/j.aap.2022.106639

Theiss, L., Lindheimer, T., & Ullman, G. L. (2018). Closed Course Performance Testing of a Work Zone Intrusion Alarm System. *Transportation Research Record: Journal of the Transportation Research Board*, *2672*(16), 57–67. https://doi.org/10.1177/0361198118796736

Ullman, B. R., Ullman, G. L., Dudek, C. L., & Williams, A. A. (2007). Driver Understanding of Sequential Portable Changeable Message Signs in Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, *2015*(1), 28–35. https://doi.org/10.3141/2015-04

Ullman, G. L., Iragavarapu, V., & Brydia, R. E. (2016). Safety Effects of Portable End-of-Queue Warning System Deployments at Texas Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*, *2555*(1), 46–52. https://doi.org/10.3141/2555-06

Ullman, G. L., Trout, N. D., & Theiss, L. (2016). *Driver Responses to the AWARE Intrusion Alarm System*. Texas A&M Transportation Institute.

Ullman, G. L., Ullman, B. R., Dudek, C. L., Williams, A., & Pesti, G. (2005). *ADVANCED NOTIFICATION MESSAGES AND USE OF SEQUENTIAL PORTABLE CHANGEABLE MESSAGE SIGNS IN WORK ZONES*.

US Bureau of Labor Statistics. (2021). *Fatal occupational injuries by event or exposure*. Graphics for Economic News Releases. https://www.bls.gov/charts/census-of-fatal-occupational-injuries/fatal-occupational-injuries-by-event-drilldown.htm

VDOT. (2019). Work Zone Safety: Guidelines for Temporary Traffic Control. In *Virginia Department of Transportation*.

Velinsky, S. A., & White, W. A. (2004). Automated machine for highway cone placement and retrieval. *International Journal of Heavy Vehicle Systems*, *11*(2), 174. https://doi.org/10.1504/IJHVS.2004.004038

Wang, F.-Z., Sui, H.-C., Kong, W.-D., & Zhong, H. (2021). Application of BIM + VR Technology in Immersed Tunnel Construction. *IOP Conference Series: Earth and Environmental Science*, *798*(1), 012019. https://doi.org/10.1088/1755-1315/798/1/012019

Wang, J.-H., Collyer, C. E., & Yang, C.-M. (2005). *ENHANCING MOTORIST UNDERSTANDING OF VARIABLE MESSAGE SIGNS*.

Wang, X., Liang, C.-J., Menassa, C. C., & Kamat, V. R. (2021). Interactive and Immersive Process-Level Digital Twin for Collaborative Human–Robot Construction Work. *Journal of Computing in Civil Engineering*, *35*(6), 4021023. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000988

Wang, Z., He, W., Zhang, X., Wang, Y., Wu, B., & Wang, Y. (2021). Lane-based vehicular speed characteristics analysis for freeway work zones using aerial videos. *Canadian Journal of Civil Engineering*, *48*(3), 274–283. https://doi.org/10.1139/cjce-2019-0131

Wang, Z., Zhao, X., Xu, Z., Li, X., & Qu, X. (2020). Modeling and field experiments on autonomous vehicle lane changing with surrounding human-driven vehicles. *Computer-Aided Civil and Infrastructure Engineering*, *36*(7), 877–889. https://doi.org/10.1111/mice.12540

Washington Department of Transportation. (2009). *Automated Enforcement in Work Zone Pilot Project*.

Washington Traffic Safety Commission. (2013). *Automated Speed Enforcement Pilot Project Evaluation*.

Wei, H., & Pavithran, M. (2006). CONCEPT OF DYNAMIC MERGE METERING APPROACH FOR WORK ZONE TRAFFIC CONTROL. *IFAC Proceedings Volumes*, *39*(12), 374–379. https://doi.org/10.3182/20060829-3-NL-2908.00065

Weng, J., & Meng, Q. (2012). Effects of environment, vehicle and driver characteristics on risky driving behavior at work zones. *Safety Science*, *50*(4), 1034–1042. https://doi.org/10.1016/j.ssci.2011.12.005

Weng, J., & Meng, Q. (2013). Estimating capacity and traffic delay in work zones: An overview. *Transportation Research Part C: Emerging Technologies*, *35*, 34–45. https://doi.org/10.1016/j.trc.2013.06.005

Wilson, A. B., & Saito, M. (2012). Evaluation of the Effectiveness of Variable Advisory Speed System on Queue Mitigation in Work Zones. *Procedia - Social and Behavioral Sciences*, *43*, 662–670. https://doi.org/10.1016/j.sbspro.2012.04.140

Wittenberg, G. (1995). Training with virtual reality. *Assembly Automation*, *15*(3), 12–14. https://doi.org/10.1108/01445159510094570

Wu, W., Sun, R., Ni, A., Liang, Z., & Jia, H. (2020). Simulation and evaluation of speed and lane-changing advisory of CAVS at work zones in heterogeneous traffic flow. *International Journal of Modern Physics B*, *34*(21), 2050201. https://doi.org/10.1142/s021797922050201x

Xiong, H., Cheng, Y., Zhao, W., & Liu, J. (2019). Analyzing scientific research topics in manufacturing field using a topic model. *Computers & Industrial Engineering*, *135*, 333–347. https://doi.org/10.1016/J.CIE.2019.06.010

Xu, C., Wu, Y., Rong, J., & Peng, Z. (2020). A driving simulation study to investigate the information threshold of graphical variable message signs based on visual perception characteristics of drivers. *Transportation Research Part F: Traffic Psychology and Behaviour*, *74*, 198–211. https://doi.org/10.1016/j.trf.2020.08.023

Xu, W., Zhao, X., Chen, Y., Bian, Y., & Li, H. (2018). Research on the Relationship between Dynamic Message Sign Control Strategies and Driving Safety in Freeway Work Zones. *Journal of Advanced Transportation*, *2018*, 1–19. https://doi.org/10.1155/2018/9593084

Xu, Z., Wang, Y., Wang, G., Li, X., Bertini, R. L., Qu, X., & Zhao, X. (2021). Trajectory Optimization for a Connected Automated Traffic Stream: Comparison Between an Exact Model and Fast Heuristics. *IEEE Transactions on Intelligent Transportation Systems*, *22*(5), 2969–2978. https://doi.org/10.1109/TITS.2020.2978382

Yamazaki, A., Ito, T., Sugimoto, M., Yoshida, S., Honda, K., Kawashima, Y., Fujikawa, T., Fujii, Y., & Tsutsumi, T. (2021). Patient-specific virtual and mixed reality for immersive, experiential anatomy education and for surgical planning in temporal bone surgery. *Auris Nasus Larynx*, *48*(6), 1081–1091. https://doi.org/10.1016/j.anl.2021.03.009

Yang, H., Ozbay, K., Ozturk, O., & Xie, K. (2014). Work Zone Safety Analysis and Modeling: A State-of-the-Art Review. *Traffic Injury Prevention*, *16*(4), 387–396. https://doi.org/10.1080/15389588.2014.948615

Yang, H., Ozbay, K., Ozturk, O., & Xie, K. (2015). Work Zone Safety Analysis and Modeling: A State-of-the-Art Review. *Traffic Injury Prevention*, *16*(4), 387–396. https://doi.org/10.1080/15389588.2014.948615

Yu, Y., Weng, J., & Zhu, W. (2019). Optimizing Strategies for the Urban Work Zone with Time Window Constraints. *Sustainability*, *11*(15), 4218. https://doi.org/10.3390/su11154218

Yulong, P., & Leilei, D. (2007). Study on Intelligent Lane Merge Control System for Freeway Work Zones. *2007 IEEE Intelligent Transportation Systems Conference*, 586–591. https://doi.org/10.1109/ITSC.2007.4357778

Zaker, R., & Coloma, E. (2018). Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: a case study. *Visualization in Engineering*, *6*(1), 4. https://doi.org/10.1186/s40327-018-0065-6

Zech, W. C., Mohan, S. B., & Dmochowski, J. (2008). Evaluation of Messages on Changeable Message Signs as a Speed Control Measure in Highway Work Zones. *Practice Periodical on Structural Design and Construction*, *13*(1), 11–18. https://doi.org/10.1061/(ASCE)1084-0680(2008)13:1(11)

Zhang, K., & Hassan, M. (2019). Identifying the Factors Contributing to Injury Severity in Work Zone Rear-End Crashes. *Journal of Advanced Transportation*, *2019*, 1–9. https://doi.org/10.1155/2019/4126102

Zhang, Z., & Pan, W. (2021). Virtual reality supported interactive tower crane layout planning for high-rise modular integrated construction. *Automation in Construction*, *130*, 103854. https://doi.org/10.1016/j.autcon.2021.103854

Zhao, L., Rilett, L. R., & Tufuor, E. (2022). *Intelligent Work Zone Using Automatic Queue Detection Systems*.

Zhao, W., Ma, Z., Yang, K., Huang, H., Monsuur, F., & Lee, J. (2020). Impacts of variable message signs on en-route route choice behavior. *Transportation Research Part A: Policy and Practice*, *139*, 335–349. https://doi.org/10.1016/j.tra.2020.07.015

Zhao, Y., & Cen, Y. (2014). *Data Mining Applications with R*. Elsevier. https://doi.org/10.1016/C2012-0-00333-X

Zheng, Z. (2014). Recent developments and research needs in modeling lane changing. *Transportation Research Part B: Methodological*, *60*, 16–32. https://doi.org/10.1016/j.trb.2013.11.009

Zheng, Z., Ahn, S., & Monsere, C. M. (2010). Impact of traffic oscillations on freeway crash occurrences. *Accident Analysis & Prevention*, *42*(2), 626–636. https://doi.org/10.1016/j.aap.2009.10.009

Zhou, Y., & Ahn, S. (2019). Robust local and string stability for a decentralized car following control strategy for connected automated vehicles. *Transportation Research Part B: Methodological*, *125*, 175–196. https://doi.org/10.1016/j.trb.2019.05.003

Zulkarnain, & Putri, T. D. (2021). Intelligent transportation systems (ITS): A systematic review using a Natural Language Processing (NLP) approach. *Heliyon*, *7*(12), e08615. https://doi.org/10.1016/J.HELIYON.2021.E08615