SAFETY EFFECTS OF PORTABLE END-OF-QUEUE WARNING SYSTEM DEPLOYMENTS AT TEXAS WORK ZONES

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ABSTRACT

Reducing upstream end-of-queue crashes at work zone lane closures has been a focus of the Texas Department of Transportation (TxDOT) for several years. An ongoing widening effort on Interstate 35 (I-35) through central Texas prompted officials to examine and implement technologies to help mitigate the impacts of end-of-queue warning crashes. An end-of-queue (EOQ) warning system was established, consisting of a highly-portable work zone ITS of easily-deployable radar speed sensors linked to one or more portable changeable message signs (PCMS), and highly-portable transverse rumble strips. The EOQ system is deployed upstream of nighttime lane closures where queues are expected to develop.

Although the sample sizes are relatively small, the trends do suggest that the systems are having a positive effect in reducing crashes. Overall, the EOQ warning system was estimated to have reduced crashes 44 percent from what they would have otherwise been if the system had not been used. The crashes that did occur were less severe, most likely because fewer of them were of the high-speed rear-end collision variety. Using traditional societal crash cost values updated to 2014 dollars, the use of the EOQ warning system at nighttime lane closures reduced crash costs by $1.36 million over the analysis period. This equates to $6,313 in crash cost savings per night of deployment. Compared to the approximate costs of procurement and deployment of these systems, a break-even point is achieved after 95 to 190 nights of use.

keywords: *work zone safety, smarter work zones, work zone ITS, rear-end collisions*

INTRODUCTION

Statement of the Problem

Work zone safety has been an area of concern to highway agencies, the construction industry, and the traveling public for many years. A number of studies have been performed during that time to try to understand how work zones and their design and operation affect crash frequency and severity, manner of collisions, and other crash characteristics. Most studies conclude that rear-end collisions experience the greatest frequency increase in work zones, and are usually the predominant type of collision that occurs *(1, 2, 3,4, 5, 6*). On freeway facilities, one study has shown that rear-end collisions is dependent upon traffic demands, work activity, time-of-day, and whether or not a temporary lane closure is in place reducing capacity (*7*). As might be expected, temporary lane closures (those in place only for a single work shift) were the most hazardous, increasing overall crash risks at a location by 61 to 66 percent during daytime or nighttime periods, respectively (*7*). Many have hypothesized that it is the speed differential between high-speed traffic approaching the back of a traffic queue that has formed at a temporary lane closure and the much slower traffic moving within the queue that is a significant contributor to the higher crash risks experienced at these types of work zones. In addition, when such crashes occur, they tend to be quite severe. Countermeasures that can reduce this rear-end collision potential at work zones where queues develop is of high interest to most agencies and contractors nationally.

Literature Review

Practitioners and researchers alike have searched for effective countermeasures to reduce or minimize work zone crashes. Many have focused on strategies designed to reduce travel speeds approaching and passing through a work zone, hypothesizing that a speed reduction will translate to improved safety. Various speed management strategies have been tested, usually resulting in only incremental effects on speeds (*8*). In addition, the presumed causal relationship between reduced speeds and improved safety in work zones has not been rigorously demonstrated.

Although most technologies deployed to reduce speeds in work zones have limited effect, fortunately the same does not have to be said regarding the deployment of law enforcement in or near a work zone. Several studies have confirmed the effect of enforcement by typically showing a 5 to 10 mph traffic speed reduction when present at a work zone (8, *9*). At least one study has also suggested that enforcement presence does have a crash reduction benefit in work zones as well (*10*). Practices vary in terms of how enforcement is utilized at a work zone. Some agencies encourage active monitoring and citation of traffic law (mostly speed) offenders; other promote the enforcement use in more of a traffic-calming mode, with the enforcement vehicle and officer positioned in a location where they can be seen upstream of a hazardous location (such as a temporary lane closure where workers are on foot without positive protection between them and traffic).

A few agencies also deploy enforcement specifically for end-of-queue protection (*11*). In these applications, the officer places the enforcement vehicle a short distance upstream of the lane closure with its lights flashing, and attempts to keep the vehicle upstream of the end of the traffic queue as it propagates upstream. In this type of application, the primary intent of the enforcement is to reduce driver inattention and distraction, thus raising their immediate situational awareness of the driving task. Some agencies have had good experience with this technique, but others have found it difficult to implement law enforcement in some work zones due to limited shoulder widths, a lack of shoulder continuity across large bridges or shoulder closure locations, etc. In addition, desires for enforcement staffing at work zones often exceeds available resources in the region.

Another countermeasure which has received some attention relative to its potential safety benefits is the provision of work zone intelligent transportation systems (ITS). Once considered an experimental technology, use of ITS in work zones has grown significantly and it is now considered a useful tool in most agency work zone safety and mobility impact mitigation toolboxes (*12*). Systems that 1) automatically detect current traffic conditions such as volumes, speeds, lane occupancy, etc. at periodic points along a facility prior to and within a work zone, and 2) activate real-time messages warning of downstream conditions such as stopped or slow traffic, delays, travel times, etc. are especially seeing increased usage. The intent of these automated real-time messages is to improve driver expectancy, reduce driver distraction, and positively influence driving behavior. Unfortunately, assessments of the effects of these types of systems on safety have been mostly anecdotal, with officials often stating that fewer crashes had occurred than what they had "expected" without specific analyses applied and results documented (*13*). However, one study has indicated that the technology holds promise as a safety countermeasure (*14*). In that analysis, rear-end crashes in the work zone with work zone ITS technology deployed were found to be 14 percent lower than when the technology was not deployed. This occurred despite an increase in traffic and a greater number of temporary lane closures within the project.

Reducing upstream end-of-queue crashes at work zone lane closures has been a focus of the Texas Department of Transportation (TxDOT) for several years. An ongoing widening effort on Interstate 35 (I-35) through central Texas prompted officials to examine and implement technologies to help mitigate the impacts of end-of-queue warning crashes. This paper examines the effectiveness of their efforts to date.

PROJECT DESCRIPTION

TxDOT has been overseeing a $2 billion dollar widening effort of Interstate 35 (I-35) from four to six lanes along 96 miles through central Texas. The widening effort is being accomplished through multiple construction projects and contractors (labeled as "sections" in Figure 1). I-35 in this part of the state is predominantly rural, but does pass through the city of Waco and several smaller cities. Traffic volumes along this section of I-35 are between 55,000 and 110,000 vehicles per day (vpd). The route is heavily utilized by large trucks, accounting for 35 percent of traffic during the day and increasing up to more than 70 percent at night. The majority of the work occurs behind portable concrete barrier in the median and in the separation area between the main lanes and the frontage road. However, some lane closures are required for periodic pavement maintenance, materials deliveries, traffic switches between lanes, cross-street bridge demolitions and beam-setting, etc. All lane closures on the freeway main lanes are restricted to nighttime hours beginning 7 pm or later and removed by 7 am the next morning. Nevertheless, there are certain areas of this corridor where a nighttime lane closure does still create traffic queues. Unfortunately, driver expectancy of any traffic queues along this corridor is normally pretty low, especially at night. Thus, the emphasis on finding ways to mitigate the safety impacts of these nighttime lane closures was of great interest to TxDOT.

In 2011, TxDOT began working with researchers at the Texas A&M Transportation Institute (TTI) to examine potential technological options to mitigating end-of-queue crashes during nighttime lane closures. Work zone intelligent transportation systems that automatically detect when queued traffic conditions developed and provide warning messages to drivers approaching a queue were seeing increased use nationally, and so were an interesting possibility. However, the amount of equipment that would be needed to cover the entire corridor at a level of granularity sufficient to quickly detect queues wherever lane closures were deployed was seen as potentially prohibitive. More importantly, much of that equipment would likely need to reside in the areas where contractors were normally working. Given the aggressive schedule that TxDOT placed on getting the contracts completed, the need for contractors to frequently move equipment (or wait for someone to move it for them) was viewed as potential hindrance. Likewise, frequent movement of certain types of devices, if deployed, would require nearly-continuous recalibration efforts to keep the systems operational.

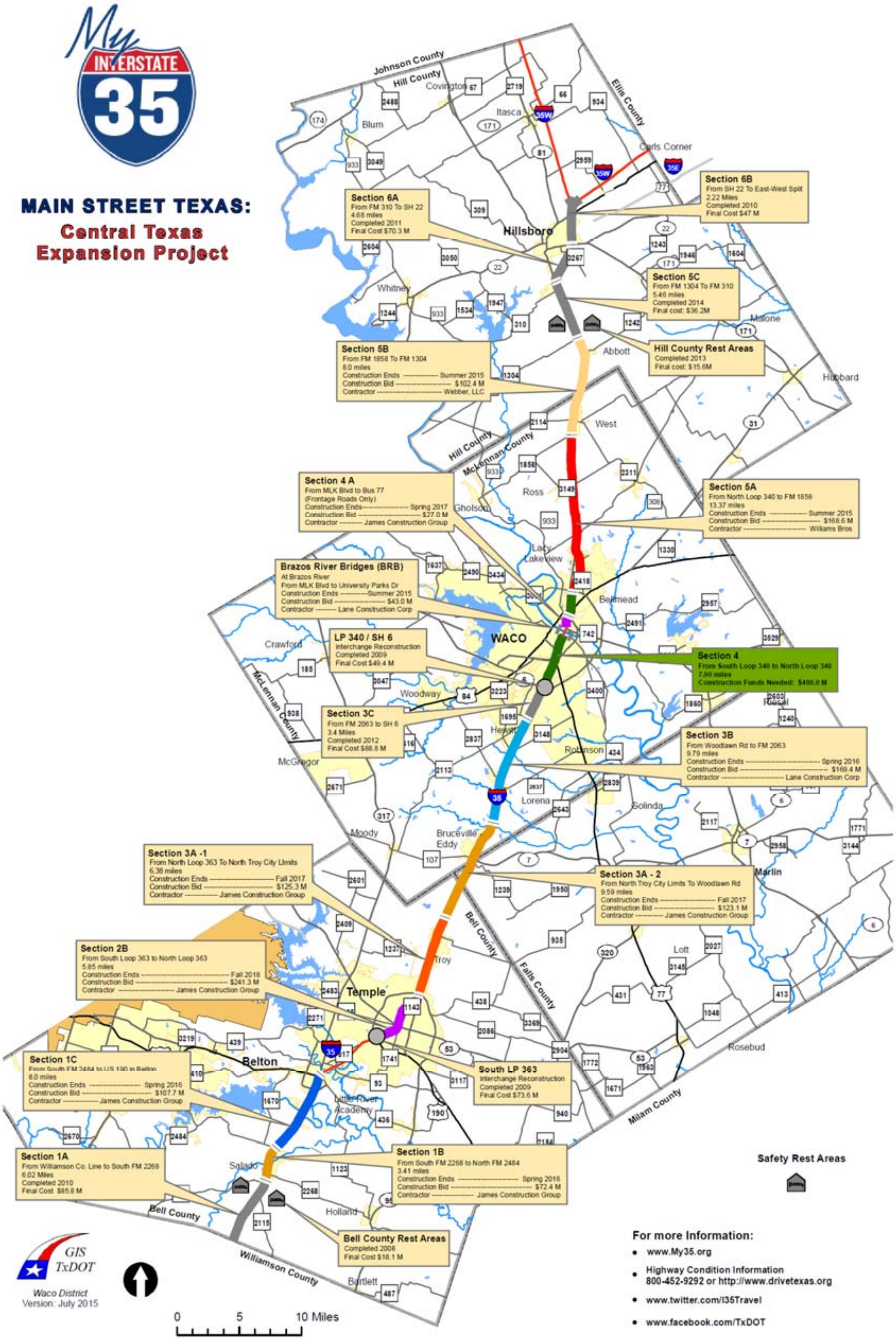


FIGURE 1 TxDOT Interstate 35 widening effort through central Texas.

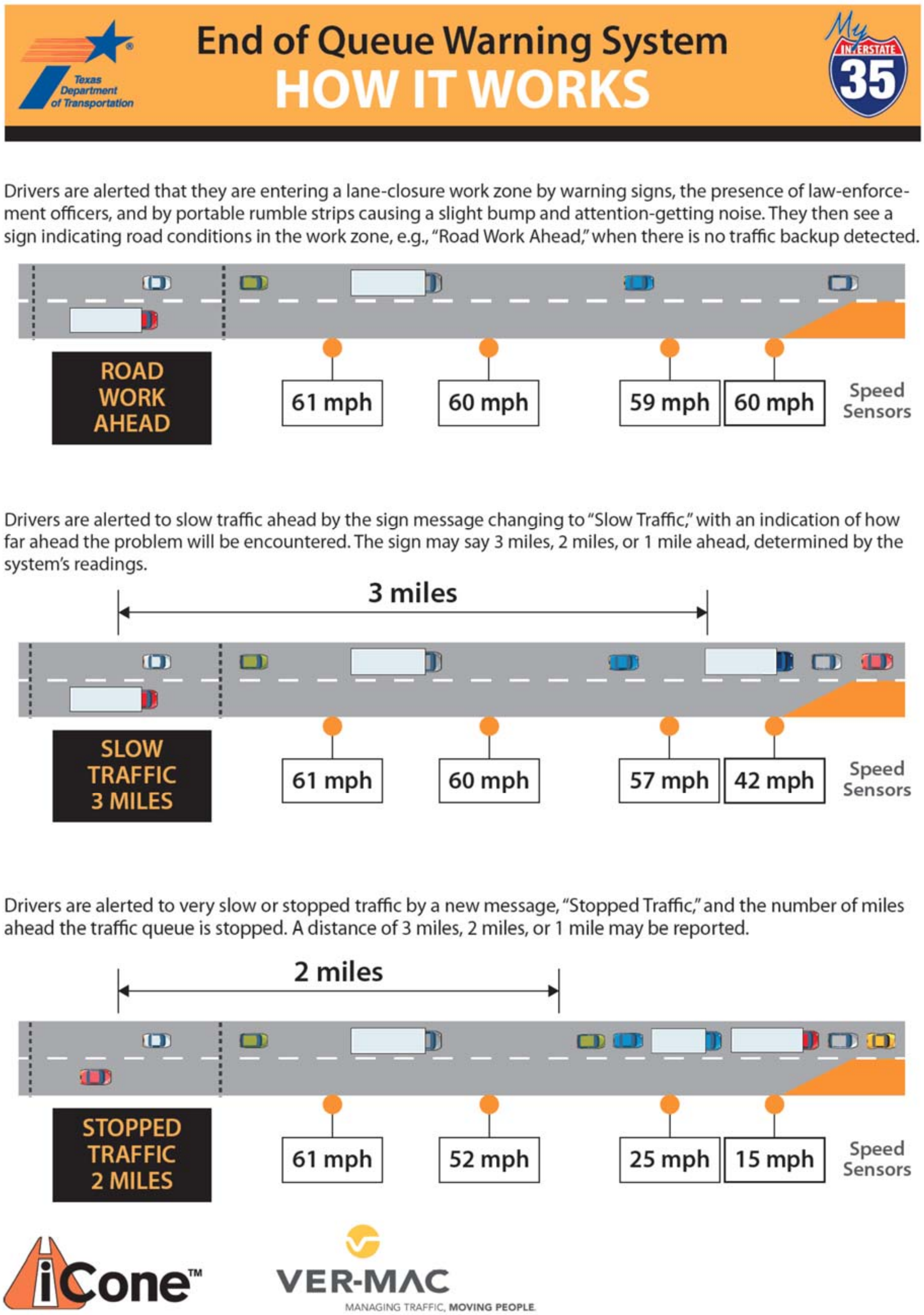
Because of these practical concerns about the use of traditional work zone ITS technologies to mitigate end-of-queue crashes, TTI assisted TxDOT in evaluating alternative technologies. Ultimately, the preferred solution was a highly-portable work zone ITS concept based on easily-deployable radar speed sensors (to minimize calibration requirements) that are linked to one or more portable changeable message signs (PCMS). System logic evaluates the status of the sensors, and automatically displays an appropriate queue warning message based on the distance from the sign to the location of closest sensor detecting slowed or stopped traffic (see Figure 2). In one configuration, sensors are placed at the lane closure merging taper and then at 0.5, 1.5, and 2.5 miles upstream of the taper. A portable changeable message sign (PCMS) is placed 3.5 miles upstream of the taper. For lane closures where longer queues are expected, additional sensors are placed 3.5, 4.5, 5.5, and 6.5 miles upstream of the taper, and a second PCMS is positioned 7.5 miles upstream of the taper. The concept requires minimal calibration (sensors simply need to be aimed towards oncoming traffic properly) and so could be easily incorporated into the setup of the temporary traffic control for the lane closure each night it was needed, and quickly removed the next morning (see Figure 3).

Another technology of interest to TxDOT was the use of portable transverse rumble strips. Although it was acknowledged that rumble strips in general do not typically have a dramatic effect on vehicle speeds in work zones (8), it was hypothesized that the tactile and auditory stimuli they can provide could be beneficial in gaining the attention of distracted drivers approaching a work zone lane closure. Until recently, transverse rumble trip applicability to work zones was limited to long-term deployments, as a durable and portable rumble strip that could be put down without adhesives and then easily picked up and re-used at another location did not exist. However, one vendor introduced a new rumble strip product to TxDOT which could be quickly put down and picked up and which was reported to be able to remain in place relatively well under traffic (*15*). Figure 4 illustrates the selected product deployed approaching a work zone on I-35.

TxDOT ultimately opted to combine the portable work zone ITS concept and the portable rumble strips into an end-of-queue (EOQ) warning system for I-35 when nighttime lane closures were needed that would likely create a traffic queue. Two sets of rumble strips are used, one set of three strips placed 0.25 miles upstream of the PCMS, and a second set placed within 0.5 miles of the maximum expected queue length for that night. Rumble strip warning signs are also placed 700 feet upstream of the first set of rumble strips.

Business processes were established to identify in advance when and where nighttime lane closures were planned in the corridor. Contractors or project engineers submit an electronic notice of each proposed lane closure (time, direction, location). A queue prediction analysis that compares the expected traffic demands on the planned night of the closure to the expected work zone capacity is then automatically performed for each lane closure. If a queue is predicted to occur, the EOQ warning system is to be deployed at that location. Additional details about these business rules can be found elsewhere (*16*).

At the time that this analysis was performed, the EOQ system had been deployed at over 200 nighttime lane closures within the corridor. As discussed in the sections that follow, the evidence so far suggests that the system is being effective in reducing end-of-queue crashes at lane closures in the corridor due to increased awareness of downstream conditions and potential corresponding reductions in inattentive and distracted driving



End of Queue Warning System

HOW IT WORKS

Drivers are alerted that they are entering a lane-closure work zone by warning signs, the presence of law-enforcement officers, and by portable rumble strips causing a slight bump and attention-getting noise. They then see a sign indicating road conditions in the work zone, e.g., "Road Work Ahead," when there is no traffic backup detected.

Drivers are alerted to slow traffic ahead by the sign message changing to "Slow Traffic," with an indication of how far ahead the problem will be encountered. The sign may say 3 miles, 2 miles, or 1 mile ahead, determined by the system's readings.

Drivers are alerted to very slow or stopped traffic by a new message, "Stopped Traffic," and the number of miles ahead the traffic queue is stopped. A distance of 3 miles, 2 miles, or 1 mile may be reported.

FIGURE 2 Conceptual Operation of the Portable End-of-Queue Warning System.

(a) iCone™ speed radar sensors housed in a channelizing drum.

(b) Ver-Mac speed radar sensors attached to a tripod.

FIGURE 3 Portable radar speed sensors used on I-35.

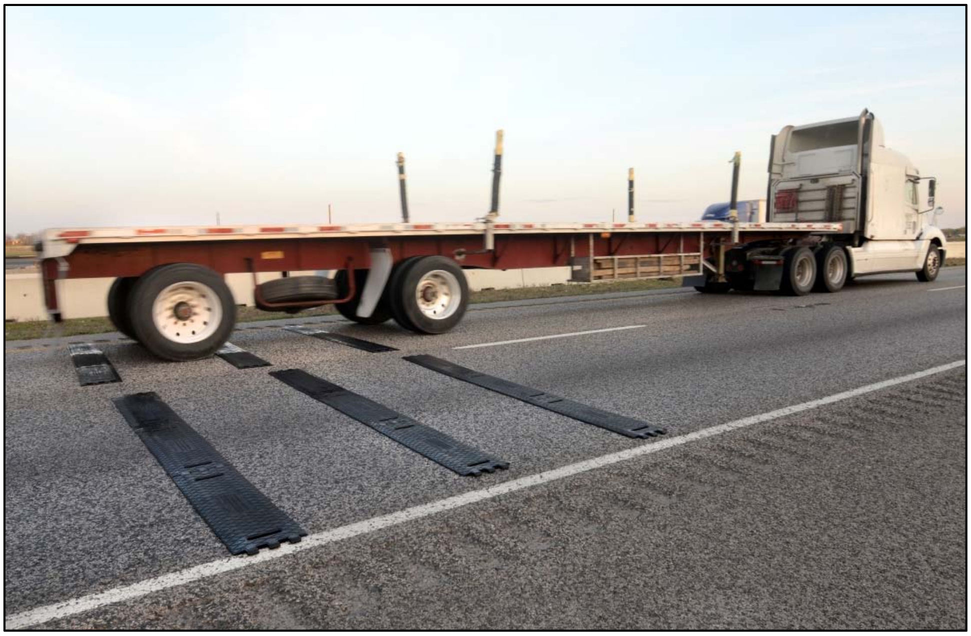


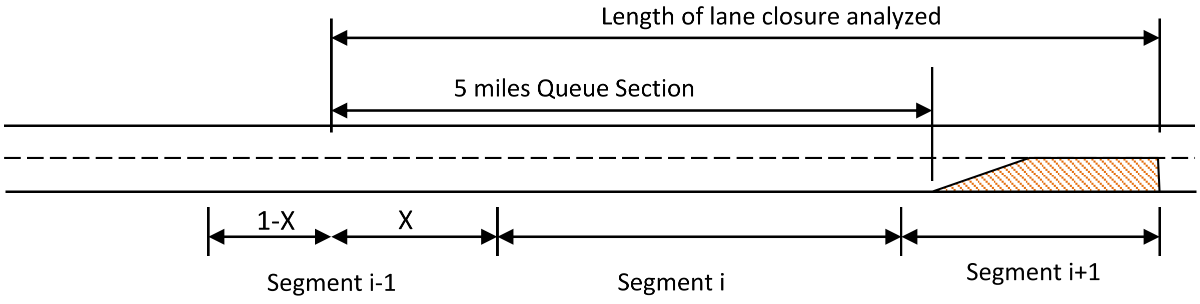
FIGURE 4 Portable rumble strips used on I-35.

. SAFETY ANALYSIS METHODOLOGY

The location of lane closures changed continuously throughout the corridor as contractors worked on and completed various tasks within each project. Also, the frequency of nighttime lane closures varied over time depending on the requirements of the work activities underway within each project. TTI researchers did have information on nights and locations where lane closures had been implemented and queues were expected but an EOQ system was not implemented (i.e., prior to when the EOQ system was procured), as well as on nights when queues were expected and the EOQ system was implemented. However, the fact that the non-EOQ system lane closures and EOQ lane closures were not necessarily at the same locations meant that it was not appropriate to simply compare crashes occurring on EOQ nights to those that occurred on non-EOQ nights. Similarly, simply examining the frequency of crashes occurring on nights when the EOQ was deployed would not provide a way to determine how many crashes would have occurred at those locations on those lane closure nights if the EOQ system had not been deployed.

The analysis approach ultimately adopted was to use the with-EOQ and without-EOQ lane closure nights as "treatment" and "control" group datasets, and compare crashes occurring during both sets of nights to what would have been expected on those nights if the corridor had not been under construction. To accomplish this, the corridor was divided into a set of discrete homogenous segments and Empirical-Bayes analysis methodologies applied for years 2003-2009, using the Enhanced Interchange Safety Analysis Tool (ISATe) (*17*) which is based on models proposed for inclusion in the next iteration of the *Highway Safety Manual*. The result of that analysis was an expected number of crashes/year in each segment. The average proportion of crashes occurring during the same nighttime hours that lane closures were allowed during construction was then calculated from the calibration data, and applied to each of the segments to obtain the expected nighttime crashes/year. Dividing these yearly values by 365 yielded an expected number of crashes/night within each segment.

Next, the expected crashes per night (ECN) for each lane closure where queues were expected to have occurred (with and without EOQ) was determined. The lane closure section analyzed included a queue section that extended from 5 miles upstream of the beginning of the lane closure and the length of the lane closure. The discrete homogenous (ISATe) segments corresponding to that lane closure and queue section was determined, and the expected number of crashes from the ISATe analysis corresponding to that lane closure section determined. In cases where the lane closure section began or ended within one of the discrete homogenous segments, the expected crash/night value was adjusted based on the proportion of the segment overlaid by the lane closure section. Figure 5 illustrates the estimation process.



$$ECN_{\text{lane closure section}} = x{*}ECN_{\text{Segment } i-1} + ECN_{\text{Segment } i} + ECN_{\text{Segment } i+1}$$

where,
ECN = Expected Crashes/Night
Segment i = i^{th} Homogeneous segment in corresponding ISATe model
X = Proportion of ISATe segment within the analysis section

FIGURE 5 Method of estimating expected crashes per night within lane closure analysis section.

RESULTS

Table 1 summarizes the available data used in the analysis. .

TABLE 1 Sample Size Statistics

	No EOQ Deployed	**EOQ Deployed**
Total nights of lane closures (where queues were expected) analyzed	234	216
Total miles of lane closure segments included in analysis	829	1290
Total number of crashes expected if no work zone present	10.4	10.2
Total number of crashes that actually occurred	19	13

One sees that sample sizes are very small in terms of both expected and actual crashes in both the non-EOQ and EOQ lane closure nights. This is because less than one year's worth of nighttime lane closures from each condition was available for analysis. Even so, the results of the analysis do suggest favorable trends with regards to crash mitigation. An odds ratio analysis of the with- and without-EOQ crash datasets, using the expected crash numbers as a control group, was performed (*18*). Computations for estimating of the proportion effect of the EOQ and the standard error of the estimate are shown in equations 1 and 2.

$$CMF_{EOQ} = \frac{\frac{TA_{EOQ}TE_{no\ EOQ}}{TE_{EOQ}TA_{no\ EOQ}}}{\left(1+\frac{1}{TE_{no\ EOQ}}+\frac{1}{TE_{EOQ}}+\frac{1}{TA_{no\ EOQ}}\right)} \qquad (1)$$

$$SE(CMF_{EOQ}) = \sqrt{\frac{{CMF_{EOQ}}^{2}\left(\frac{1}{TA_{EOQ}}+\frac{1}{TE_{no\ EOQ}}+\frac{1}{TE_{EOQ}}+\frac{1}{TA_{no\ EOQ}}\right)}{\left(1+\frac{1}{TE_{no\ EOQ}}+\frac{1}{TE_{EOQ}}+\frac{1}{TA_{no\ EOQ}}\right)^{2}}} \qquad (2)$$

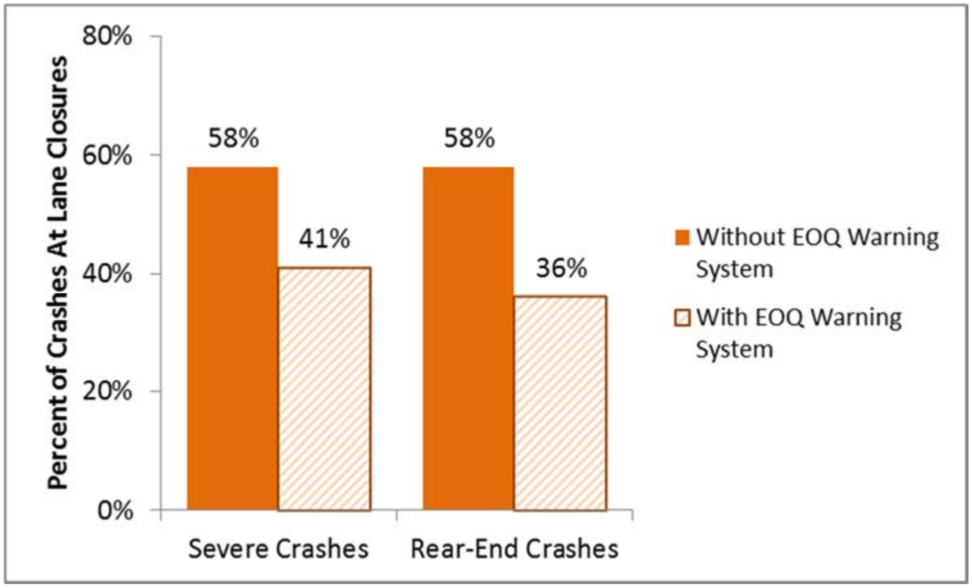
Where,
CMF_{EOQ} = crash modification factor representing the proportional effect of the EOQ deployments on crashes
TA_{EOQ} = total crashes actually occurring during nights when an EOQ was deployed
$TA_{no\ EOQ}$ = total crashes actually occurring during nights when no EOQ was deployed
TE_{EOQ} = total crashes expected during nights when an EOQ was deployed if no work zone had been present
$TE_{no\ EOQ}$ = total crashes expected during nights when an EOQ was not deployed if no work zone had been present

The results of the analysis are presented in Table 2. The computed CMF for the EOQ deployment is 0.559, corresponding to a 44.1 percent reduction in crashes. The level of marginal significance (p-value) is 0.085, providing strong evidence that the system is having a real crash-reducing effect.

TABLE 2 Analysis Results

Metric	**Value**
CMF	0.559
Standard Error (CMF)	0.255
Level of Marginal Significance (p-value)	0.085

In addition to evaluating the effect of the EOQ system deployments upon the frequency of crashes during nighttime lane closures, TTI researchers examined the differences between the severity and types of traffic crashes occurring during those lane closure nights without the EOQ system deployed as well as nights with the system deployed. The results, shown in Figure 4, provide further evidence that the EOQ system is having a positive effect on crashes. Crashes occurring on lane closure nights with the EOQ system deployed were less severe on average than nights without the EOQ system deployed (41 percent versus 58 percent, respectively). This correlates with the similar reduction in the percent of crashes that involved rear-end collisions, going from 58 percent of the crashes on nights without the system deployed to only 36 percent on nights when the system was deployed.



Note: Severe crashes include all crashes other than property-damage-only (PDO) crashes

FIGURE 6 Effect of the EOQ system deployment on crash types.

Finally, the results of the analysis were converted into equivalent crash cost savings at the lane closure nights where the EOQ system was deployed by applying the inverse of the CMFs to the actual crashes to estimate how many crashes would have occurred at those sites if the EOQ had not been deployed there. The results are shown in Table 3. Costs for severe and PDO crashes were extracted from (*19*) and updated to 2014 dollars using the consumer price index. Overall, the calculations suggest that the deployment of the EOQ system over the 216 lane closure nights so far has reduced crash costs by $1.36 million due to fewer, less severe crashes when the system is being deployed. This translates to an approximate average per night crash cost savings of $6,313 in the I-35 corridor. Experiences on the I-35 projects indicate that these types of EOQ systems can be obtained for less than $250,000 each, and cost between $3,700 and $5,000 per night in labor and other expenses to deploy and then pick up. Therefore, the crash cost savings being achieved in the corridor offset the costs of these systems after 95 to 190 nights of use.

TABLE 3 Analysis of Crash Cost Savings from EOQ System Deployments

Metric	Value
# Crashes reduced over 216 nights	5.7
Total savings in crash costs[a]	$1,363,505
Crash cost savings/night	$6,313

[a] This includes both the reduced crash frequency and the reduced severity of crashes which do occur

SUMMARY AND CONCLUSIONS

Although the sample sizes are relatively small, the trends do suggest that the systems are having a positive effect in reducing crashes. Overall, the EOQ warning system was estimated to have reduced crashes 44 percent from what they would have otherwise been if the system had not been used. The crashes that did occur were less severe, most likely because fewer of them were of the high-speed rear-end collision variety. Using traditional societal crash cost values updated to 2014 dollars, the use of the EOQ warning system at nighttime lane closures reduced crash costs by $1.36 million over the analysis period. This equates to $6,313 in crash cost savings per night of deployment. Experiences on the I-35 projects indicate that these crash cost savings offset the costs of the EOQ system after 95 to 190 nights of use.

Continued monitoring of these EOQ warning system deployments is needed increase the statistical strength of these results. In addition, further research should be performed to correlate EOQ warning system effectiveness with the actual traffic conditions occurring at the nighttime lane closures. Although queues were expected at all nights examined in this study, no attempt was made to actually determine whether queues had actually formed on those nights. Incorporating actual traffic condition information into the analysis would further improve the understanding of the benefits of deploying these systems at future work zone lane closures where queues are anticipated.

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