**JOINT TRANSPORTATION RESEARCH PROGRAM**

INDIANA DEPARTMENT OF TRANSPORTATION
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# Best Practices for Maximizing Driver Attention to Work Zone Warning Signs


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**16. Abstract**

Studies have shown that rear-end crashes in the advance warning area for a work zone are the most common type of work zone crashes. Driver inattention (or distraction) is reported as the most common issue and a major contributing factor to those types of crashes. As such, there is a need to identify the technologies that are successful in alerting drivers when approaching work zones.

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# EXECUTIVE SUMMARY

# BEST PRACTICES FOR MAXIMIZING DRIVER ATTENTION TO WORK ZONE WARNING SIGNS

## Introduction

Studies have shown that rear-end crashes in the advance warning area for a work zone are the most common type of work zone crashes. Driver inattention (or distraction) is reported as the most common issue and a major contributing factor to those types of crashes. As such, there is a need to identify the technologies that are successful in alerting drivers when approaching work zones.

The objective of this synthesis study is to identify the best practices and investigate the effectiveness of existing technologies in alerting drivers when approaching work zones. For organizational purposes, the project is divided into four tasks: (1) create a framework for the synthesis study, (2) perform a critical review of the literature, (3) identify possible countermeasures to prevent driver distraction, and (4) identify pilot programs for implementation in Indiana.

Deliverables of the project are (1) a comprehensive synthesis report along with an executive summary and (2) an interactive database that archives and summarizes results of the various technologies that were reviewed in this study.

## Findings

- Usually two to three sets of rumble strips are used together, with two or three strips in each set. Studies suggest that 6-inch-wide strips may generate sound 4 dBA higher than 4-inch-wide strips. Eight strips per set may increase the sound up to 5 dBA higher compared with 4 strips per set. The ease of installation and removal are major concerns for using rumble strips, and portable rumble strips are recommended for short-term work zones. The majority of the studies found reductions in vehicle speeds up to 10 mph.
- Changeable message signs (CMS) are ideal for short-term and mobile work zones due to their portability. For CMS displaying text messages, innovative use of fonts and content may achieve greater speed reduction. Graphic-aided CMS are found to be more legible and recognizable compared with text-message CMS. The location of CMS has significant impact on the effectiveness of this technology; placing in advance of a work zone is recommended.
- The presence of police cars may reduce car speeds by 4.4 mph and truck speeds by 5 mph (in a 45 mph speed zone). High-speed drivers are found to be more affected by police enforcement. Despite the effectiveness of police cars, "halo" effects and high costs are known to be the two main drawbacks of the technology.
- Implementations of variable speed limit (VSL) resulted in reduced speed variance, increased speed compliance, and improved traffic throughput and safety. The heart of VSL is the control algorithm, which determines appropriate speed limit; the speed-flow-density algorithm is shown to have good performance based on simulation experiments. Field studies suggested that VSL could be used to increase speed limit at the bottleneck of work zones.
- The effectiveness of drone radars to alert drivers depends on the number of radar detectors. It has been reported that radar drones are not effective in reducing vehicle speed.
- Public response in supporting intelligent transportation systems (ITS) deployment was found to be very positive (95%). However, ITS technologies are inefficient in decreasing speeds or increasing diversion in cases of low traffic volume. The type of ITS setting plays an important role in determining the driver's preferred speed through work zones. Graphics-based signs are easier for drivers to interpret quickly and result in a greater reduction of mean speeds (13% to 17%). Driver diversion rate varies from 5.3% to 10% (on average) based on ITS implementation. Finally, crashes could potentially decrease by 2.5% to 10% using ITS.
- Auditory technology with loudspeakers is an innovative method which draws drivers' attention to work zones. The effectiveness of loudspeakers varies, and an array of multiple ordinary loudspeakers in an appropriate pattern is found to be the most suitable for long-distance auditory warnings. When this technology was implemented in a mobile work zone, a speed reduction of 2 mph and increased merging distance of 122 ft. were reported.
- Studies have suggested that an advance warning system, 400 meters (1,312 ft.) upstream from truck mounted attenuators (TMA), outperforms any other practice. Drivers' TMA recognition distance can also increase at night due to lower traffic volumes.
- Workers are found to be safer and more efficient behind the mobile barrier trailer MBT-1 in most cases. Drivers are also positively affected by the MBT-1, and the mean vehicle speeds (~49.21 mph) past the work zone are faster during daytime hours with the MBT-1 present than without the MBT-1 (~45.24 mph). This difference is more prominent during nighttime hours.

## Implementation

The searchable database was developed as an implementation of the project using Netbeans IDE under JAVA environment. The database input is the synthesized information from the literature and is stored in Microsoft Access.

The database is constructed to fulfill the following functions: inserting and updating the current information in the database, searching and browsing the studies reviewed, and searching and browsing the technology implementations.

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# 1. INTRODUCTION

The purpose of this study is to synthesize existing technologies that contribute to alerting drivers when approaching the work zone. There are two deliverables from this project: (1) a searchable database which helps to quickly obtain information about the large collection of available technologies efficiently, and (2) a synthesis report which synthesizes the details and key findings related to the technologies. Both deliverables will assist INDOT to assess candidate solutions for improving driver alertness for future implementation in construction work zones.

Studies have shown that rear-end crashes in the advance warning area for a work zone are the most common type of work zone crash. Driver inattention (or distraction) is reported as the most common issue and a major contributing factor to those types of crashes.

Temporary traffic control devices (such as flaggers, traffic signs, pavement markings, channelizing devices, etc.), intelligent transportation systems (such as variable message signs, dynamic lane merge systems) and variable speed limits are some examples of mitigation strategies to improve drivers' attention at work zones. The effectiveness of each strategy varies by the type of work zone and corresponding characteristics, such as roadway type (two-lane versus multilane facility), the availability of accurate and timely traffic data (to accurately estimate work zone capacity), daytime versus nighttime construction, and other factors. For example, the likelihood of a rear end crash during nighttime construction might be lower due to lower traffic volumes and congestion, but the back-of-queue crash risk might increase because of driver inattention and fatigue at night.

# 2. PROJECT SUMMARY

The objective of the project is twofold. First, this project will synthesize the available technologies that alert drivers as they approach the work zones. Since there is significant amount of literature on this topic, we organize the literature under a set of master categories which classifies various work zone alerting technologies based on the frequency and importance of past implementation studies. The list of master categories is given in Table 2.1.

TABLE 2.1
**List of master categories.**

| No. | Name | # of Implementations |
|---|---|---|
| 1 | ITS technologies | 34 |
| 2 | Changeable Message Signs (CMS) | 10 |
| 3 | Rumble Strips | 10 |
| 4 | Truck Mounted Attenuators (TMA) | 6 |
| 5 | Variable Speed Limit | 4 |
| 6 | Speed Display | 4 |
| 7 | Radar Drones | 3 |
| 8 | Police enforcement (ghost police vehicles) | 3 |
| 9 | Mobile Barriers | 4 |
| 10 | Auditory technologies | 3 |
| 11 | Vehicle-Activated Signs (VAS) | 2 |
| 12 | Others | 12 |
| | Total Implementations | 97 |
| | Number of studies reviewed | 87 |

A comprehensive synthesis is conducted for all 12 master categories. Literature related to implementations of each master category in work zones is searched and reviewed. The synthesis of the literature mainly focuses on extracting the study goals and objectives, the type of work zone, the data collected, the performance measures for evaluation, as well as key findings. The synthesis of the project reviewed 97 technology implementations from 87 studies, which include 46 research papers, 40 project reports and 1 presentation. The report synthesizes implementations of 9 most popular and applicable technologies, while the other implementations are recorded in the database

The second objective of the project is to develop a searchable database that allows users to search, visualize and quickly browse relevant work zone technologies. The overall framework of the database is presented in Figure 2.1. The database can help engineers to quickly identify the pros and cons of various work zone alerting technologies. The database is constituted of three main components: (1) the *reference* section which includes the basic information of the reviewed literature, (2) the *implementation* section which summarizes implementation directions and key findings, and (3) the *technology summary* section which concludes the pros and cons associated with each master category. Note that the three sections are interconnected by reference title and technology name so that users can switch easily among the three sections. More detailed descriptions of the database can be found in Section 4.

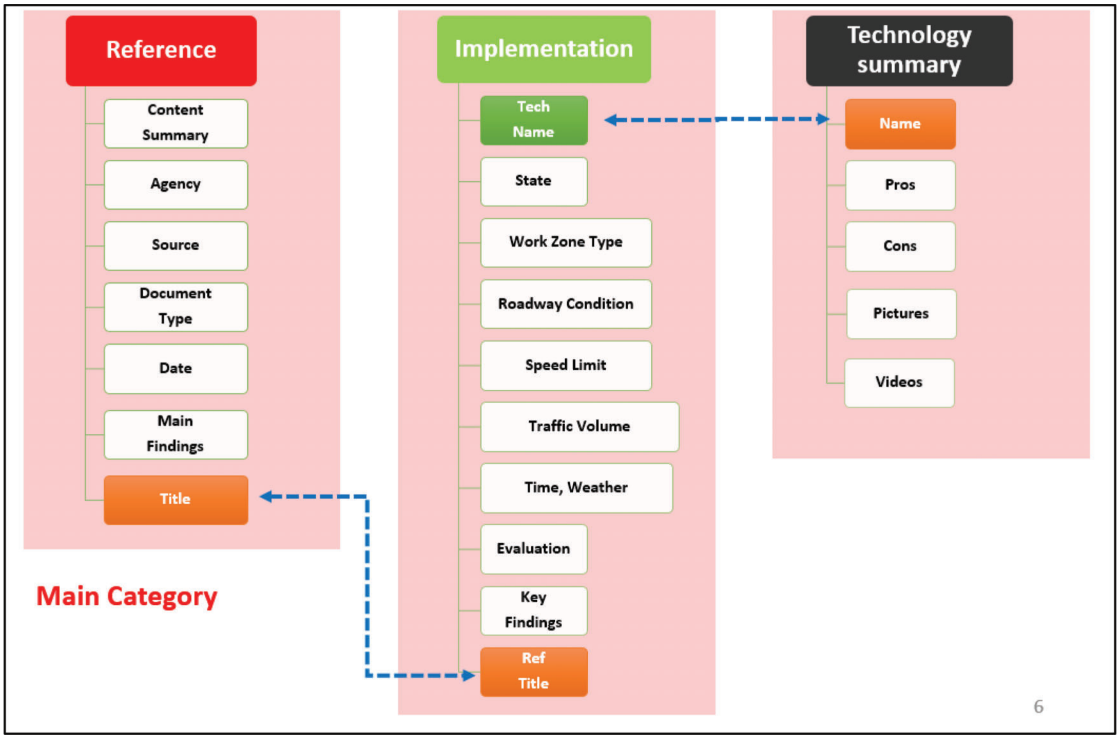



**Figure 2.1** Framework for the database.

## 3. TECHNOLOGY SYNTHESIS

### 3.1 Rumble Strips

Rumble strips are one of the most widely implemented technologies to gain attention of drivers when approaching the work zone. According to a survey in 1993 (Harwood, 1995), 89% of the state highway agencies had deployed rumble strips at key locations such as intersections, horizontal curves and work zones. Rumble strips are formed either by cutting grooves into the pavement or creating raised ridges by adding materials. Drivers are alerted by the generated sound and vibration when driving through. The formal method may damage the pavement and are more often used on the shoulder to avoid lane departure. For the implementation of rumble strips in work zones, the latter method is considered more appropriate and there are several variants of rumble strips which will be discussed in this section.

#### *3.1.1 Orange Rumble Strips*

Meyer (2000b) examined the effectiveness of orange removable rumble strips in a rural bridge repair work zone. The study focused on the decrease in mean speed and 85th percentile speed. The data collected included speed and classification data for approximately 1 day before installation of the removable rumble strips and approximately 1 day afterward.

The removable rumble strips were placed upstream of the standard rumble strips (Figure 3.1). Each group of strips consisted of 6 strips with 0.305 m (1 ft.) between strips. The strips evaluated were 3.175 mm (0.125 in.) thick. The strips ran from centerline to edge line. The mean speed at point 1 decreased by 0.64 km/h (0.4 mph) for passenger cars and 4.7 km /h (2.9 mph) for trucks. The reductions in mean speeds observed at data point 3 compared with data point 1 after the installation of the removable rumble strips were 2.7 km/h (1.7 mph) greater for passenger cars, and 1.45 km/h (0.9 mph) for trucks. At data point 4, the reductions were 3.54 km/h (2.2 mph) for passenger cars and 3.7 km/h (2.3 mph) for trucks.

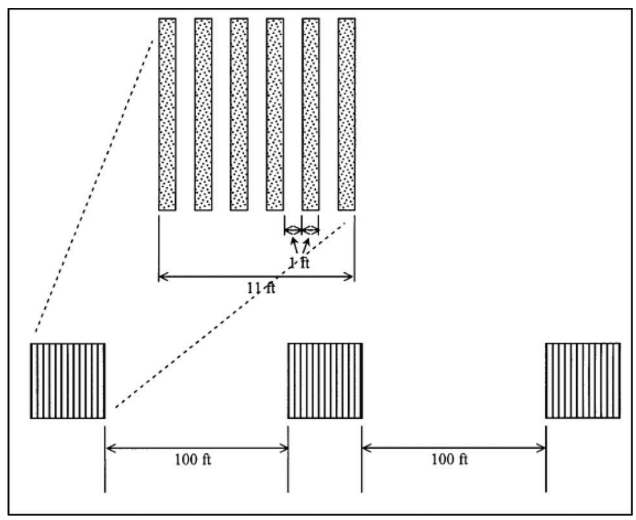



**Figure 3.1** Configuration of the orange removable rumble strip (Meyer, 2000b).

Bernhardt et al. (2001) also investigated the use of orange rumble strips on Interstate 70 (I-70) passing through Columbia, Missouri. Each set in the work zone contained six rumble strips, which were placed on 3.05-m (10-ft.) centers at the site farthest from the lane drop, 1.5-m (5-ft.) centers at the next site, and 0.6-m (2-ft.) centers (Figure 3.2) at the remaining sites. Vehicle speeds, volumes and vehicle classifications in 15-min intervals, before and after the device was placed, were collected for evaluation. The rumble strips were used together with citizens band (CB) wizard. Little additional effect was observed beyond using CB alone for lane distribution but a greater improvement in mean speed was found. No significant effect was observed for speed variation.

**Figure 3.2** Orange rumble strips on 0.6-m centers (Bernhardt et al., 2001).

### *3.1.2 Temporary Rumble Strips*

Elghamrawy et al. (2012) conducted a field study to investigate the use of temporary rumble strips. The objective of the study was to test the effectiveness of different strip configurations and provide practical recommendations for improving the design and layout of temporary rumble strips. The study was performed on a closed segment of airport taxiway rented from the Rantoul National Aviation Center at the University of Illinois at Urbana Champaign (Figure 3.3). The segment was 4,300 ft. long and 72 ft. wide, divided into six equal 12-ft. lanes. A total of 162 scenarios were considered and the sound level for each scenario was recorded. The authors found that temporary rumble strips at the edge of work zones generated adequate sound levels compared with those produced by permanent rumble strips. The authors recommended increasing the number of strips per set as practically as feasible and using temporary rumble strip with larger widths. Also, the study cautioned that the sound level generated by trucks was lower than those generated by sedans and vans.

Sun, Edara, and Ervin (2011) studied the use of temporary rumble strips at low-volume highway work zone. The work zone was a MUTCD (Manual of Uniform Traffic Control Devices) Typical Application (TA) 12 work zone for bridge replacement project. In that study, two pairs of strips were placed each at approximately 3 ft. apart from center to center. The strips were deployed at an angle of approximately 60° to the direction of travel, so that drivers can feel 4 impacts per strip. The authors reported that the use of temporary rumble strips contributed to an average increase of up

**Figure 3.3** Experiment setup in Elghamrawy et al. (2012) study.

**Figure 3.4** Example of portable rumble strips (Wang et al., 2012).

to 10.49% in percentage of braking vehicles and an average decrease in speed of 3.71 mph for braking vehicles. 2.9% more vehicles complied with the speed limit, and average speed reduction of 1% was achieved for all vehicles (though not statistically significant). The researchers recommended deploying the rumble strips perpendicularly (see Figure 3.4) rather than with an angle and in greater numbers than just two per set.

### *3.1.3 Portable Rumble Strips*

Fontaine and Carlson (2001) studied the use of both rumble strips and speed displays at a short-term (one-day) rural-maintenance work zone. Two sets of six rumble strips were installed each day. Each set of rumble strips was placed perpendicular to the direction of travel, and each of the six strips in the set was spaced 45.7 cm (18 in.) from one another. The data collected included the spots speed as well as the traffic volume. The study found that the installation time was 40 min, which might be too long for rural maintenance work-zone. Speed reductions of 3.2 km/h (2 mph) were observed near the "Left Lane Closed Ahead" sign when the rumble strips were installed, Average truck speeds declined between 3.2 and 11.3 km/h (2 and 7 mph) at the data collection stations after the rumble strip installations. The average truck speed within the activity area was between 4.8 and 6.4 km/h (3 and 4 mph) less than with normal work-zone traffic control. The percentage of passenger cars exceeding the speed limit declined by up to 7% after the installation of each set of rumble strips as compared with normal work-zone traffic control.

Wang et al. (2012) delivered a comprehensive report on the use of portable rumble strips at three different work zones. All work zones were of short-term, flagger controlled and with different work starting and ending time. Two or three sets of plastic portable rumble strips (PPRSs) were placed perpendicular to the direction of travel. Each set of PPRSs included four strips with a space of 91.4 cm (36 in.) between strips. With three sets of PPRS, the mean speeds of cars reduced significantly by 15.9, 21.5, and 22.2 km/h (9.9, 13.4, and 13.8 mph) as the vehicles passed through the PPRSs at counters 3, 2, and 1 respectively. Forty-one percent of car drivers hit their brakes for the first set of PPRSs, 59% as drivers approached the second set, but decreased to 54% for the third set. Fifteen percent of car drivers activated brakes for the first set of PPRSs and 50% for the last set of PPRSs. Only one truck driver applied the brake for the first set of PPRSs faced, but 14 of the 18 truck drivers (78%) used the brakes for the second set, and about 61% of truck drivers applied their brakes and three avoided the strips altogether for the third set of PPRSs. With two sets of PPRS, the mean speeds of cars reduced significantly by 9.7 and 11.9 km/h (6.0 and 7.4 mph) at counters 2 and 1. The decrease in the 85th percentile speed was reported when three sets of PPRSs were in place.

### *3.1.4 Key Findings*

- Rumble strips alert drivers by generating sound and vibrations.
- Removable rumble strips are widely applied in short-term work zones.
- The ease of installation and removal are major concerns for application.
- Most often two to three sets of rumble strips are used together, with two to three strips in each set and placed in a perpendicular manner rather than at an angle.
- Orange rumble strips provide visual alertness in addition to vibration and sound.

- Studies suggest that 6 inches wide strip may increase sound level by 4 dBA compared with strip 4 inches wide.
- 8 strips per set may increase the sound level by 5 dBA compared with 4 strips per set.
- Rumble strips were reported to reduce vehicle speed by up to 10 mph.

### 3.2 Changeable Message Sign

Changeable message signs (CMS) are most commonly used as a means of providing advisory information on warnings, traffic condition and upcoming road work information. If equipped with radar devices, the CMSs are also widely implemented as speed displays, which inform individual driver of the travel speed when passing by. The portable feature and the ease of installation make the CMS an ideal technology for speed control in advance of a work zone. Based on the content displayed, the CMS can be divided into three categories: speed display, text-only CMS, and graphic-aided CMS.

*Speed Display*

The CMS with radar devices is also known as the speed display, or speed monitoring display. It informs drivers of their speeds when passing by. The hypothesis of using the speed display is that drivers will actively slow down if they see their speeds above the posted limit.

Fontaine and Carlson (2001) investigated the effectiveness of the portable speed displays at a rural-maintenance work zone on US 62 eastbound in Texas. The speed limit of the road segment was 70 mph and the traffic volume was approximately 1,000 vehicles per day. The maintenance work was completed within a single day. Two speed displays were used as shown in Figure 3.5. It took only 10 minutes to set up the displays, which was suggested as a huge benefit for short-term work zones. In addition, car speed was observed to be 2 to 9 mph lower and truck speed was reduced by 3 to 10 mph. A 15% to 20% reduction in the number of passenger cars exceeding speed limit was also reported.

Pesti & McCoy (2001) evaluated the long-term effectiveness of speed displays in long-term work zones. They implemented speed displays in a long-term work zone on I-80 near Lincoln, NE. The 2.7-mile long section was on a four-lane divided interstate highway, with posted speed limit of 55 mph and 38,000 annual daily traffic (ADT). The Speed Guard radar speed reporting system was implemented, which had a configuration of three speed displays deployed at both upstream and downstream of the work zone (Figure 3.6). Traffic speeds were collected before and after the deployment of speed displays, as well as after the removal of speed displays. The results suggested that speed displays were effective in lowering speeds and increasing the uniformity of speeds over a period of 5 weeks. The mean speed was reduced by 3 to 4 mph, the 85th percentile speed was reduced by 2 to 7 mph and the percentage of vehicles complying with the 55-mph speed limit increased by 20% to 60% over the 5-week period.

Chen et al. (2007) also investigated the long-term effectiveness of speed displays on drivers' speed. The study site was a 0.87-mile long construction zone on STH 29, four-lane divided highway with two 12-ft. lanes in each direction. The posted speed limit reduced from 65 mph to 55 mph. The traffic volume and speed before and after the implementation of speed displays were recorded to evaluate the long-term effectiveness. It was reported that speed displays significantly decreased both average speed and percentage of speeding drivers during nighttime hours, but only slight impact was observed on the daytime speed.

The Maryland State Highway Administration (2005b) studied the use of portable speed displays prior to a work zone. The study was conducted before the implementation of speed display, immediately after, one week, three weeks, five weeks, and seven weeks after the implementation of speed display, as well as one week after the removal of speed display. The speed data under congested conditions and non-congested conditions were collected for comparison. After one week of placing the speed display, the speed reductions ranged from 5.6 to 7.9 mph depending on time of day. The magnitude of speed reduction gradually decreased over time. Once the displays were removed, the traffic speeds returned to normal. Before the implementation of speed displays, the percentage of vehicles speeding excessively (i.e. vehicles travel 10 mph over posted speed limit) was up to 80%. One week after the speed displays were put into place, the percentage dropped from 80% to 44% at

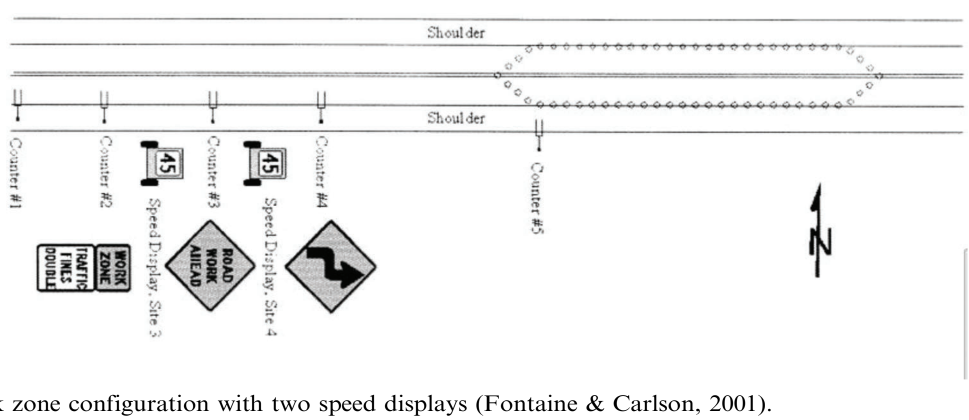



**Figure 3.5** Work zone configuration with two speed displays (Fontaine & Carlson, 2001).

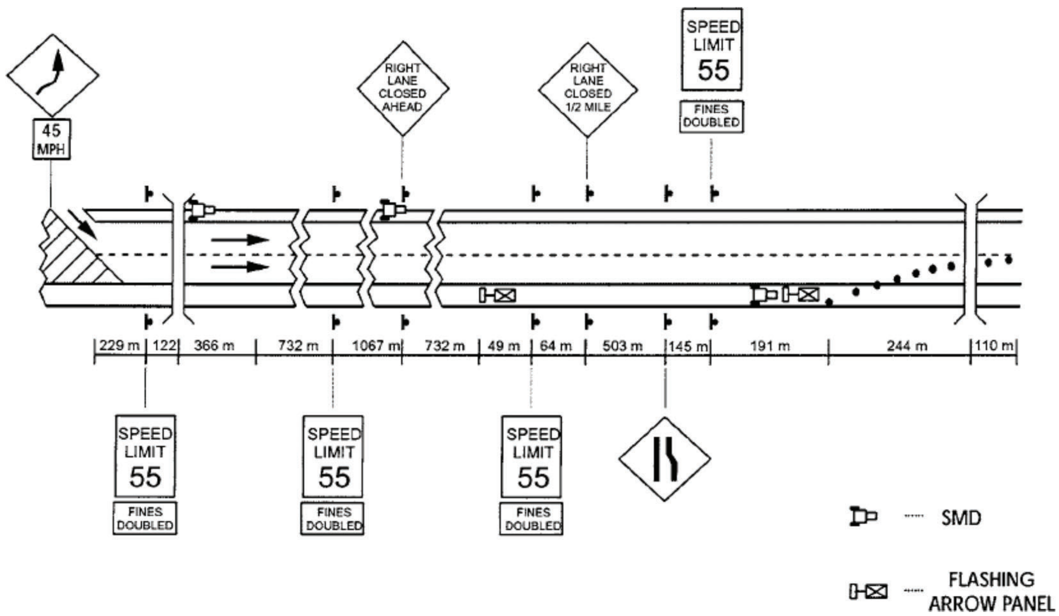



**Figure 3.6** Work zone configuration with three speed displays (Pesti & McCoy, 2001).

the first speed display, and the percentage dropped 80% to 33% at the second speed display. This speed reduction decreased over time but significant percent reductions of 21% still remained after seven weeks of the speed display implementation.

*3.2.2 Changeable Message Sign (Text)*

Benekohal and Shu (1992) conducted one of the earliest studies regarding the effectiveness of the CMS. The CMS was used to display both speed and information messages inside a bridge deck repair work zone on I-57 near Mattoon, Illinois. There were two lanes per direction and one lane was closed in each direction. The speed limit was 65 mph and the traffic volume was 11,800 ADT. Three experiments were conducted, which included using one CMS in advance of the work zone, using one CMS inside the work zone and using two CMSs inside the work zone. The results suggested that the location of deployment was essential for speed control. Placing CMS in advance of the work zone reduced the mean speed of cars and trucks by 2.8 mph and 1.4 mph. The CMS inside work zone reduced average speed of cars by 1.7 mph. The deployment of two CMSs was found to be very effective. Speed reduction near the first CMS was 4.6 mph for cars and 3.7 mph for trucks, and 4.7 mph and 2.6 mph near the second CMS, respectively.

A crucial factor for the effectiveness of the text-only CMS is the design of the information message. Wang et al. (2003) evaluated the effectiveness of the innovative message signs with radar in rural two-lane highway work zones. The innovative message signs with fluorescent orange sheeting and high-intensity sign sheeting were tested, as shown in Figure 3.7. The study concluded that the innovative signs resulted in a speed reduction ranging from 0.2 to 2.6 mph and had little effect on nighttime driving conditions.


**Figure 3.7** Design of innovative signs (Wang et al., 2003).

Brewer et al. (2006) evaluated a combination use of speed display and text-only CMS at work zones on both rural interstate highways and US highways. The goal was to evaluate traditional measures such as speed limit enforcement and identify new technologies that may be suitable for work zones. The CMSs used in the study had a full matrix of LEDs or bulbs to permit text of different sizes or even graphics. When the radar detected a vehicle traveling above a preset threshold, the display changed from the default message to a message urging the driver to slow down to a compliant speed (see Figure 3.8).

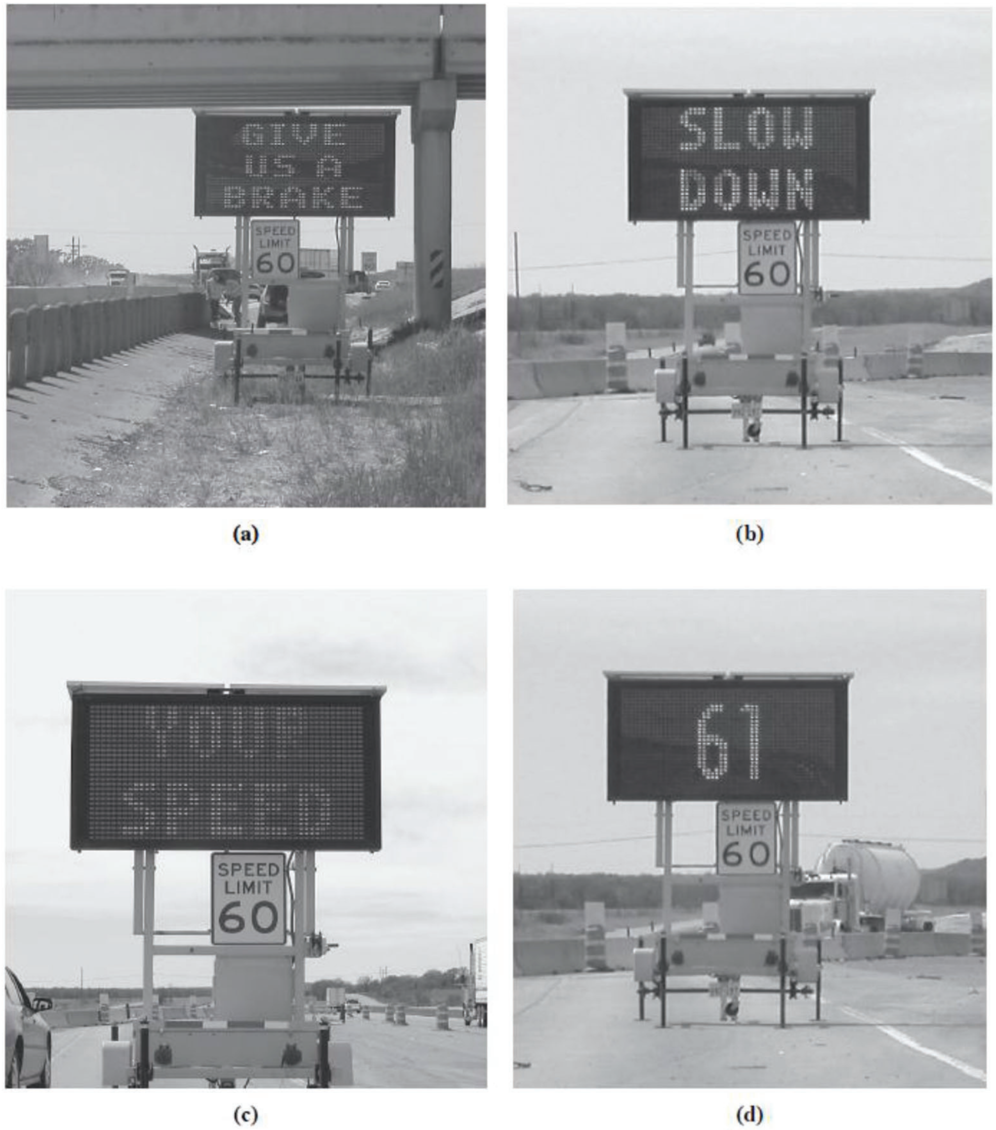



FIGURE 2 Messages on portable changeable message sign with radar: (*a*) default PCMR message, (*b*) first phase for violators, (*c*) second phase for violators, and (*d*) final phase for violators.

**Figure 3.8** Design of the messages on CMS in Brewer et al. (2006).

Once the vehicle either sufficiently slowed down or passed the CMS, the display reverted to its default message. Speed, vehicle count, vehicle classification and headway were collected for evaluation. The results suggested that the CMSs might reduce the $85^{th}$ speed of cars by 5 mph and that of trucks by 10 mph. It was also observed that drivers tended to travel as fast as they felt comfortable without the threat of enforcement. Devices that display approaching driver's speed showed considerable potential for reducing speeds and improving work zone limit compliance.

Garber and Srinivasan (1998) investigated the impact of duration of exposure to a CMS on the effectiveness to reduce vehicle speeds in work zones. The CMS equipped with a radar was placed a short distance behind the first set of tubes to detect vehicle speeds as they entered the work zone. The radar activated the CMS when it detected a speed higher than the preset threshold. The message displayed on the CMS was "You Are Speeding Slow Down," which was found to be the most effective message in the first phase of the study. The sites selected were on I-81 South at Bristol, I-81 North at Bristol, and Route 19 North in Lebanon, Virginia. The configuration at the site can be found in Figure 3.9. The results indicated that the mean speed reductions between Stations 1 and 2 and Stations 1 and 3 on both sites on I-81 were between 8.04 and 16.08 km/h (5 and 10 mph). The data also indicated larger reductions [12.86 to 19.30 km/h (8 to 12 mph)] on Route 19. The CMS with radar was found effective in reducing the

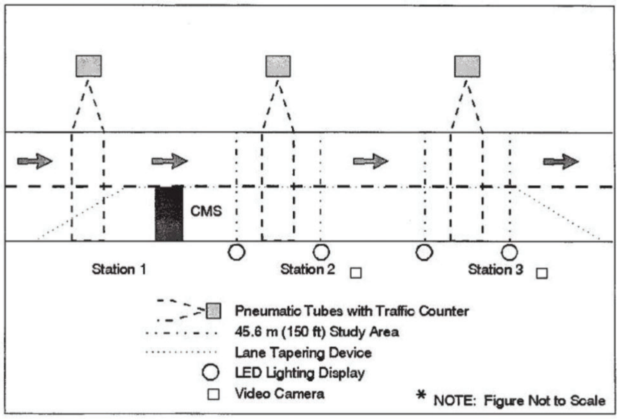



FIGURE 1 Layout of equipment at a typical site.

**Figure 3.9** Site configuration in Garber and Srinivasan (1998).

speeds of speeding drivers in a work zone for short durations (1 week or less). It remained an effective speed control technique even when used for prolonged periods of time (up to 7 weeks).

Bai, Finger, and Li (2010) examined motorists' responses to temporary traffic signs in rural two-lane highway work zones. The work zones were on US-36 and US-73 in Kansas following a construction company as it moved from one segment to another. The posted speed limit inside work zone was 45 mph. The messages displayed on CMSs including "Slow Down, Drive Safely" and "Road Work Ahead." The use of CMSs was proved to be effective in reducing vehicle speeds in two-lane work zones. When the portable changeable message signs (PCMS) was turned on, the device reduced passenger car vehicle speeds by 3.9 mph, truck vehicle speeds by 4.7 mph, and semitrailer vehicle speeds by 3.1 mph over a 500-ft. distance. When the PCMS was turned off, passenger car vehicle speeds were reduced by 2.4 mph, truck vehicle speeds by 3.7 mph, and semitrailer vehicle speeds by 3.0 mph over a 500-ft. distance.

Zech et al. (2008) compared three commonly used CMS messages in reducing vehicle speeds and speed variance in highway work zones. The study site was a 2–3 mile movable construction work zone for milling/paving operation on I-90 eastbound in New York State. The posted work zone speed limit was 45 mph. The three CMS messages were CMS1: RIGHT LANE CLOSED KEEP LEFT, CMS2: WORK ZONE MAX SPEED 45 MPH BE PREPARED TO STOP and CMS3: LEFT LANE CLOSED KEEP RIGHT. Vehicle speed data classified by date, time, lane designation and vehicle types were collected. It was found that properly selected CMS messages could be significantly effective in reducing speeds of all classes of vehicles. Of the three CMS types used in this research, CMS2 was very effective in reducing vehicle speeds by 3.3 to 6.4 mph in the driving lane and 3.7 to 6.7 mph in the passing lane. This CMS message, however, increased the speed standard deviation from approximately 1 to 2 mph. The other two CMS messages were not found to be effective.

Sorrell et al. (2007) also investigated the effectiveness of four CMS message sequences on reducing vehicle speeds within work zones (Figure 3.10). Four different work zones were selected and the configurations are shown in Figure 3.11. The vehicle speed data before and after deploying the CMSs were collected for evaluation. It was found that radar equipped changeable message signs were effective in reducing mean speed, 85th percentile speed, and percentage of vehicles exceeding the speed limit. Specifically:

- **Message 1,** "YOU ARE SPEEDING" followed by "SLOW DOWN," was used as a baseline for comparison in this study to other more novel message variations. However, based on data collected in phase 1, and as reflected extensively in previous studies, this message has been proven effective in reducing speeds in work zone areas.
- **Message 2,** "YOUR SPEED IS ____" followed by "SLOW DOWN," was determined to be effective in reducing work zone speeds through Phase 1 data collection; However, it was primarily included to serve as a basis for comparison to Message 3 which included positive feedback for compliant drivers.
- **Message 3,** "YOUR SPEED IS ____" followed by either "THANKS FOR NOT SPEEDING" or "SLOW DOWN," performed similarly in the study and did not significantly differ from Message 2, despite the belief that positive feedback for compliant drivers would be useful in addressing the tendency of drivers to increase their speeds at station 3, downstream from the CMS.
- **Message 4,** "YOU ARE SPEEDING" followed by "MINIMUM FINE $200," showed comparable speed reductions to the other messages and incorporated a novel approach for displaying possible consequences for speeding.

### *3.2.3 Graphic-Aided Changeable Message Sign*

Besides only displaying text messages, an innovative way that may potentially improve the performance of the CMS is to show graphics along with text messages.

Huang and Bai (2014) conducted the study to compare the mean speed reduction rates from using text CMS, text-graphic CMS and graphic-only CMS. It was suggested that traditional text-based CMS had several limitations such as having a short range of legibility and being difficult to read by elderly and non-English-speaking drivers. The use of graphic-aided CMS may be more legible on a given size of sign, more easily recognizable under adverse viewing conditions, more quickly extracted by drivers when concentrating on driving, and more interpretable to drivers having difficulty understanding text. Examples of the graphic-aided CMS are given in Figure 3.12.

The site selected in the study was a paving construction work zone with one lane closed for pavement resurfacing. The speed limit was 65 mph and the traffic volume was 1,200 AADT. Speed data with CMS on and off from 6 am to 8 pm for a total of 5 working days were collected

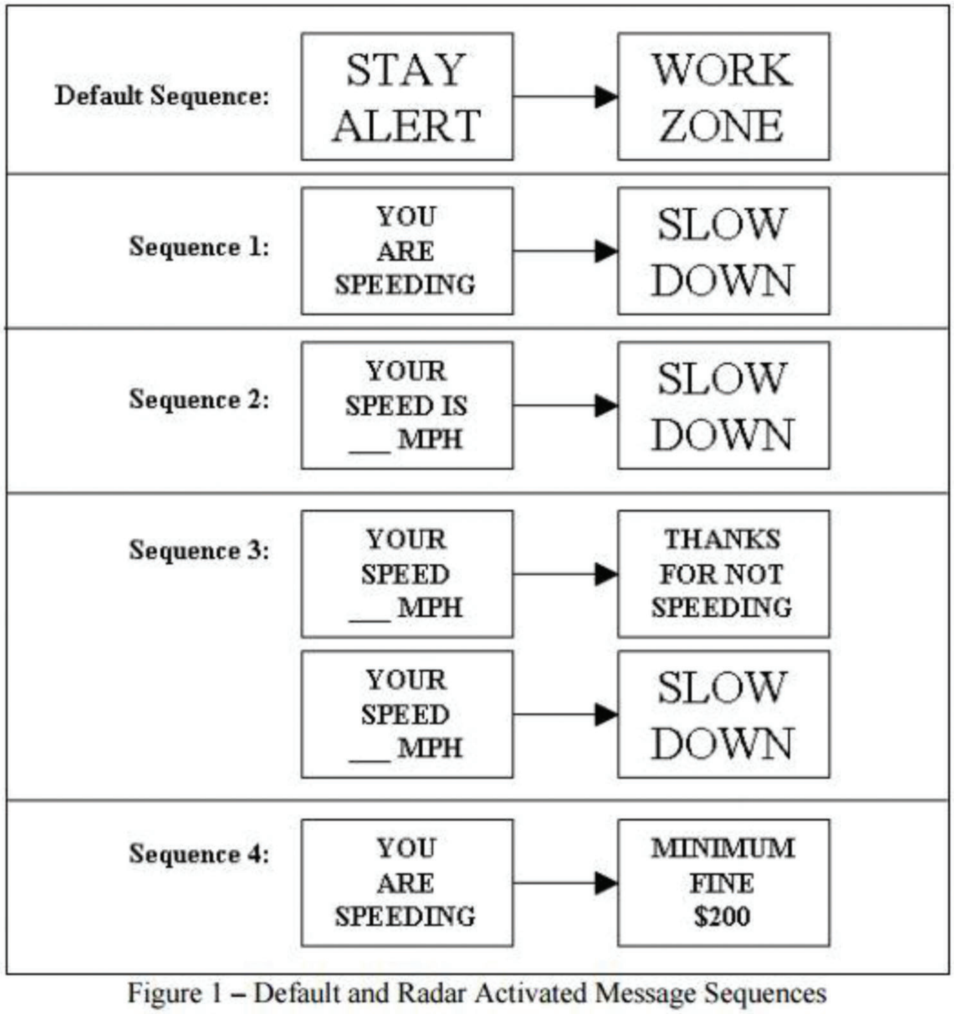



**Figure 3.10** CMS message sequences studied in Sorrell et al. (2007).

Table 1 – Summary of Work Zones Evaluated

| Work Zone Location | Collection Dates | Length | Speed Limit | Non-work zone Speed Limit | Construction Description | Study Phases |
|---|---|---|---|---|---|---|
| I-585 | 2/22/06<br>3/07/06<br>3/15/06 | 6.0 miles<br>(9.7 km) | 45 mph | 55 mph | New interchange, controlled access | Phases 1 & 2 |
| SC 72 | 2/21/06<br>3/09/06<br>3/16/06 | 4.0 miles<br>(6.4 km) | 55 mph | 55 mph | Widening from 2 to 5 lanes | Phases 1 & 2 |
| SC 290 | 3/22/06 | 6.0 miles<br>(9.7 km) | 45 mph | 55 mph | Widening from 2 to 5 lanes | Phase 2 |
| SC 101 | 3/23/06 | 8.1 miles<br>(13.0 km) | | 45 mph | Widening from 2 to 5 lanes | Phase 2 |

**Figure 3.11** Work zones selected in Sorrell et al. (2007).

for evaluation. CMSs were placed in the upstream of the work zone, each message was displayed for 2–3 hours every working day. Hours that each message was displayed in the morning, noon and afternoon were balanced throughout the five working days. The results indicated that Graphic-aided CMSs reduced mean vehicle speeds between 13% and 17% in the upstream of a work zone. Using a graphic-aided PCMS was generally more


**Fig. 2.** Text PCMS.


**Fig. 3.** Text-graphic PCMS with the work zone graphic.


**Fig. 4.** Text-graphic PCMS with the flagger graphic.

**Figure 3.12** The use of graphic-aided CMS in Huang and Bai (2014).

effective in reducing mean vehicle speeds than using a text PCMS. The effectiveness of graphic-aided PCMS depended on the quality of graphic design.

### *3.2.4 Key Findings*

- Typical categories of CMS include speed display, text-only CMS and graphic-aided CMS.
- CMS has the portable feature and is easy to set up, which makes it an ideal technology for short-term and mobile work zones.
- The speed display is effective in reducing both car speeds and truck speeds (up to 10 mph reduction with speed limit of 70 mph and 4 mph reduction with speed limit of 55 mph). In addition, it also contributes to an increase in the percentage of vehicles complying with the speed limit.
- The speed display can be effective for long-term implementation as well.
- The location of the text-only CMS has significant impact on its effectiveness. Placing the CMS in advance of a work zone and the use of multiple CMSs are recommended.
- The text-message displayed should be designed carefully. Innovative fonts and contents may achieve higher speed reduction.
- Commonly used text messages include "You Are Speeding Slow Down," "Road Work Ahead," and "Your Speed Is _MPH, SLOW DOWN." Displaying the consequences of speeding such as "Minimum Fine $200" is also an innovative choice.

- Graphic-aided CMS has the advantages of being more legible and recognizable. Use of graphic-aided CMSs may reduce mean speeds by up to 17% (speed limit of 65 mph).
- The effectiveness of graphic-aided CMS depends on the quality of graphic design.

## 3.3 Police Enforcement

Police enforcement, or the presence of a police car at a work zone site, either patrolling the area or parked by the side of the road, is argued to be one of the most effective methods for reducing vehicle speeds. Drivers are likely to slow down and obey the work zone speed limit in order to avoid getting a speeding ticket. However, the concerns such as "halo" effect (lasting effects after police are gone) and high cost usually restrain wide implementations of the technology.

Benekohal et al. (1992) examined the effectiveness of policy presence at a rural interstate highway work zone and the "halo" effect. The work zone was for bridge deck repair on I-57 in Illinois and the speed limit was 45 mph inside the work zone. In the study, the marked police vehicle circulated within the work zone and patrolled both the northbound and southbound directions of the highway. Vehicle speed and traffic count data were collected for evaluation. The results indicated that the average speeds of the cars inside the work zone were 4.3 to 4.4 mph lower when police were patrolling the work zone. Trucks presented speed reductions of 4.3 to 5.0 mph. The percentage of cars and trucks exceeding the speed limit decreased by 14% and 32%, respectively. During a one-hour period immediately following the police departure, the average speed of cars increased by 2.4 to 3.0 mph, but for trucks the increase was only 0.3 to 0.4 mph.

Chen et al. (2007) investigated the long-term effectiveness of police enforcement strategy in reducing drivers' speed. The site selected was a 3.77-mile long work zone on STH 164 in Waukesha County, Wisconsin. The speed limit inside the work zone was 45 mph. The police enforcement strategies in the study included both mobile and static enforcement. Traffic volume and speed data before and after the implementation were collected to validate the effectiveness. Mobile enforcement led to significant reductions in average speed in daytime; intensive enforcement (two police cars for static enforcement) accomplished the same in nighttime, which suggested that a combination of various enforcement methods may yield the best result for work zone speed management. It was also found that intensive enforcement encouraged more high-speed drivers to reduce operating speeds in work zones.

Chen and Tarko (2012) studied how to improve the process for prioritization of work zones for police enforcement to distribute the patrolling activities among work zones that promise the greatest safety benefit. The study was based on a questionnaire survey among project engineers in charge of Indiana Department of Transportation work zones. A key finding in the study was that a 41.5% reduction in the frequency of crashes was attributable to police enforcement based on the survey responses.

### *3.3.1 Key Findings*

- Having a police car circulate within the work zone or parked on the side of the work zone are two typical ways of police enforcement.
- Police enforcement may reduce car speeds by 4.4 mph and truck speeds by 5 mph (45 mph speed limit).
- Mobile enforcement is found to result in significant speed reductions during daytime and intensive static enforcement achieves the same in nighttime.
- Intensive static enforcement encourages more high-speed drivers to reduce their speeds.
- Police enforcement may contribute to a 41.5% reduction in the frequency of crashes.
- High costs and "halo" effects are the two main drawbacks of the technology.

## 3.4 Variable Speed Limit

Compared to the posted speed limit, the variable speed limit (VSL) has the flexibility to vary speed limit dynamically. The philosophy behind the use of VSL is that it may better serve the road traffic by displaying more reasonable speed limit based on traffic conditions. According to Lyles et al. (2004), the benefits of using VSL include providing more credible speed limit, achieving better compliance of speed limit and improving safety and traffic flow. However, one critical issue related to VSL is how to set a proper speed limit giving the dynamically varying traffic conditions.

Kwon et al. (2007) developed a variable advisory speed limit system for work zones and evaluated the system in the field (see Figure 3.13). The work zone was located on I-494 southbound and the section was around 2.5 miles in length. The posted speed limit of the road segment was 55 mph. In the study, it was determined that the advisory speed limit would be varied every 1 minute in 5-mph increments. Further, the upper limit of the advisory speed limit at the upstream sign was set to 50 mph, while that of the two downstream signs was set to 45 mph to reflect the current posted advisory speed limit for the existing curve section. It was observed that the speed variations were reduced within the work zone and the traffic throughput downstream increased by 7%. Up to 60% speed compliance level was achieved by properly correlating the posted speed limit upstream and downstream on the speed limit signs.

McMurtry et al. (2009) investigated the applicability and effectiveness of VSL signs at work zones in Utah. A "crack and seal" work zone from milepost 185 to 191 on I-80 was selected as the study site. 30 inches by 36 inches speed limit signs were used (see Figure 3.14). The results suggested that VSL signs resulted in smaller speed variation than static speed limit signs. At night,


FIGURE 7 Variable advisory speed limit sign installed near Highway 61 interchange.

**Figure 3.13** The VSL in Kwon et al. (2007).

when VSL signs were set to 65 mph, the standard deviation of speeds was reduced to 0.5 mph to 1.0 mph, down from 1.5 mph to 5.0 mph with the static signs.

Fudala and Fontaine (2010) conducted a study to determine the importance of different VSL system parameters on the overall effectiveness of the system and assess the effect of different network and driver behavior characteristics on VSL performance. The selected site was a major interchange reconstruction project on I-95/I-495 in Washington D.C. The work zone was 5.2-mile long and there were five interchanges within this area. The posted static speed limit was 65 mph and the traffic volume was 154,000 vehicles per day. The results were assessed in VISSIM. The results of the simulations revealed that the control logic of VSL could have a significant impact on operations and safety surrogate measures. The speed–flow–density algorithm performed better than the field-tested code a majority of the time, likely because it allowed for unique speeds to be posted to every sign instead of larger aggregate zones. Locating VSL signs to facilitate outflow past the work zone taper was very important. If no VSL was positioned shortly after the final lane closure, travel times may artificially increase if drivers continue to comply with the reduced speed limit. Speed limits should be increased past a bottleneck to "pull" vehicles through the capacity reduction. The speed harmonization benefits of VSLs can have significant benefits in terms of delaying the onset of congestion with compliance levels as low as 20%.


(Photo by Thomas McMurtry, July 2007)

**Figure 3.14** VSL sign used in McMurtry et al. (2009).

### *3.4.1 Key Findings*

- VSL provides the flexibility to vary the speed limit dynamically.
- The main objective of using the VSL at work zones is to increase the speed compliance so that the traffic throughput and safety are improved.
- Using VSL signs may reduce speed variance.
- The key element of the VSL system is the control algorithm, which is used to derive the proper speed limit. The speed-flow-density algorithm is found to have good performance based on simulation experiments.
- It is recommended to use VSL to increase speed limit just past the bottleneck of work zones.

## 3.5 Drone Radar

Drone radar is inexpensive, small and lightweight. It emits radio signals to active radar detectors so that drivers are alerted by warning messages. The main objective of the radar drone is to alleviate the speeding problems in work zones. An important assumption of the use of radar drone is that drivers equipped with radar detectors usually drive faster than speed limit. While there are numerous studies investigating the effectiveness of the drone radar, few studies have been conducted on the use of drone radars in work zones.

The Maryland State Highway Administration (2005a) provided a brief introduction on the drone radar and discussed the potential of the drone radars in improving work zone safety. Based on the synthesis, the drone radar was found to reduce the proportion of excessive speeders up to 33% and reduce mean traffic speed by up to 4 mph. But it was also mentioned that the drone radar only targeted at motorists with radar detectors and did not reduce traffic speeds to desired level. A survey was also presented which investigated the preference on radar drones of different state DOTs.

Meyer (2000a) examined the implementation of drone radars on an interstate rural work zone. The work zone was 5 miles long and speed limit was set to 60 mph. The main objective of that study was to assess the consistency on the use of drone radars in work zones and two drone radar unites were deployed at either end of a 1 mile segment of the work zone. It was found that drone radar might cause a small decrease in the 85th percentile speed near the unit, but that speeds increased farther downstream. Based on that study, the use of a radar drone did not seem to be an effective device for reducing speeds in highway work zones.

Oliveira et al. (2002) studied the frequency of radar detector equipped drivers react to the radar transmissions. The study was conducted in a work zone on GA State Route 20, which had two lanes in each direction. Reactions of drivers were evaluated by collecting time mean speed, average vehicle acceleration and individual vehicle trajectories. The preliminary analysis conducted on the aggregate speed data collected did not show significant speed changes that could be attributable to the use of radar transmissions. Nevertheless, the procedure for obtaining vehicle traces presented in the study had potential applications on other fields of transportation research.

Eckenrode et al. (2007) presented one of the most comprehensive work related to the use of drone radars in work zones. The study investigated five work zones, which covered both rural two-lane roads and interstate highways. The objectives of the study were to determine the effectiveness of radar drones in reducing speed in work zones and determine the proportion of vehicles with radar detector in the traffic streams. Results from that study showed a 2-mph decrease in mean speeds of all highway vehicles and a 6-mph decrease with those equipped with radar detectors. Tractor-trailers had a higher reduction in mean speeds on interstates because non-interstate primary and secondary highways had lower speed limits than interstate facilities. The effectiveness of drone radar was reported to depend on the number of radar detectors in the traffic stream. The comparison of mean speeds with drone radar on and those with drone radar off in the five work zones was provided in Table 3.1.

### *3.5.1 Key Findings*

- Drone radars alert drivers by triggering radar detectors in vehicles.
- Aggressive drivers are assumed to be more likely to install radar detectors.
- Drone radars were reported to be effective in reducing the number of aggressive drivers (up to 33%).
- Drone radars were reported to be ineffective in reducing vehicle speeds.
- The penetration rate is a big concern for implementations. The effectiveness of drone radars mainly depends on the number of radar detectors in the traffic.

## 3.6 Auditory Warning

Auditory Warning is one of the innovative technologies for alerting drivers and may have a huge potential to draw drivers' attention when approaching work zones. The main idea of the auditory warning is to use a set of loud speakers to generate long distance directional sound so that drivers are alerted before they enter work zone areas. Note that this technology can alert not only drivers but also inform workers of potential risks.

Phanomchoeng et al. (2010) reviewed the current available directional sound technologies that could potentially be used to develop a long-distance auditory warning system in highway work zones. There were four widely used directional sound technologies, including normal loudspeaker, reflector-based loudspeaker, parametric array of hypersonic sound and arrays of multiple loudspeakers. These technologies differentiated from the direction of sound, the level of sound and price and size, which might greatly affect work zone applications. The authors reported that an array of multiple ordinary loudspeakers arranged in an appropriate pattern was most appropriate for long distance auditory warnings in highway work zones. The technology was portable, easy to install and maintain. The comparison of the sound technologies is given in Table 3.2.

TABLE 3.1
**Mean speed with drone radar on and off (Eckenrode et al., 2007)**.

| | | | Mean Speed with Drone Off (mph) | | Mean Speed with Drone On (mph) | |
|---|---|---|---|---|---|---|
| **Location (County)** | **Time of Day** | **Speed Limit (mph)** | **Entire Traffic Stream** | **Radar Detector Users** | **Entire Traffic Stream** | **Radar Detector Users** |
| Laurens SC-72 | AM | 55 | 56.1 | N/A | 54.7 | N/A |
| Greenville 1-385 | AM | 65 | 68.6 | N/A | 68.3 | N/A |
| | PM | 65 | 65.8 | 71.0 | 65.8 | 63.1 |
| Spartanburg 1-85 | AM | 60 | 62.3 | 64.3 | 63.3 | 59.9 |
| Oconee S-488 | AM | 35 | 34.8 | 39.3 | 36.7 | 33.2 |
| Spartanburg 1-585 | AM | 45 | 54.9 | 55.6 | 49.8 | 50.4 |
| | PM | 45 | 45.5 | 54.8 | 47.3 | 48.8 |

TABLE 3.2
**Summary of the directed sound technologies (Phanomcheoeng et al., 2010).**

| | Directional Sound | Size | Weight | Install and Maintenance | Price | Overall Appropriateness |
|---|---|---|---|---|---|---|
| **Normal Loudspeakers** | Poor | Small | Light | Easy | Cheap | Poor |
| **Refractor-Based** | Fair | Large | Heavy | Difficult | Expensive | Fair |
| **Parametric Array (LARD)** | Excellent | Medium | Medium | Difficult | Expensive | Good |
| **Arrays of Multiple Loudspeakers** | Good | Large | Light | Easy | Cheap | Good |


**Figure 3.15** SonoBlaster!® Work Zone Intrusion Alarm (Krupa, 2010).

In 2010, the New Jersey Department of Transportation (NJDOT) launched a study to evaluate how effective the auditory warning would be to alert maintenance workers (Krupa, 2010). The device evaluated was called "SonoBlaster! Work Zone Intrusion Alarm." A close-up figure of the device is given in Figure 3.15. The alarm was an impact- or tilt-activated safety device that was mounted on work zone barriers. It could be activated by an errant vehicle and emits alarms to both workers and drivers when vehicles entering the buffer zone. The device was implemented in a maintenance work zone on U.S. Route 1. Fourteen device-equipped cones were used to delineate the buffer area for the work zone. The author reported that the mounting of the device was time-consuming, the sensor was very sensitive and must be handled carefully but no concrete conclusions could be made on the effectiveness of this technology due to light traffic within the study period.

The auditory warning technology was also implemented recently in the mobile work zone (Brown et al., 2015). The auditory warning technology in that study is named Directional auditory System (DAS) and the DAS was attached to the construction vehicle with the truck-mounted attenuator. The DAS includes parametric speaker arrays and the Long Range Acoustic Device. Figure 3.16 gives the setting of the technology in the study. The objective of the study was to evaluate the effectiveness of mobile work zone alarm systems and the performance was tested on I-435 in the Kansas City area. The segment was a 6-lane interstate highway with 21,534 AADT. The authors reported that the DAS resulted in an increase of 122 ft. for the merging distance and reduced the average vehicle speed of 3 mph.

### *3.6.1 Key Findings*

- Auditory warning produces directional sounds over distances to alert drivers.
- The type of loudspeakers applied is critical to the effectiveness of driver alertness. Multiple ordinary loudspeakers were recommended for long distance warning. The array and the timing of the speakers should be adjusted properly to obtain the best effects.
- One study also investigated alerting workers by auditory warnings. No concrete conclusions were drawn from the study. But the evaluation of auditory warnings on workers may serve as a potential pilot program in Indiana.
- A field study of auditory warning in mobile work zone reported that mean vehicle speed was reduced by 2mph and the merging distance was increased by 122 ft.
- The technology is recommended to be implemented following national noise standards.

## 3.7 Work Zone Intelligent Transportation Systems (ITS)

A number of State Departments of Transportation (DOTs) had been regularly deploying Intelligent Transportation Systems (ITS) in work zones. ITS is also known as 'Smart Work Zone Systems' since it smoothens traffic operations and increases safety by forwarding real-time information to drivers and monitoring traffic conditions. An ideal framework for evaluating the effectiveness of ITS deployments is unavailable despite a number of ITS deployments in work zones so far (Edara et al., 2013). In order to evaluate numerous implementations of smart work zone systems, Edara et al. (2013) proposed a framework to measure ITS effectiveness for different work zone projects based on five performance measures: diversion rate, delay time,


**Figure 3.16** Construction vehicle with TMA for DAS (Brown et al., 2015).

queue length, crash frequency, and speed. This framework allows for consistency in performance measures across different ITS studies, for making comparisons across studies or for a meta-analysis.

### *3.7.1 ITS Use to Improve Traffic Operations*

Among several studies related to ITS deployments in work zones, a major portion in that body of literature presented ITS deployments in improving traffic operations. Table 3.3 presents the summary for these studies.

Zwahlen (2002) evaluated Travel Time Prediction System (TIPS). The travel times of I-75 were displayed with the help of Changeable Message Signs (CMS) (Figure 3.17) in order to influence driving choices. The accuracy of TIPS was determined by making comparisons between measured travel times and TIPS estimations of travel times. Travel times were estimated by 5 microwave sensors, while measured travel time came from individuals driving through the work zone who used recording equipment. The system had an overall accuracy of 88% given that the system rounded the displayed travel times to the nearest 4 mph. Figure 3.18 shows how the sensor station trailer was configured with traffic sensor, microwave antenna and solar panel. The study recommended improving the placement of sensors.

Bushman and Berthelot (2005) conducted a survey along with the North Carolina DOT. The survey revealed how drivers perceived Portable Changeable Message Signs (PCMS) (Figure 3.19) along the work zone on I-95 in North Carolina. The overall response from the public was very positive with 95% supporting ITS deployment. Only 3% of drivers thought that the messages never provided accurate information. Recommendations were made to deploy ITS on freeways work zones with high traffic volume.

Horowitz and Notbohm (2003) studied warning message on freeways of slowed traffic ahead named as "Intellizone" (Figure 3.20). Detectors average the highway speeds every three minutes if speeds were less than 50 mph and display a 10 mph range of speeds. The warning message displayed stopped traffic below 20 mph. As compared to TIPS, Intellizone was found to be cheaper but the detectors were less accurate. The study recommended that multiple detectors should accompany a portable message sign in order to provide improved accuracy.

Pesti et al. (2002) studied a Work Zone Speed Advisory System (WZSAS) on I-680 in Nebraska. Speeds and volumes were recorded using video detection technique (Figure 3.21). Speeds below 55 mph were displayed on the Changeable Message Signs (CMS). The Nebraska Department of Roads (NDOR) was notified of a possible incident if speeds dropped below 15 mph. The system was inefficient in decreasing speeds or increasing diversion because of the low levels of demand in the area. A survey was conducted but only 35 people responded to the survey. The study considered the use of a website to be a success as well as the accuracy of the Changeable Message Signs (CMS).

Horowitz et al. (2003) also evaluated the effectiveness of TIPS. The study considered diversion and delay as the relevant performance measures. Delay times were posted with the help of Portable Changeable Message Signs (PCMS). Static signs were used in order to increase driver diversion, which decreased the amount of messages to be displayed on the PCMS. The study found that high volumes resulted in longer delay times displayed, but the study was unable to assess the effect of TIPS on diversion. The study recommended applying a simulation based approach to identify the benefits of TIPS.

Tudor et al. (2003) studied and compared two work zone ITS deployments on I-40 in Arkansas: Automated Data Acquisition and Processing of Traffic Information in Real-time (ADAPTIR) (Figure 3.22) and Computerized Highway Information Processing System

TABLE 3.3
**Summary: Work zone ITS deployments in improving traffic operations.**

| Study Name | ITS Name | State of Implementation | ITS Components | Key Findings |
|---|---|---|---|---|
| Zwahlen (2002) | Travel Time Prediction System (TIPS) | OH | 3 changeable message signs (CMS), 5 microwave radar sensors, control center, and radios | 88% of predicted travel times were within 4 minutes of measured travel time; Maximum error was 18 minutes |
| Bushman and Berthelot (2005) | Travel Messenger System | NC | 3 portable changeable message signs (PCMS), 3 sensors, 3 more message signs on alternative routes, and website | 90.9% of drivers had seen the PCMS; 42.6% of drivers thought signs were always accurate; 40.5% of drivers were influenced regarding alternative routes; Near 100% for readability; 95.3% recommended continued use of ITS; 93% of drivers do not use the website |
| Horowitz and Notbohm (2003) | Intellizone by Highway Information Systems | WI | Wireless detectors and portable message signs | Drivers were satisfied with speed signs; Diversion was high due to driver awareness, not necessarily advisory signs; Delay was approximately the same for diverted and non-diverted traffic; The posted delay times on the message boards did not match delay times described by drivers |
| Pesti et al. (2002) | Work Zone Speed Advisory System (WZSAS) | NE | 2 video detectors, control system at NDOR, 2 changeable message signs (CMS), and traffic website | High number of diversion routes also let other traffic onto highway without seeing messages; High levels of demand occurred about 15 minutes per day; The system did not significantly decrease speeds, increase diversion, or decrease demand |
| Horowitz et al. (2003) | Travel Time Prediction System (TIPS) | WI | TIPS ($179,000) : 4 portable changeable message signs (PCMS), 5 microwave detectors, alternative route static signs, and base station | Diversion between 7% and 10%; Maximum delay was 32 minutes |
| Tudor et al. (2003) | Automated Data Acquisition and Processing of Traffic Information in Real-time (ADAPTIR) and Computerized Highway Information Processing System (CHIPS) | AR | ADAPTIR ($322,500 by The Scientex Corporation): 5 changeable message signs (CMS), highway advisory radio (HAR), 5 Doppler radar sensors, and radio central control; CHIPS ($490,000): 2 changeable message signs (CMS), highway advisory radio (HAR), 15 traffic sensors, and radio central control | ADAPTIR messages were made more generic because estimates were off; CHIPS had communication problems due to equipment but still had a 90% accuracy of delay time messages; ADAPTIR had a longer response time then CHIPS |
| Chu et al. (2005) | Computerized Highway Information Processing System (CHIPS) | CA | Computerized Highway Information Processing System (CHIPS), which include a 5 queue trailers using Remote Traffic Microwave Sensors, 5 portable message signs, and 3 CCTV camera trailers | 78% of exiting vehicles diverted due to traffic conditions; Only 36% responded that CHIPS improved safety; 5.3% to 8.7% diversion rates therefore around 3 minutes were saved from delay time |
| Luttrell et al. (2008) | Real-Time Work Zone System (RTWS) | DC | 8 traffic sensors, 13 DMS, 2 remote traffic microwave sensors, 3 pagers, and 2 cameras | Maximum occurring diversion rate of 90%, average of 52%; Managing reoccurring congestion combined with work zones is possible |
| Luttrell et al. (2008) | Detection Trailer, Message Sign, Camera, internet, System Software | TX | 6 microwave detection trailers, 6 message signs, 3 cameras, internet website, and system software | Average diversion rate of 10%; The agency in charge of data should coordinate equipment early and communicate to construction personnel early |

*(Continued)*

TABLE 3.3
*(Continued)*

| Study Name | ITS Name | State of Implementation | ITS Components | Key Findings |
|---|---|---|---|---|
| Luttrell et al. (2008) | Dynamic Lane Merge (DLM) System | MI | 5 trailers spread out by 1500 ft. with lighted no passing signs | Dynamic Lane Merge (DLM) system works in reducing late merges; Evidence inconclusive for decreased delays |
| Luttrell et al. (2008) | Automated Work Zone Information System (AWIS) | AR | 47 vehicle detector sensors, 4 radio transmitters, 15 DMS, 8 stationary video, HAR, and internet website | 49% drivers agree that system works regarding safety; 95% drivers use DMS, 24% for HAR, and 5% for website; Portable closed circuit video was a hindrance in the work zone |
| Luttrell et al. (2008) | DMS, Sensors and Internet | NC | 10 DMS, 10 traffic sensors, and internet website | The volume was never past the threshold value to activate the ITS system; Agencies should evaluate data output to see if field adjustments are necessary |
| Benekohal et al. (2009) | Speed photo enforcement (SPE) van and detectors | IL | Speed photo enforcement (SPE) van and detectors | Speed of 50 mph means a reduction of 4.5 mph using SPE; Speed of 65 mph means a reduction of 8.4 mph using SPE |
| Chan (2009) | ASE Equipment: Road Working Area Safety System (RWASS), EVT-300 , Nu-Metrics and Trans-Q | CA | Tested ASE Equipment: Road Working Area Safety System (RWASS) by Sensys Traffic AB, Sweden, EVT-300 by Eaton-Vorad Technologies, Nu-Metrics NC-200 by Quixote Technology, and Trans-Q by Quixote : Control was SR-12 Caltrans Traffic Station Technology | SR-12 Caltrans Traffic Station, most reliable; RWASS, underestimates vehicle count due to low position; EVT-300, model out-of-date so it was used to compare data; NC-200, closest results to control, not all positions credible; Trans-Q, underestimates speeds; Radar has natural errors, use redundant measurements, and use tracking radar equipment |
| Jackson (2010) | Side-fire radar | OR | Side-fire radar | Construction times linked to ITS system provides less delay and greater safety |
| Edara (2011) | DMS and PCMS | MO | One site had a permanent dynamic message sign (DMS) and the other had a portable changeable message sign (PCMS): 2 cameras, DMS, static signs, and VISSIM simulation | Crash rates increased for the one year of data with DMS; 94% of drivers followed directions displayed on DMS; 98% of truck drivers followed directions; 41% of drivers only receive traffic details from DMS; 3.6 and 1.25 mph speed reductions observed; |
| Fontaine and Edara (2007) | VISSIM Simulation | N/A | VISSIM simulation software; Simulated location for 24 hour period | Table results show the number of days until the benefit/cost is > 1.0 or benefit/cost could be found given a specific number of days; Use of a SWZ may result in a higher benefits than cost depending on said variables |
| Sun, Edara, Hou, et al. (2011) | Sequential Lights, cameras, and a radar gun | MO | NA | Mean speed reduced 2.21 mph and 85th percentile speed reduced by 1mph; More effective towards rural areas and commercial trucks |
| Brydia et al. (2013) | PCMS, Bluetooth Readers, Traffic Counter, CCTV | TX | 21 portable changeable message signs, Bluetooth readers, Wavetronix traffic counters and Closed Circuit Television | Maximum queue length exceeded 3.5 miles during an incident; Speeds reduced by 40 mph during an incident; Traffic recovery took 3.5 hours following an incident; Bluetooth showed that lane closures did not significantly decrease speeds |

*(Continued)*

TABLE 3.3
*(Continued)*

| Study Name | ITS Name | State of Implementation | ITS Components | Key Findings |
|---|---|---|---|---|
| Huang and Bai (2014) | Speed Sensors and PCMS | KS | 5 JAMAR TRAX Apollyon speed sensors and portable changeable message signs | Phase 1; 8 mph reduction, Text only = 13%; 6 mph reduction, Text and Graphic = 10%; 11 mph reduction, Graphic only = 17% . Phase 2; 8 mph reduction, Text-Graphic 1 = 13%; 8 mph reduction, Text-Graphic 2 = 13%; 7 mph reduction, Text-Graphic original = 11%; Graphics are significantly more effective than using only text on portable changeable message signs. |
| McCanna (2013) | PCMS, Sensors, Sign and Markings, Computer Program | OR | Portable Changeable Message Signs, traffic sensors, static signs and markings, reduced speed zones, screens to minimize gawking, pan-tilt-zoom cameras, and the Work Zone Traffic Analysis (WZTA) computer program | Traffic communications need to be specific about either traffic operations or safety; Products need to be tested on large construction project with a long-term duration |


**Figure 3.17** Changeable message sign in TIPS system displaying distance to the end of the work zone (Zwahlen, 2002).

**Figure 3.18** Sensor station trailer configured with traffic sensor, microwave antenna and solar panel (Zwahlen, 2002).

(CHIPS) (Figure 3.23). The systems aimed to reduce queue length to prevent collisions and improve safety. 144 travel times were measured by personnel driving through the road segment where the ADAPTIR system was deployed. For travel times, ADAPTIR had a maximum overestimate greater than 12 minutes and a maximum underestimate of greater than 2 hours and 11 minutes. CHIPS was found to be more expensive as compared to ADAPTIR but had a better accuracy of the messages displayed on the changeable message signs. The study recommended displaying queue lengths rather than delay times.

Chu et al. (2005) also evaluated the performance of CHIPS, which is an automated work zone information system (Figure 3.24). The study was carried on I-5 in California and considered diversion, delay, queuing, and speed as the specific performance measures. The Portable Message Signs (PMS) were updated when a queue formed and the posted messages suggested a specific alternative route. About 5.3% to 8.7% of the mainline vehicles diverted due to the high volume of traffic during the holiday weekend and saved 3 minutes off their delay time. The study conducted a postcard survey in order to identify the utility of the message signs. The survey results suggested that 78% of exiting vehicles diverted onto alternative routes due to traffic conditions while only 36% responded that CHIPS improved safety.

Luttrellet al. (2008) summarized several ITS benefits in work zones in a report prepared for the Federal Highway Administration (FHWA). The report includes five key hypotheses: (i) ITS information will be timely and accurate; (ii) ITS will divert traffic during congestion; (iii) ITS will decrease delay; (iv) ITS will decrease congestion, and (v) ITS will improve safety. From the field studies, three of the results can be summarized as follows: (i) In Washington, D.C., there was a 52% reduction in mainline volume during congestion due to ITS. (ii) In Waco, TX, there was an average of 10% diversion of traffic during congestion due to ITS with a 28% maximum diversion. (iii) In Kalamazoo, MI, Dynamic Lane Merge (DLM) system with flashing lights on signs which denoted when to merge early, reduced forced merges by a factor of seven and dangerous merges by a factor of three.

The study made several recommendations on the use of ITS which are useful. For example, last-minute merges decreased when flashers were on at a lane closure. By using appropriate messages in congested traffic, diversion rates could increase; it also allowed improved management of incidents in work zones. In addition, drivers perceived messages concerning 'stopped traffic ahead' to be helpful and that provided additional safety at work zones. Moreover, the use of ITS may not decrease delays for low traffic volumes since drivers were found to be compliant with speed limits when ITS was used. The study suggested that agencies considering ITS need to be aware of the necessity for system maintenance, the increased impact on alternate routes, and deploying ITS only when traffic demand is adequate to justify the investment.

Benekohal et al. (2009) studied how Speed Photo Enforcement (SPE) can reduce speed, thus reducing probability of rear end collisions due to speed differentials. The study found that the type of ITS equipment plays an important role in determining the driver's preferred speed through work zones. The study also


**Figure 3.19** Roadside message sign providing delay information (Bushman & Berthelot, 2005).

**Figure 3.21** WZSAS camera mounted above roadway (Pesti et al., 2002).


**Figure 3.20** Two alternative messages displayed by the Variable Message Sign located on the median of US 41 (Horowitz and Notbohm, 2003).

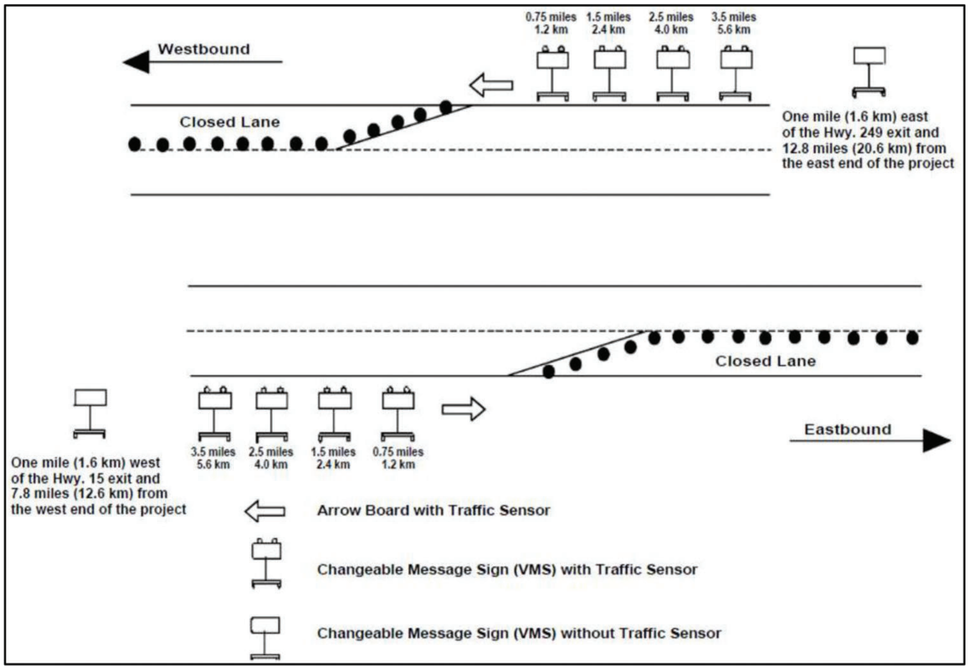



**Figure 3.22** ADAPTIR system layout (Lonoke county site) (Tudor et al., 2003).

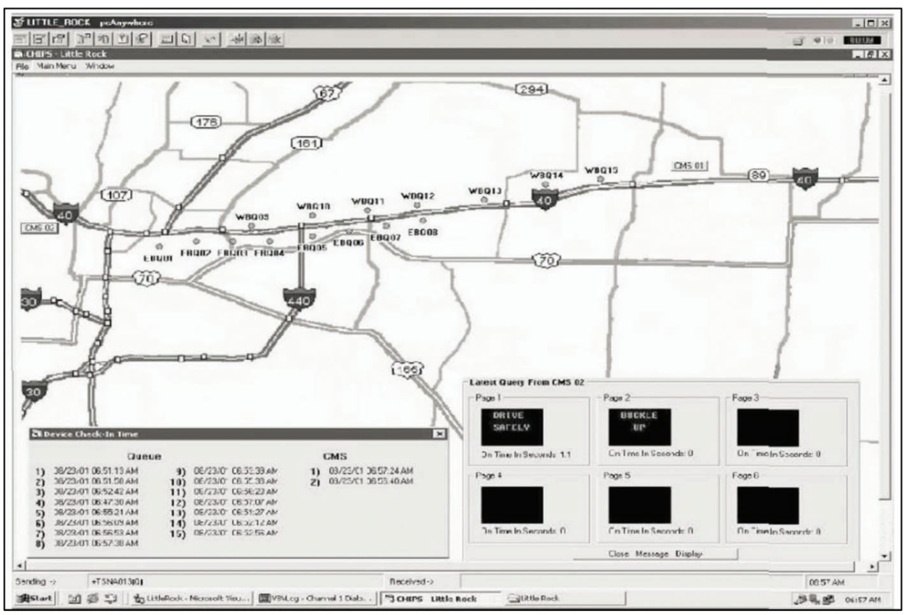



**Figure 3.23** CHIPS host computer screen, located in resident engineer's office (NLR site) (Tudor et al., 2003).

found that the speeds are significantly reduced when one considers the limited space of a work zone combined with the presence of workers and recording sensors. The study considered the speed-flow relationship in order to accurately measure the road capacity in a work zone. The diversion rates and overall traffic flow characteristics could be reasonably determined by estimating capacity.

Chan (2009) conducted a field study on four types of Automated Speed Enforcement (ASE) equipment and made recommendations for deployment (Figure 3.25). These four types were: (i) Road Working Area Safety System (RWASS) by Sensys Traffic AB, Sweden, (ii) EVT-300 by Eaton-Vorad Technologies, (iii) Nu-Metrics NC-200 by Quixote Technology, and (iv) Trans-Q by Quixote Technology. The SR-12 Caltrans Traffic Station system was used as the experimental control and was the most consistent of all of the devices. In the correct position on the road, NC-200 produced the closest values to the control measurements. The study recommended using devices which use redundant measurements, using tracking radar equipment instead of

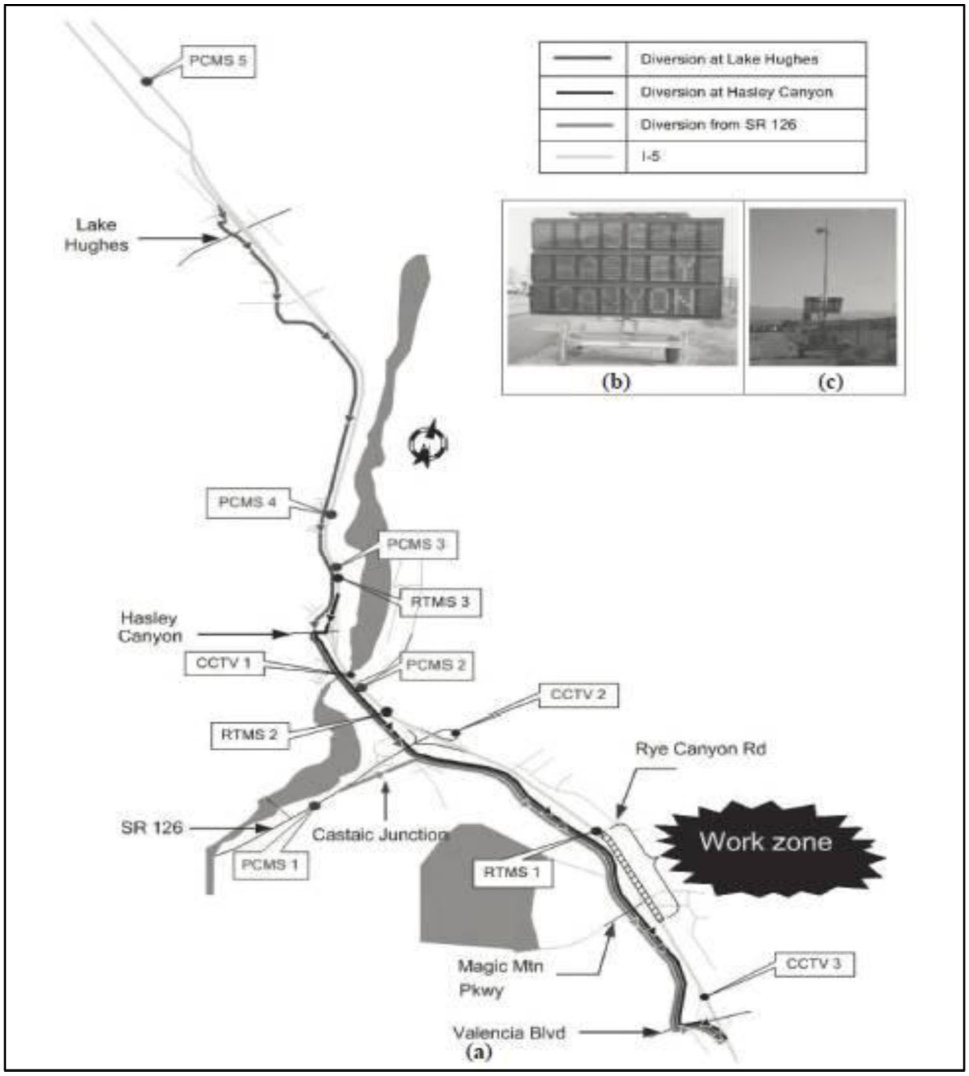



**Figure 3.24** CHIPS setup: (a) work zone site, (b) portable CMS, and (c) remote traffic microwave sensor (Chu et al., 2005).


**Figure 3.25** Devices used in data collection for technical evaluation (Chan, 2009).

conventional radar, and accounting for the natural errors which occur when using radar.

Jackson (2010) explained how to determine work zone scheduling on a highway. The study considered threshold values that were set depending on the construction site and maximum free flow characteristics. The study recommended that lanes should not be closed in case of volumes higher than the site-specific threshold. Advanced warning systems associated with smart work zones can be updated by recording travel times and speed in order to increase driver awareness.

Edara et al. (2011) studied the effects of Dynamic Message Signs (DMS) on rural roadways. According to this study, cameras recorded changed in volumes due to

**Figure 3.26** Sequential warning light (Sun, Edara, Hou, et al., 2011).

a bridge closure, and VISSIM simulation calculated the diversion rates. The resulting benefits for three days of DMS usage ranged from $5,163 to $55,929 with an average of $21,365. The effectiveness of DMS on crashes was not evaluated because of the unavailability of data. Based on a survey, the study found that the public, especially commercial truck drivers, used the DMS, and the messages enhanced diversion and speed reductions.

Fontaine and Edara (2007) studied the benefits of work zones with the help of simulations techniques to determine impacts of Smart Work Zones (SWZ). The study found that the benefit to cost ratio increased with increasing congestion. However, the initial costs were higher than the benefits for scenarios with a short time-frame and a peak volume greater than the capacity of the road. In addition, the study revealed that driver response to ITS information improves with familiarity, specific alternative routes or pairing signage with clearly visible alternative routes increase diversion rates, and reduced speed limit signs are effective at reducing speeds when congestion is present.

Sun, Edara, Hou, et al. (2011) studied and evaluated the use of sequential lights (Figure 3.26) during a night-time work zone. The study found that taper cones have lights, which flash in sequential order to aid in guiding drivers into the open lane. In addition, sequential light deployment resulted in lower speeds. A larger number of merges occurred farther from the work zone taper; however, the area closest to the work zone taper showed an increase of merges as compared to when sequential lights were not used. The study found that the benefit/cost ratio value for sequential lights was between 5 to 1 and 10 to 1.

Brydia et al. (2013) evaluated Bluetooth readers and Portable Changeable Message Signs (PCMS). The study considered the construction of I-35 that was supplemented with ITS for 5 years. A survey was distributed before construction began in order to identify the preferred ITS by the local residents. The survey results revealed that drivers prefer to have images of the freeway or to know the current speeds of the road before they travel. The key to meeting the objectives of minimizing traffic congestion was the end-of-queue monitoring and identifying alternative routes. The Bluetooth stations were distributed along the highway and Bluetooth range was 5 to 8 miles for a rural setting and 2 to 3 miles for an urban setting. The study also found that lane closure information was used by the public and that lane closure messages displayed to the public should be carefully monitored to provide the most accurate information to drivers.

Huang and Bai (2014) studied the effectiveness of portable changeable message signs with graphics on rural, two-lane highways in Kansas. Graphics of flaggers and construction workers were compared to messages with only text and a combination of graphics and text (Figure 3.27 and Figure 3.28). Text-Graphics were then compared to two alternative graphics. The study found that graphics reduced mean speeds between 13% and 17%.


**Figure 3.27** Text PCMS (Huang & Bai, 2014).

**Figure 3.28** Graphic PCMS (Huang & Bai, 2014).

The authors concluded that graphics are quicker to interpret by drivers and result in a greater reduction of mean speeds.

McCanna (2013) presented that the State of Oregon replaced 365 bridges which significantly decreased highway mobility between 2005 and 2011. Oregon followed the example of other State's Department of Transportation (DOT) by applying ITS in work zones starting in 2010. ODOT developed a 'Qualified Products List' allowing them to consistently compare vendor's equipment. The author recommended increasing law enforcement at construction zones in an overtime program and replacing outdated signs.

### *3.7.2 ITS Use to Improve Traffic Safety*

In addition to a number of studies on ITS improving traffic operations, there are also several reports discussing the effectiveness of ITS on traffic safety. Table 3.4 summarizes the ITS components as well as the key findings in these studies.

As far as a work zones are concerned, both safety and operations are important to consider, but safety can be a challenge to measure (Edara et al., 2013). Safety is mainly based on communications. Edara et al. (2013) suggested crash rates and speed as the performance measures concerning safety. Crash rates can be obtained by historical data, lane change distributions, forced merges, and mathematical models whereas speeds can be measured using mean, standard deviation, 85th percentile, mean of highest 15th percentile, 10 mph pace, and speed compliance according to this study. In that study, reduced speeds referred to reduced capacity but increased safety and low volumes refer to greater compliance with speed limits. The following studies are summarized in this regard.

King et al. (2004) evaluated IntelliZone, an ITS technology, for its use in measuring safety. The study used only 2 variable message signs (VMS) to display traffic warning to drivers ahead of the work zone. They included speed averages and variances as the performance measures which were gathered from detectors. They found that 2 of 20 days had congested data and the congestion never reached a point where the VMS messages were displayed without a lane closure. The key finding is that the speeds were effectively reduced by about 7 mph.

TABLE 3.4
**Summary: Work zone ITS deployments for improving traffic safety.**

| Study Name | ITS Name | State of Implementation | ITS Components | Key Findings |
|---|---|---|---|---|
| King et al. (2004) | IntelliZone | MO | 2 variable message signs (VMS), 6 magnetic and video detectors, and a mobile command unit | From survey, 63% slowed down and 3.6% diverted due to VMS; On average, speeds reduced by 7 mph |
| FHWA (2002) | Automated Portable Real-Time Traffic Control System (RTTCS) | IL | 17 DMS, 8 sensors, 4 closed circuit television (CCTV) cameras, Internet website | No significant queues; Communicate well between engineers, construction personnel, and emergency response |
| FHWA (2002) | Temporary Traffic Management System (TTMS) | MI | 17 cameras, 12 DMSs, six queue detectors, and National Sign and Signal's 'ITSworkzone' software, Internet website, Management Staff | Advance information provided to drivers, police, and emergency response; Clearly define capabilities of the vendor in the beginning |
| FHWA (2002) | CCTV, DMS, Arrow Signs, Portable Traffic Management Systems, Highway Advisory Units | NM | 8 fixed CCTV cameras, 8 DMS, 4 arrow dynamic signs, 4 all light (LED) portable DMS trailers, 4 ADDCO, Inc. Smart Zone portable traffic management systems, 4 highway advisory radio (HAR) units, internet website, and management Staff | Incident clearance time reduced from 45 minutes to 25 minutes; Portability and access to ITS equipment is necessary; 60% of survey agreed with the data accuracy |
| FHWA (2002) | Automated Work Zone Information System (AWIS) | AR | 12 queue detectors, 5 remotely controlled DMS, 3 highway advisory radio units, 5 pagers, and an email alert system | Delay decreased; Faster response time to incidents; Needed to allow for an override to the system |
| Bushman and Berthelot (2004) | PCMS , Static Signs and Sensor Trailers | NC | Portable changeable message signs (PCMS), static signs, and 3 sensor trailers | 22 crashes total; Due to short amount of time the work zone did not have ITS, no conclusions can be made about crash reduction |
| McCoy and Pesti (2002) | Automated Data Acquisition and Processing of Traffic Information in Real-time (ADAPTIR) by Scientex Corporation | NE | 3 portable changeable message signs (PCMS), radar sensors, cameras, and arrow board | Slightly reduced speeds during high density; Not as efficient due to low traffic volumes; PCMS signs would be more efficient if separation was less |
| Maze et al. (2004) | Signs and Optical Speed Bars; Drone Radar, Rumble Strips and Speed Monitoring Display | TN | Signs and Optical Speed Bars; Drone Radar, Rumble Strips and Speed Monitoring Display. | A majority of state agencies use regulatory reduced speed limit signs in work zones; however, only 7% of states consider the signs to effectively reduce speeds; No single ITS equipment provides significant speed reductions alone, therefore, a combination of equipment is preferential |
| Lyles et al. (2004) | Variable Speed Limits (VSL) | MI | The VSL included microwave traffic detectors, speed display message boards, pneumatic tube sensors, and 7 communication trailers | Average speeds were slightly higher with VSL present; Travel times were reduced up to 6%; Changes to the 85th percentile speeds and speed variance were inconclusive; percentage of vehicles over 60 or 70 mph decreased to some degree; Speeds were more consistent during off-peak and nighttime use; VSL did not contribute to crash rates |
| Bushman and Berthelot (2004) | PCMS, Traffic Sensors, QuickZone Software and Website | NC | Portable changeable message signs (PCMS), traffic sensors, and website; QuickZone software | ITS reduced maximum queue length by 1.64 miles; User delay reduced by 8.2 minutes; Emissions is calculated to be $0.90 per hour of delay; Crashes were reduced by 2.5% to 10% |

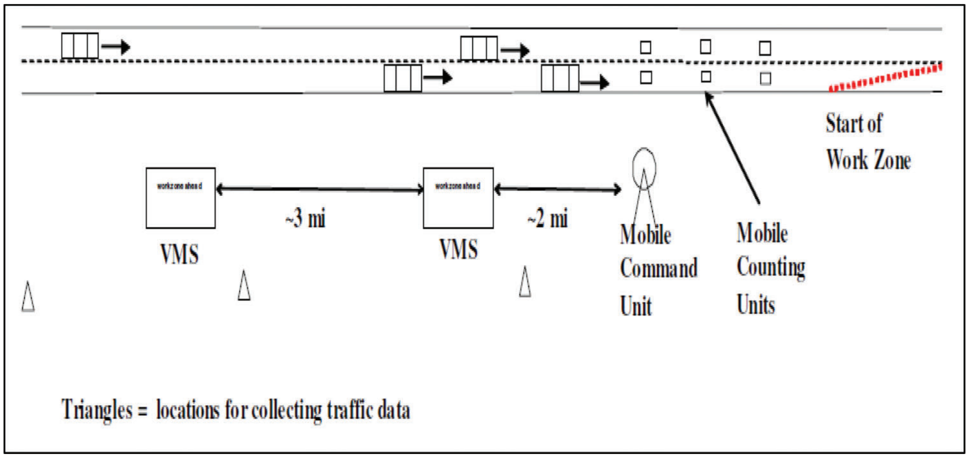
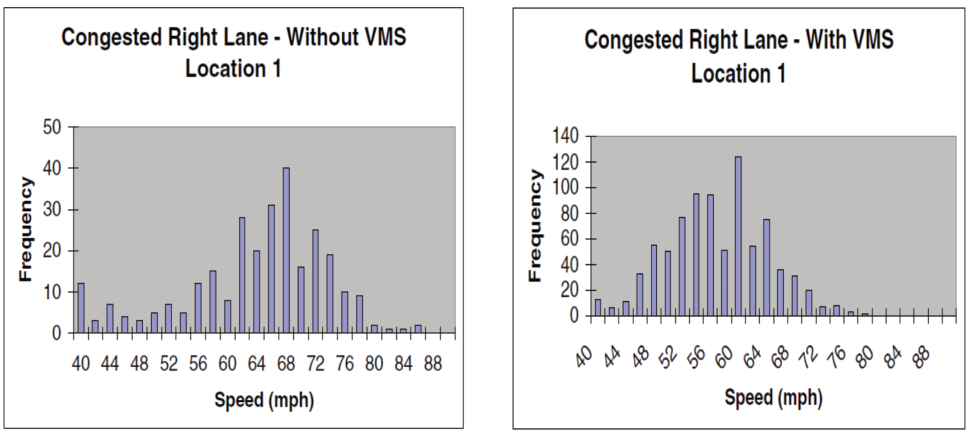



**Figure 3.29** Conceptual diagram of evaluation setup (King et al., 2004).




(a) Before Condition (b) After Condition

**Figure 3.30** Speed distribution at location 1 (King et al., 2004).

They conducted a survey which showed that more drivers understand the meaning of the messages on VMS even if the entire message was not read. The study recommended using more cameras and VMS for similar studies. Figure 3.29 shows the conceptual diagram that they used for their evaluation followed by a before/after assessment of speed distribution at a given location in Figure 3.30.

The Federal Highway Administration (2002) also conducted a study on ITS applications in work zones to depict important considerations for smart work zones in four case studies as well as the lessons learned from those experiences. According to that study, ITS was generally used for managing traffic that includes providing real-time messages to the public, improving crash response time, tracking behavior changes, and even enforcement of traffic law. The main operations of the case studies were to primarily detect the traffic congestion and send messages to the public via dynamic message signs (DMS) along the road, the radio, and/or the internet. From the four case studies, the following lessons learned in terms of testing ITS equipment for reliability. Most of the information on these case studies were obtained from Becker (2004).

**(a) Springfield, IL**. The Illinois DOT (IDOT) used ITS in a 40-mile work zone on I-55. The Real-Time Traffic Control System (RTTCS) included 17 remotely-controlled portable DMSs connected to a base station server via wireless communication, 8 portable traffic sensors connected to the server via wire line, and 4 portable cameras linked to the base station server via wireless communication. IDOT leased the system for the duration of the reconstruction project. The lease included a provision for contractor personnel to monitor the system. The system operated in an automatic mode; however, one person was assigned to check system performance periodically during weekdays. After hours and during weekends, contractor personnel were on-call to handle problems. Specific costs for the RTTCS were not available; however, the cost to lease the system was less than 10% of the total project cost annually for the two-year project.

**(b) Lansing, MI**. The Michigan DOT (MDOT) used a Temporary Traffic Management System (TTMS) during a construction project in downtown Lansing. The system was deployed from March 2001 to October 2001 and removed at the completion of the construction project. The project involved a complete closure of portions of I-496. The $40 million construction project included the rebuilding of 32 bridges, reconstructing one mile and repairing seven miles of freeway, and adding a third lane/merge weave in each direction for a section of the freeway. The TTMS was used throughout the construction project. The system included 17 cameras, 12 DMSs, six queue detectors (microwave sensors), and a commercial off the-shelf (COTS) software package which ran on a server located at the Construction Traffic Management Center (CTMC). Based on data from the detectors, appropriate messages from a bank of predefined messages would be displayed on each DMS and on the Internet. Operators had the option of manually updating the messages. MDOT purchased some of the hardware components of the work zone system (e.g., communications tower, antenna, queue detectors, and cameras) and software license, but most of the system was leased. The cost of the lease was $2.4 million which is about 6% of the total project cost.

**(c) Albuquerque, NM**. The New Mexico State Highway and Transportation Department (NMSHTD) used ITS in a 2-year construction project of "The Big I" interchange where I-40 and I-25 intersect. The primary purpose of employing ITS was to aid in incident management and response. The 2-year project began on June 30, 2000 and involved construction of 111 lane-miles, 45 new bridges, and 10 rehabilitated bridges. The ITS included eight fixed CCTV cameras, eight modular (expandable) DMSs, four arrow dynamic signs, four portable DMSs, four portable traffic management systems (a single integrated platform for camera and DMS), and four highway advisory radio (HAR) units. Components were linked to base station computers via wireline and wireless communications. Camera images were monitored at the traffic management center by NMSHTD staff from 5:00 am to 8:00 pm. Information on traffic conditions were provided via the HAR and DMS, and via other outlets to include website, radio, fax, and email distribution lists. Although pre-defined messages could be activated automatically, the system was set for manual initiation. NMSHTD purchased the ITS with the intent of incorporating much of the system into a freeway management system once construction was completed. Other components would be used in future work zone projects. The ITS work zone system cost $1.5 million.

**(d) West Memphis, AR**. The Arkansas State Highway and Transportation Department (AHTD) employed an ITS for a 3-mile concrete reconstruction project in West Memphis on I-40 near the intersection with I-55. The work zone was near a bridge across the Mississippi River from Memphis, Tennessee and abutted a Tennessee work zone on the bridge. The reconstruction project was expected to last 12 to 18 months and cost $13.8 million. The work zone was expected to be in place for the duration of the construction project. The Automated Work Zone Information System (AWIS) included 12 queue detectors and five remotely controlled DMS which were linked to a central base station server via wireless communications, three HAR units, five pagers, and an email alert system. The traffic detectors were installed one mile on each side of the work zone. The DMSs were deployed over approximately 9 miles on each side of the work zone. The HARs range was approximately 23 miles. The server processed data from the queue detectors and disseminated messages to the DMS and HAR based on predefined messages for specific traffic 11 SD2003-16 Applications of ITS in South Dakota Work Zones conditions. AHTD and Tennessee DOT staff, contractors for both work zones, traffic reporters and other media were informed of traffic conditions via email and pager alert systems. The AWIS was leased for the duration of the work zone project. The lease included personnel to monitor the system. Usually one person was required for periodic system maintenance and to be on-call after hours. The terms of the lease called for a daily fee paid to the contractor and a lump sum for the HARs. The fee was assessed each day the system was operational, thereby the state did not pay for any system down time. The total cost of the AWIS was $495,000, which included the daily fee and purchase of three HARs. The AWIS cost was less than 4% of the total reconstruction cost.

Bushman and Berthelot (2004) studied crash rates in smart work zones. The study recorded speeds and volumes by trailer sensors, which triggered messages on the portable changeable message signs. Crash rates were used as the performance measure. The days when ITS was used was compared to a control, i.e. the days when the system was down and there were less crashes when ITS was not in operation. Because of the short amount of time and low number of crashes when ITS was not in operation, no significant conclusions could be made. The study recommended to have more days to balance amount of crash records with and without ITS deployment.

Next, McCoy and Pesti (2002) studied the effect of portable changeable message signs (PCMS) on reducing speeds. In this study, 3 PCMS were used to display warnings of slowed traffic ahead. The PCMS closest to the work zone taper had the largest effect on reducing speeds. The study also conducted a survey in this regard and found that 79% of the drivers surveyed saw a PCMS. 28% thought that a blank sign meant that the system was not working. Due to low levels of congestion, the speed was only slightly reduced. The survey showed the driver confusion regarding messages displayed. Figure 3.31 presents the study area followed by the traffic control plan in advance of work zone in Figure 3.32. Figure 3.33 shows how the PCMS deployments were made in this study.

Maze et al. (2000) conducted a survey with multiple variables in order to control vehicle speeds in work zones.

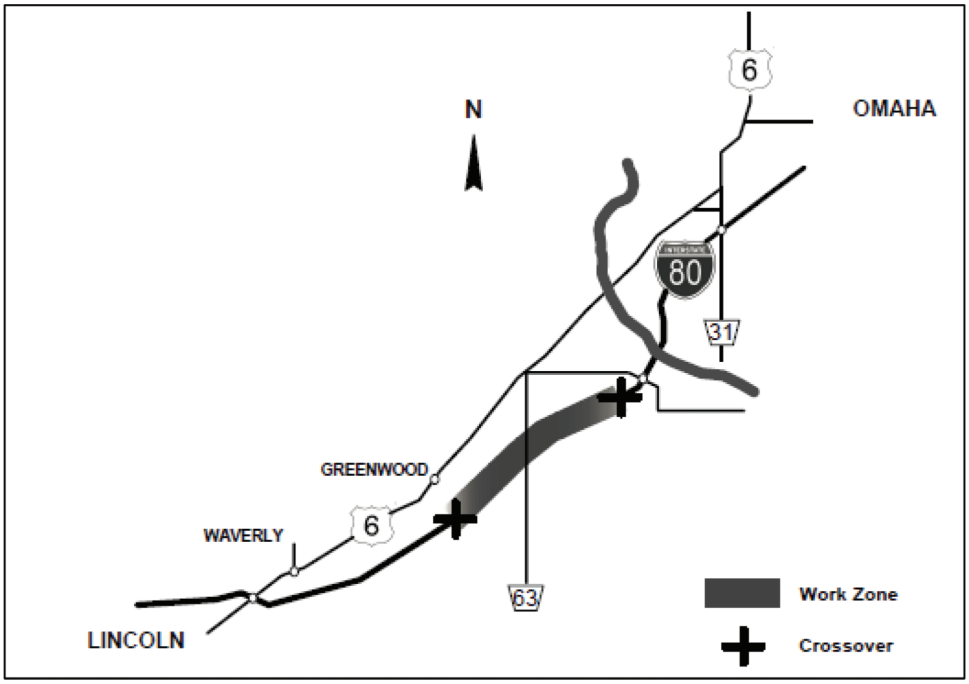



**Figure 3.31** Study area (McCoy & Pesti, 2002).

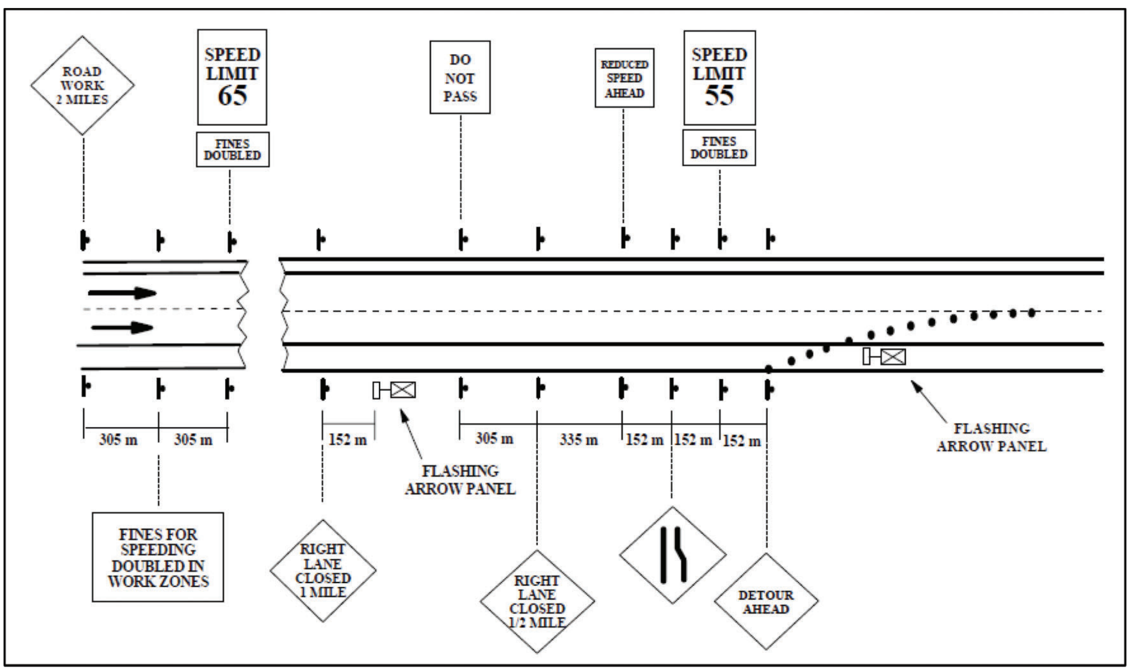



**Figure 3.32** Traffic control plan in advance of work zone (McCoy & Pesti, 2002).

The study listed the preferences concerning strategies to decrease speeds of each U.S. state with a view to providing a good basis for comparison. In Missouri, there was no information provided in the survey for the effectiveness of the 12 strategies. These were Regulatory SL Signs, Advisory SL Signs, Changeable Message Signs, Police Enforcement, Ghost Police Car, Flaggers, Speed Display, Drone Radar, Rumble Strips, Lane Narrowing, Pavement Markings, and Highway Advisory Radio. While the study found that flagging and police enforcement have very positive results overall, these strategies require an unrealistic amount of man-hours. ITS systems can thus be implemented which could save costs on labor. The survey went on to evaluate the speed limit policies for each state. In Missouri, moving work zones on a two-lane road had an existing speed limit of 55 to 65mph with an advanced speed limit of 35 mph. For all other scenarios, including multiple

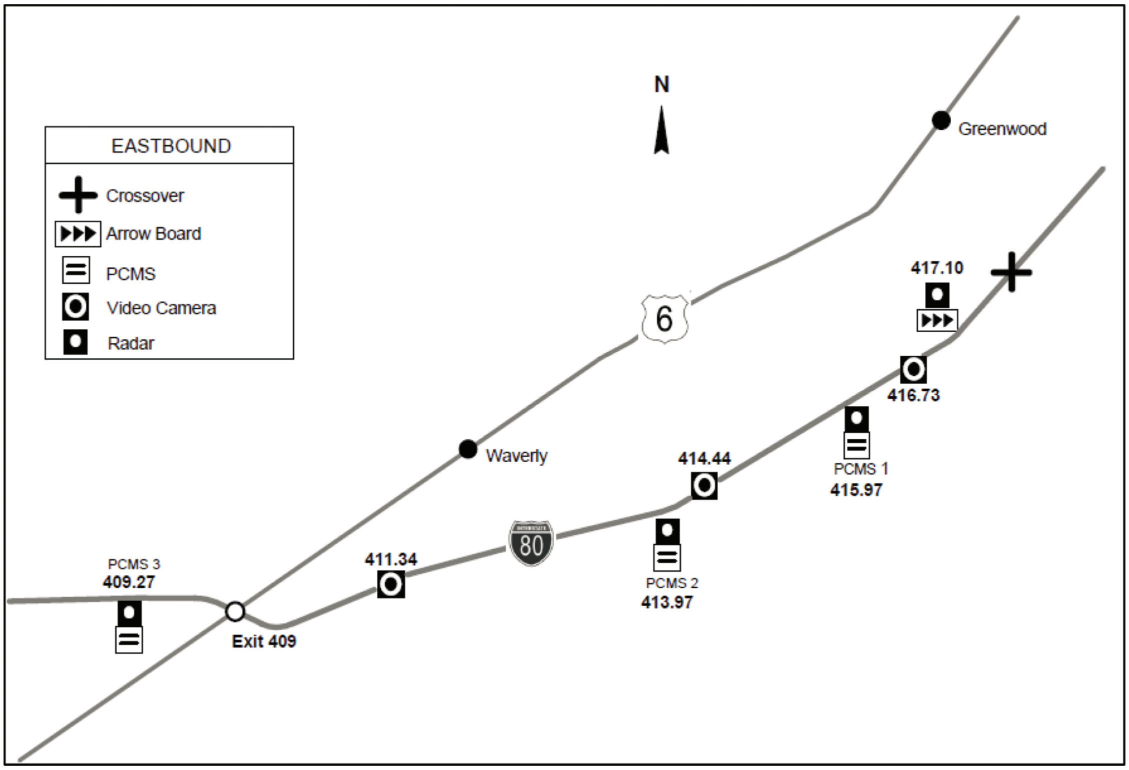



**Figure 3.33** PCMS deployment (McCoy & Pesti, 2002).

lanes with or without concrete barriers, lane shifts, or a median crossover, the existing speed limit was 65 to 70 mph for rural and 60 mph for urban roads with an advanced speed limit reduction of 10 to 20 mph. 10 mph was used in protected areas with concrete barriers or other safety devices while 20mph was used for completely unprotected areas. The lowest reduced speed in Missouri is 35mph.

Lyles et al. (2004) conducted a study in Michigan and evaluated variable speed limits (VSL). The optimum result of VSL is to decrease speed variance by applying a realistic speed limit. According to this study, VSL had the option to adjust traffic speeds between 40 and 70 mph. Within the work zone, speed limits were 50 mph when workers were present and 60 mph when no workers were present. After exiting the work zone, the speeds gradually increased yet, at off ramps, speeds decreased to below the posted VSL. The study found that speeds were slightly better managed and that crashes were not directly caused by VSL. The study recommended to reevaluate VSL so that no freeway ramp speeds could affect VSL deployment.

The study by Bushman and Berthelot (2004) used QuickZone in order to determine the benefits of ITS deployment in work zones. User delay costs of $8.70 to $12.60 per passenger vehicle and $21.14 to $50.00 per commercial truck were used based on Daniels et al. (1999). Emission costs of $3731/ton CO, $3889/ton NOx, and $1774/ton VOC were used based on the Federal Highway Administration's *ITS Deployment Analysis System User's Manual* (2000). Crash rate costs of $59,719 per injury crash and $3,000,000 per fatal crash were used also based on the same reference and a United States Department of Transportation guideline (2003). The study found that the user delay has the greatest impact on benefit/cost ratio as compared to the other performance measures. The benefit/cost ratio value of deploying ITS in work zones was found to be between 18 and 36. The study recommended to validate QuickZone software under a variety of traffic and weather conditions.

### *3.7.3 Key Findings*

- Public response in supporting ITS deployment is very positive (95%)
- ITS is inefficient in decreasing speeds or increasing diversion in case of low traffic demand.
- The type of ITS settings plays an important role in determining the driver's preferred speed through work zones.
- Driver response to ITS information improves with familiarity.
- Specific alternative routes or pairing signage with clearly visible alternative routes increase diversion rates.
- Signs displaying reduced speed limit are effective at reducing speeds when congestion is present.
- Graphics are quicker to interpret by drivers and result in a greater reduction of mean speeds (13-17%).
- Variable Speed Limits (VSL) adjust speeds between 40 and 70 mph.
- Driver diversion rate varies from 5.3% to 10% (on average) based on ITS implementation.


**Figure 3.34** Example of a TMA in use during a mobile operation (Ullman et al., 2011).

- Crashes could potentially decrease by 2.5% to 10% using ITS.

### *3.7.4 Key Recommendations*

- Multiple detectors should accompany a portable message sign in order to provide improved accuracy.
- Displaying queue lengths is better than displaying delay times.
- By using appropriate messages in congested traffic could increase diversion rates.
- Messages showing 'stopped traffic ahead' are helpful and provide additional safety at work zones.
- Agencies considering ITS need to be aware of the necessity for system maintenance, the increased impact on alternate routes, and deploying ITS only when traffic demand is adequate to justify the investment.
- Using tracking radar equipment instead of conventional radar is better.
- Lanes should not be closed when volumes are higher than the site-specific threshold.
- Increasing law enforcement at construction zones in an overtime program and replacing outdated signs.
- More duration is required to balance the amount of crash records with and without ITS deployment.

## 3.8 Truck Mounted Attenuators (TMA)

For the long-term, short-term and mobile work zones, standard traffic control devices such as Truck Mounted Attenuators (TMA) are used by almost every state and considered to be very effective (Wang et al., 2011). TMAs could significantly reduce the severity and number of crashes in addition to the overall property damage only crashes. TMAs include an attenuator or crash cushion mounted on the rear of a work zone truck in order to dissipate the energy formed by a rear-end collision (Figure 3.34). TMAs usually direct traffic to an open lane in advance of a road work site to provide safe working environment for workers while being able to withstand rear-end collisions with it. Likewise, vehicle mounted or trailer mounted attenuators can also be used on a shadow vehicle on a project-specific basis to protect workers and the shadow vehicle driver. The standards and requirements for TMAs can be found in the FHWA manual and guide (FHWA, 2009, 2010).

Humphreys and Sullivan (1991) in their study on the effectiveness of TMAs found that about $23,000 per crash was saved and reduced damage to the maintenance truck was caused (Wang et al., 2011). The injury rate was higher for maintenance vehicles that were not equipped with TMAs as was revealed in the study. In addition, the study found that the cost of crashes where no TMAs were used was considerably higher than those where a TMA was impacted.

In New Zealand, (Smith et al., 2006) reported that positioning an advance warning system, such as horizontal arrow signs or skewed arrow panel, 400 m (1,312 ft.) upstream from a TMA outperformed any other practice, resulting in 27% fewer drivers changing lanes in the last 300 m (984 ft.). Recognition distances increased at night when the traffic volumes were lower as compared to recognition distances during the day with higher traffic volumes. In addition, flashing strobe lights mounted


**Figure 3.35** Evaluation of fluorescent-yellow-green (FYG) background against orange colored TMA signs (Kamyab & Storm, 2001).

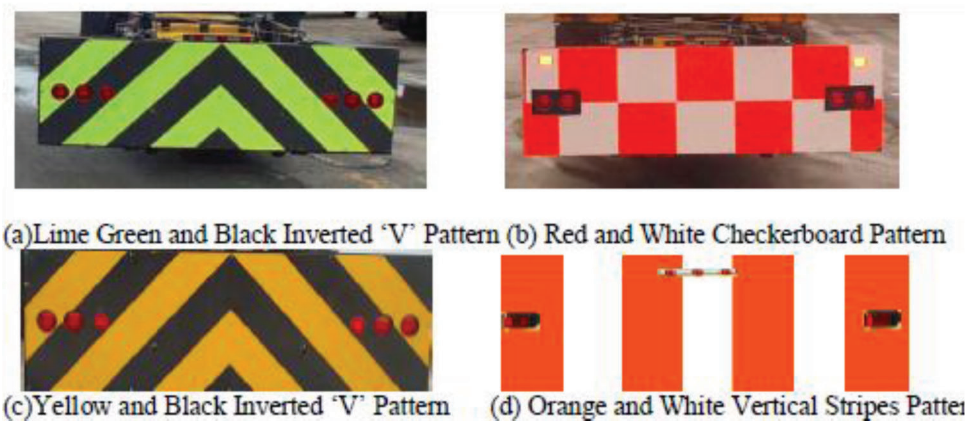



**Figure 3.36** Patterns of truck mounted attenuators.

on different trucks improved drivers' reactions. Wide retro reflective tape around the edges of the arrow board significantly improved drivers' average recognition distance of the TMA by at least 38 meters under daytime or nighttime conditions.

Several studies focused particularly on the popular color variations for TMAs and related signage in use. In Iowa, Kamyab and Storm (2001) evaluated fluorescent-yellow-green (FYG) background colored signs on TMAs against orange colored TMA signs in order to determine if the FYG color would provide additional warning to drivers (Figure 3.35). The study found that the FYG color improved the contrast between the orange color of the sign and the orange color of the Department of Transportation (DOT) truck. The study also conducted a survey of drivers at a rest area on the visibility of TMA signs with and without the FYG background. More than 50% of drivers identified the enhanced orange sign (FYG) as a sign seen on the back of truck before reaching the work zone. The study also collected traffic volumes on the left and right lanes by using a surveillance trailer and found that there was a significant decrease in traffic volumes in the lane where the truck was present after using a TMA with a FYG background compared with a TMA without it.

Hawkins et al. (2000) conducted a similar study in Texas in order to test the visibility of orange, fluorescent orange, yellow, white, and red colored signs on TMAs. Based on the driver recognition distances that were collected and analyzed, the study concluded that fluorescent colors were shown to have higher color perception accuracy and recognition distances during daylight hours but not at night. However, Atchley (2006) found in Kansas that fluorescent traffic signs offer no added advantage as compared to non-fluorescent signs. The study conducted an eye-tracking sensitivity measuring experiment in order to justify this claim.

In Missouri, Bham et al. (2009) explored the effectiveness of striping pattern and color combination used in the TMA in the mobile work zones by using a driving simulator. The study used lane change distance and speed reduction identification distance as the evaluation criteria. Results indicated that a yellow and black inverted 'V' pattern and an orange and white vertical striped pattern were more effective than a fluorescent-yellow-green (FYG) and black inverted 'V' pattern or a red and white checkerboard pattern (Figure 3.36). The study surveyed practices for TMAs in work zones from 30 states and found that 22 (77%) of DOTs use TMAs in work zones because it is a transportation agency policy, and only one agency uses TMA because it is a legislative policy. The yellow and black inverted 'V' pattern is most commonly used by DOTs and most of the agencies use TMA patterns as they use the colors and designs provided by the TMA suppliers. Most of the agencies (12, 40%) use crash data as the measure of effectiveness to evaluate TMAs in work zones.

**Figure 3.37** Balsi Beam mobile barrier system (California Department of Transportation, 2010).

*3.8.1 Key Findings*

- Advance warning system, 400 m (1,312 ft.) upstream from TMAs, outperforms any other practice.
- Recognition distances increases at night with low traffic volumes as compared to daytime.
- Flashing strobe lights mounted on different trucks improves drivers' reactions.
- Wide retro-reflective tape around the edges of the arrow board improves drivers' average recognition distance of the TMA by at least 38 meters under daytime or night-time conditions.
- Fluorescent-Yellow-Green (FYG) color improves the contrast between both the orange color of the sign and the orange color of the Department of Transportation (DOT) truck.
- A yellow and black inverted 'V' pattern is more effective than a FYG and black inverted 'V' pattern.
- An orange and white vertical striped pattern is more effective than a red and white checkerboard pattern.
- The injury rate and cost of crashes are higher for maintenance vehicles that are not equipped with TMAs compared to those that are equipped with TMAs.

## 3.9 Mobile Barriers (MB)

Mobile barriers integrate rigid wall, semi-trailer and standard semi-tractors to provide safe work environments for exposed workers who usually work behind temporary cones and barrels in temporary work zones. It serves as a physical and visual wall between passing traffic and workers. MBs have been tested or used in at least four states (California, Colorado, New Jersey, and Texas) and have been found to be very effective (Wang et al., 2011). The considerable capital investment required procuring a mobile barrier system may restrain its usage in spite of higher efficiency. However, MBs occupy 8 ft. of lane width and do not allow large equipment access into the work zone directly from the rear. An adjacent lane or shoulder is required for vehicles to access the protected work area (Wang et al., 2011).

A mobile barriers system was designed to fit the functional requirement for a highly portable positive protection system established by the Texas Transportation Institute (TTI) for FHWA (Ullman et al. 2007). Two types of mobile barrier systems are available on the market. One of them is the Balsi Beam (Figure 3.37) developed by the California Department of Transportation in 2001. The other mobile barrier system was the Mobile Barrier Trailer (MBT-1), as shown in Figure 3.38 by IWAPI Inc. which was developed in 2007 (Mobile Barriers LLC, 2009).

The Caltrans Division Chief of Maintenance funded a research project to solve the problem of errant vehicles entering work zones due to a crash along the I-280 highway in Santa Clara County, CA. The Caltrans Division of Equipment was assigned with the design and fabrication of a system that would protect workers from lateral impacts, which they named as the Balsi Beam in honor of Mark Balsi (Caltrans DRI, 2007). The Balsi Beam was developed, patented, and internally tested by Caltrans. Balsi Beam includes a tractor-trailer combination, with the trailer converting into a 30-ft. long work space between the rear axles of the tractor and the trailer with a collapsible and reversible steel beam barrier (Figure 3.37). The Balsi Beam was designed for activities that were localized, such as bridge deck repairs, bridge rail repairs, and bridge joint maintenance (Wang et al., 2011). The trailer has two telescoping expandable steel beams along each side of the trailer that rotate to provide a stackable two beam protection barrier on either side of the trailer. The beams can rotate to either side depending on the location of the work that needs to be performed. Approximately 20 to 30 ft. of workspace is available behind the beams.

**Figure 3.38** Mobile barrier trailer-1 (MBT-1) (Mobile Barriers LLC, 2009).

Workers found Balsi Beam to be a valuable safety asset since this beam provided workers with a high level of confidence in protecting them from potential intruding vehicles while working within a few feet of moving traffic. One of the limitations of the Balsi Beam was that any large equipment could not be accessed into the work zone directly from the rear that required an adjacent lane/shoulder to access the protected work area. However, this problem arises only on two-lane conventional highways or freeways with very narrow shoulders (Caltrans DRI, 2007; Wang et al., 2011). Caldwell (2011) evaluated the effectiveness of the Balsi Beam based on vehicle mass, nominal speed and nominal impact angle. The study found that Balsi Beam could successfully contain and redirect an 820-kg small car impacting at 20° and 70 km/h. In addition, it can also successfully contain and redirect a 2000-kg pickup truck impacting at 25° and 70 km/h. Any damage to the system for a given crash (similar to the tests conducted in that study) would result in small to moderate amounts of scraping and gouging of the barrier's box beams. Different amounts of vehicle sheet metal would accumulate at the overlapping joint of the box beams and would have to be removed before the barrier can be redeployed (Caldwell, 2011).

On the other hand, the MBT-1 system could provide 42 to over 100 ft. of protected space in mobile work zones (Wang et al., 2011). Gambatese and Tymvios (2014) evaluated the MBT-1 in a variety of work zone environments in order to determine the benefits and limitations to guide Oregon Department of Transportation (ODOT) in future work zone safety strategies/investments. In nearly all the case studies, workers expressed that they felt safer behind the MBT-1. The MBT-1 offers different options that help to increase worker efficiency while performing their tasks. Drivers were also positively affected by the MBT-1. Speed of vehicles passing the work zone were found to be faster with the MBT-1 present than without the MBT-1. In case study #1 (Fremont Bridge), the mean vehicle speed adjacent to the work zone with the MBT-1 present was 49.21 mph, while without the MBT-1 the mean speed was 45.24 mph. This difference is much more evident in case study #6 (I-205) where the mean speed adjacent the work zone during the night when the MBT-1 was used was 45.79 mph. The mean speed when traditional safety measures were used was 39.63 mph (Gambatese & Tymvios, 2014). When passing by the work area, the height of the MBT-1 blocks the driver's view into the work zone for most passenger cars and pick-ups resulting in less distraction.

In Colorado, Hallowell et al. (2009) studied the potential effectiveness of the application of the MBT-1 in work zones. The study focused mainly on the benefits and limitations of lighting schemes associated with the MBT-1. The study found that there were some significant advantages to the MBT-1's lighting schemes, programmable message board, crash-tested barrier, and mobility. Because the signage and lighting are integrated onto the MBT-1, they are in optimal location relative to the work activity. The study recommended using always the 12-ft. poles instead of the 9-ft. poles in order to achieve the greatest shadow reduction and least possible glare. The authors also suggested using the maximum number of light poles available for the specific MBT-1 setup. Kamga and Washington (2009), during a field test in New Jersey, concluded that the MBT-1's functional requirements followed state-of-the-art guidelines for positive protection against lateral intrusions into a work zone. According to that study, the system far exceeded the expectations to protect workers from bodily injuries caused by errant vehicles and also protected drivers from possible injuries with its ability to absorb crash energy by crushing upon impact and its integrated TMAs. When considering the implementation of this equipment on a given road construction project, truck's mobility, both to the site and on the site, is another attractive feature since it takes shorter setup time compared to more traditional traffic control devices (Kamga & Washington, 2009). However, MBT-1 requires pre-planning as it has to be manually converted between left and right side work zone operations.

Finally, the study noted that the best application of the device was on straight roadway sections without ramps in the work zone.

### *3.9.1 Key Findings*

**Balsi Beam**

- Balsi Beam provides 20 to 30 ft. of protected workspace.
- Balsi Beam can successfully contain and redirect an 820-kg small car impacting at 20° and 70 km/h.
- Balsi Beam can successfully contain and redirect a 2000-kg pickup truck impacting at 25° and 70 km/h.
- Balsi Beam should be outfitted with a Truck-Mounted Attenuator (TMA) and followed with a shadow vehicle that also has a TMA.
- Any large equipment cannot be accessed into the work zone directly from the rear for which an adjacent lane/shoulder is required.

**Mobile Barrier Trailer-1 (MBT-1)**

- MBT-1 provides 42 to over 100 ft. of protected space.
- Workers feel safer behind the MBT-1 in all cases.
- MBT-1 increase worker efficiency.
- Drives are also positively affected by the MBT-1.
- Mean vehicle speeds (~49.21 mph) passed the work zone are faster during daytime with the MBT-1 present than without the MBT-1 (~45.24 mph).
- This difference is more prominent during night. Mean vehicle speeds are 45.79 mph and 39.63 mph respectively with and without MBT-1.
- The height of the MBT-1 blocks the driver's view towards the work area.
- 12-ft. poles instead of 9-ft. poles for better lighting are recommended.
- Maximum number of poles should be used.

## 4. SEARCHABLE DATABASE

The searchable database was developed using Netbeans IDE under JAVA environment. The input of the database is the synthesized information as summarized in the previous section, which is stored in Microsoft Access. As discussed before, the database file contains the reference part, the implementation part and technology summary part. The main frame of the database is presented in Figure 4.1.

The database is constructed to fulfill the following functions: inserting and updating the current information in the database, searching and browsing the studies reviewed, and searching and browsing the technology implementations. All functions have been developed and improved based on feedback from the SAC. Further improvements will also be made based on future input.

### 4.1 Insert and Update

Figure 4.2 shows the screenshot of the database for inserting new entries and updating existing entries. The frame provides the necessary information to be filled before insertion to ensure consistency among records. Also, users can select one of the studies in the database and edit accordingly as shown in the figure.

### 4.2 Browse Literature

Figure 4.3 shows the screenshot to browse available literature. The interface consists of a table which shows the title and date of the report, an input box where users can type in the keywords they are interested in to search through the titles, and summary statistics which provide the information of the total number of works as well as the time of the study with respect to day/night given the keyword. It has the flexibility to extend the

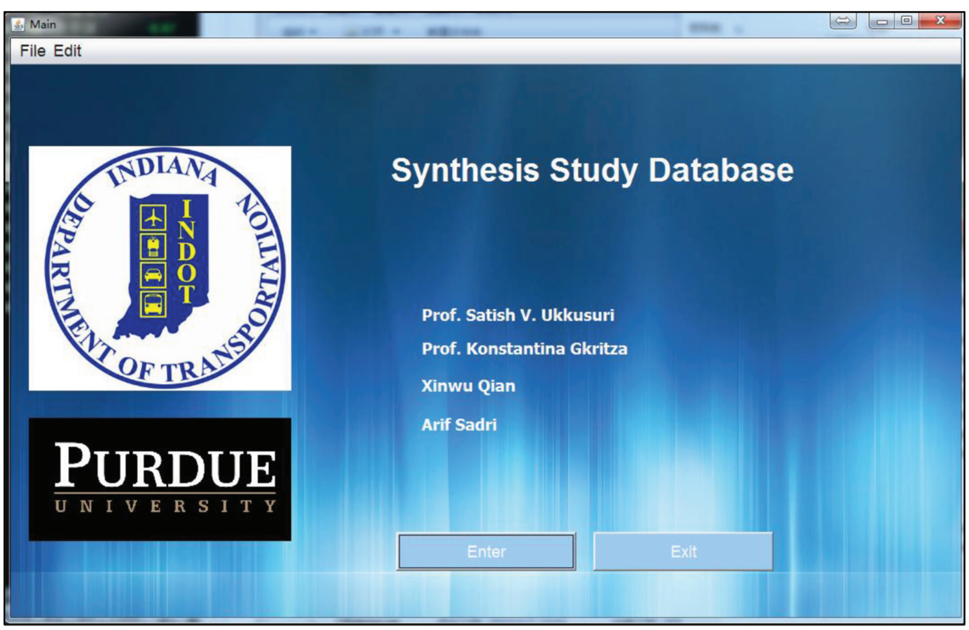



**Figure 4.1** Database main frame.

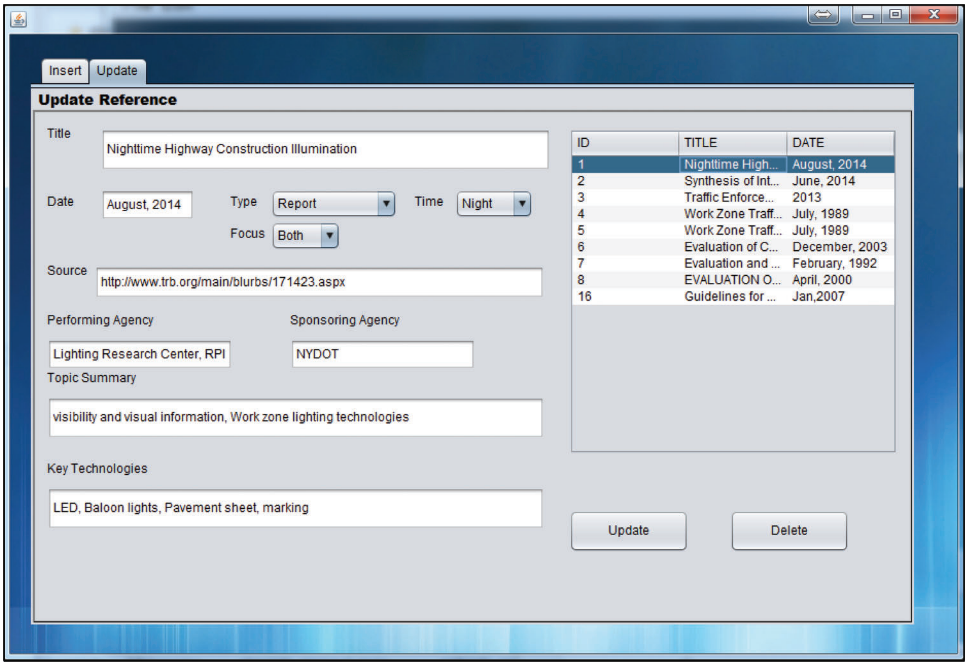



**Figure 4.2** Inserting and updating entries in the database.

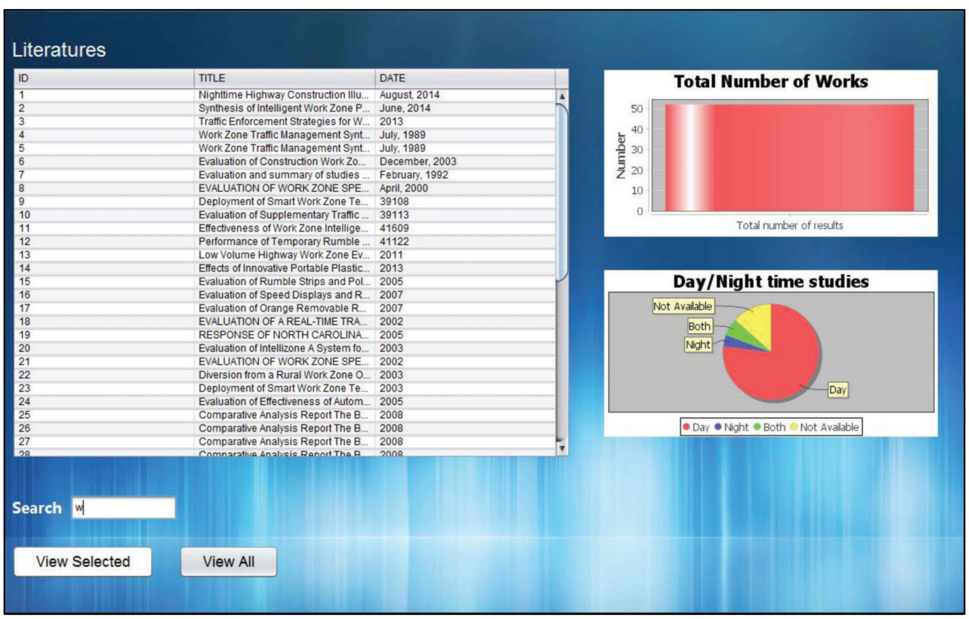



**Figure 4.3** The interface for browsing the summary list of existing studies.

content of the table as well as the display information for the summary statistics. Users can browse the summary report for the study by selecting one of the entries in the table and clicking the button '*view selected*.'

## 4.3 Browse Implementations

One important function of the database involves examining the implementation of the relevant technologies nationwide. The distribution of the technologies across states is shown in an interactive map (Figure 4.4). The map is a SVG file and the color indicates the intensity of implementations by state. The filter section is designed to help users to quickly locate the expected implementations by entering either keywords or designating corresponding master categories. It currently offers to filter by the set of master categories, the speed limit and the road attributes. By clicking the entry of a particular implementation, a new window will pop out which displays detailed information, figures and even videos associated with the implementation (see Figure 4.5). The use of figures will help users to understand the basic setting and configurations of the technology. We also provide a zoom in button next to the picture so that users can specify more details.

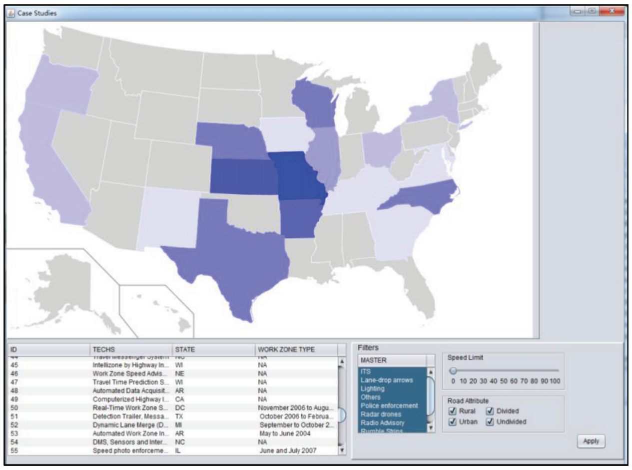


**Figure 4.4** Interactive map for technology implementations.

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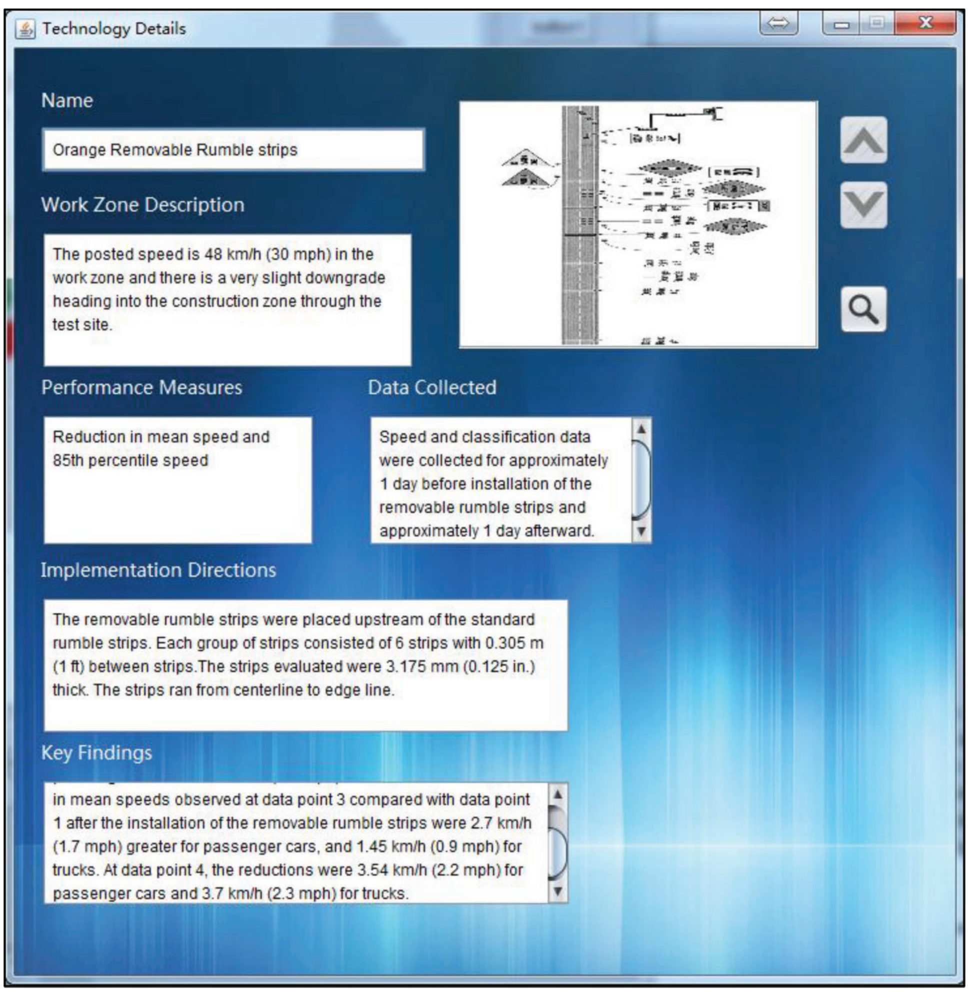


**Figure 4.5** Detailed information for technology implementations.

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## APPENDIX: SUMMARY OF TECHNOLOGIES REVIEWED

| ID | Technology | Master Category | State |
|---|---|---|---|
| 1 | Long-distance auditory warning system | Auditory technologies | – |
| 2 | SonoBlaster! Work Zone Intrusion Alarm | Auditory technologies | NJ |
| 3 | Directional auditory System | Auditory technologies | KS |
| 4 | Portable graphic-aided changeable message signs | Changeable message signs | KS |
| 5 | Changeable message signs and speed display systems | Changeable message signs | TX |
| 6 | Portable changeable message signs (PCMS) with speed display | Changeable message signs | MD |
| 7 | Changeable message signs | Changeable message signs | VA |
| 8 | Changeable message signs | Changeable message signs | IL |
| 9 | Changeable message signs | Changeable message signs | NA |
| 10 | Innovative message signs | Changeable message signs | NA |
| 11 | Changeable message signs | Changeable message signs | NY |
| 12 | Portable changeable message signs | Changeable message signs | KS |
| 13 | Radar equipped portable changeable message signs | Changeable message signs | NC |
| 14 | Permanent ITS equipment | ITS | MO |
| 15 | DMS signs, queue detection trailers, Bluetooth travel time sensors | ITS | MO |
| 16 | Travel time prediction system (TIPS) | ITS | OH |
| 17 | Travel messenger system | ITS | NC |
| 18 | Intellizone by highway Information Systems | ITS | WI |
| 19 | Work zone speed advisory system (WZSAS) | ITS | NE |
| 20 | Travel time prediction system (TIPS) | ITS | WI |
| 21 | Automated data acquisition and processing of traffic information in real-time (ADAPTIR) and computerized highway information processing system (CHIPS) | ITS | AR |
| 22 | Computerized highway information processing system (CHIPS) | ITS | CA |
| 23 | Real-time work zone system (RTWS) | ITS | DC |
| 24 | Detection trailer, message sign, camera, internet, system software | ITS | TX |
| 25 | Dynamic lane merge (DLM) system | ITS | MI |
| 26 | Automated work zone information system (AWIS) | ITS | AR |
| 27 | DMS, sensors and internet | ITS | NC |
| 28 | Speed photo enforcement (SPE) van and detectors | ITS | IL |
| 29 | ASE equipment: road working area safety system (RWASS), EVT-300, Nu-Metrics and Trans-Q | ITS | CA |
| 30 | Side-fire radar | ITS | OR |
| 31 | DMS and PCMS | ITS | MO |
| 32 | VISSIM simulation | ITS | NA |
| 33 | Statistical model | ITS | VA |
| 34 | Sequential lights, cameras, and a radar gun | ITS | MO |
| 35 | PCMS, Bluetooth readers, traffic counter, CCTV | ITS | TX |

*(Continued)*

*(Continued)*

| ID | Technology | Master Category | State |
|---|---|---|---|
| 36 | Speed sensors and PCMS | ITS | KS |
| 37 | PCMS, sensors, sign and markings, computer program | ITS | OR |
| 38 | IntelliZone | ITS | MO |
| 39 | Automated portable real-time traffic control system (RTTCS) | ITS | IL |
| 40 | Temporary traffic management system (TTMS) | ITS | MI |
| 41 | CCTV, DMS, arrow signs, portable traffic management systems, highway advisory units | ITS | NM |
| 42 | Automated work zone information system (AWIS) | ITS | AR |
| 43 | PCMS, static signs and sensor trailers | ITS | NC |
| 44 | Automated data acquisition and processing of traffic information in real-time (ADAPTIR) by Scientex Corporation | ITS | NE |
| 45 | Signs and optical speed bars; drone radar, rumble strips and speed monitoring display | ITS | TN |
| 46 | Variable speed limits (VSL) | ITS | MI |
| 47 | PCMS, traffic sensors, QuickZone software and website | ITS | NC |
| 48 | Lane-drop arrows | Lane-drop arrows | MO |
| 49 | Mobile barriers | Mobile barriers | OR |
| 50 | Mobile barriers | Mobile barriers | CO |
| 51 | Mobile barriers | Mobile barriers | NJ |
| 52 | Mobile barriers | Mobile barriers | CA |
| 53 | Flaggers/spotters and more | Others | – |
| 54 | Temporary pavement marking | Others | – |
| 55 | Reflective temporary pavement tape | Others | – |
| 56 | Moveable delineators and channelizing devices | Others | – |
| 57 | Prismatic/full-cube sheeting for signs and delineators | Others | – |
| 58 | Engineering grade or high intensity sheeting | Others | – |
| 59 | automated data acquisition and processing of traffic information | Others | AR |
| 60 | computerized highway information processing system | Others | AR |
| 61 | Photo radar enforcement | Others | OR |
| 62 | Lane merge system | Others | IN |
| 63 | Speed photo enforcement | Others | IL |
| 64 | Speed photo enforcement | Others | IL |
| 65 | Police enforcement | Police enforcement | WI |
| 66 | Police enforcement | Police enforcement | IL |
| 67 | Police enforcement | Police enforcement | IN |
| 68 | Radar drones | Radar drones | SC |
| 69 | Radar drones | Radar drones | KS |
| 70 | Safety warning system | Radar drones | GA |
| 71 | Citizen band wizard alert system | Radio advisory | MO |

*(Continued)*

*(Continued)*

| ID | Technology | Master Category | State |
|---|---|---|---|
| 72 | Orange removable rumble strips | Rumble strips | KS |
| 73 | Portable rumple strips | Rumble strips | TX |
| 74 | Orange rumble Strips | Rumble strips | MO |
| 75 | Temporary rumble strips | Rumble strips | Na |
| 76 | Temporary rumble strips | Rumble strips | MO |
| 77 | Portable plastic rumble strips | Rumble strips | KS |
| 78 | Portable plastic rumble strips | Rumble strips | KS |
| 79 | Portable plastic rumble strips | Rumble strips | KS |
| 80 | 3M Rumble Strips | Rumble strips | NY |
| 81 | Swarco Rumble Strips | Rumble strips | NY |
| 82 | Speed display | Speed display | TX |
| 83 | Speed monitoring displays (SMDs) | Speed display | NE |
| 84 | Dynamic speed display | Speed display | WI |
| 85 | Speed monitoring displays (SMDs) | Speed display | NE |
| 86 | Truck mounted attenuators | TMA | New Zealand |
| 87 | Truck mounted attenuators | TMA | New Zealand |
| 88 | Truck mounted attenuators | TMA | IA |
| 89 | Truck mounted attenuators | TMA | TX |
| 90 | Truck mounted attenuators | TMA | KS |
| 91 | Truck mounted attenuators | TMA | MO |
| 92 | Variable speed limits (VSL) | Variable speed limit | IN |
| 93 | Variable speed limits (VSL) | Variable speed limit | MN |
| 94 | Variable speed limits (VSL) | Variable speed limit | UT |
| 95 | Variable speed limits (VSL) | Variable speed limit | DC |
| 96 | Vehicle activated signs | Vehicle activated signs | SC |
| 97 | Vehicle activated signs | Vehicle activated signs | SC |

## About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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