

# Effectiveness of Work Zone Intelligent Transportation Systems

**Final Report**  
**December 2013**

**SWZDI**   
Smart Work Zone Deployment Initiative



**Mizzou**  
University of Missouri - Columbia

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<b>16. Abstract</b> <p>In the last decade, Intelligent Transportation Systems (ITS) have increasingly been deployed in work zones by state departments of transportation. Also known as smart work zone systems they improve traffic operations and safety by providing real-time information to travelers, monitoring traffic conditions, and managing incidents. Although there have been numerous ITS deployments in work zones, a framework for evaluating the effectiveness of these deployments does not exist. To justify the continued development and implementation of smart work zone systems, this study developed a framework to determine ITS effectiveness for specific work zone projects. The framework recommends using one or more of five performance measures: diversion rate, delay time, queue length, crash frequency, and speed. The monetary benefits and costs of ITS deployment in a work zone can then be computed using the performance measure values. Such ITS computations include additional considerations that are typically not present in standard benefit-cost computations. The proposed framework will allow for consistency in performance measures across different ITS studies thus allowing for comparisons across studies or for meta analysis. In addition, guidance on the circumstances under which ITS deployment is recommended for a work zone is provided.</p> <p>The framework was illustrated using two case studies: one urban work zone on I-70 and one rural work zone on I-44, in Missouri. The goals of the two ITS deployments were different – the I-70 ITS deployment was targeted at improving mobility whereas the I-44 deployment was targeted at improving safety. For the I-70 site, only permanent ITS equipment that was already in place was used for the project and no temporary ITS equipment was deployed. The permanent DMS equipment serves multiple purposes, and it is arguable whether that cost should be attributed to the work zone project. The data collection effort for the I-70 site was very significant as portable surveillance captured the actual diversion flows to alternative routes. The benefit-cost ratio for the I-70 site was 2.1 to 1 if adjusted equipment costs were included and 6.9 to 1 without equipment costs. The safety-focused I-44 ITS deployment had an estimated benefit-cost ratio of 3.2 to 1.</p>			
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# EFFECTIVENESS OF WORK ZONE INTELLIGENT TRANSPORTATION SYSTEMS

**Final Report - December 2013**

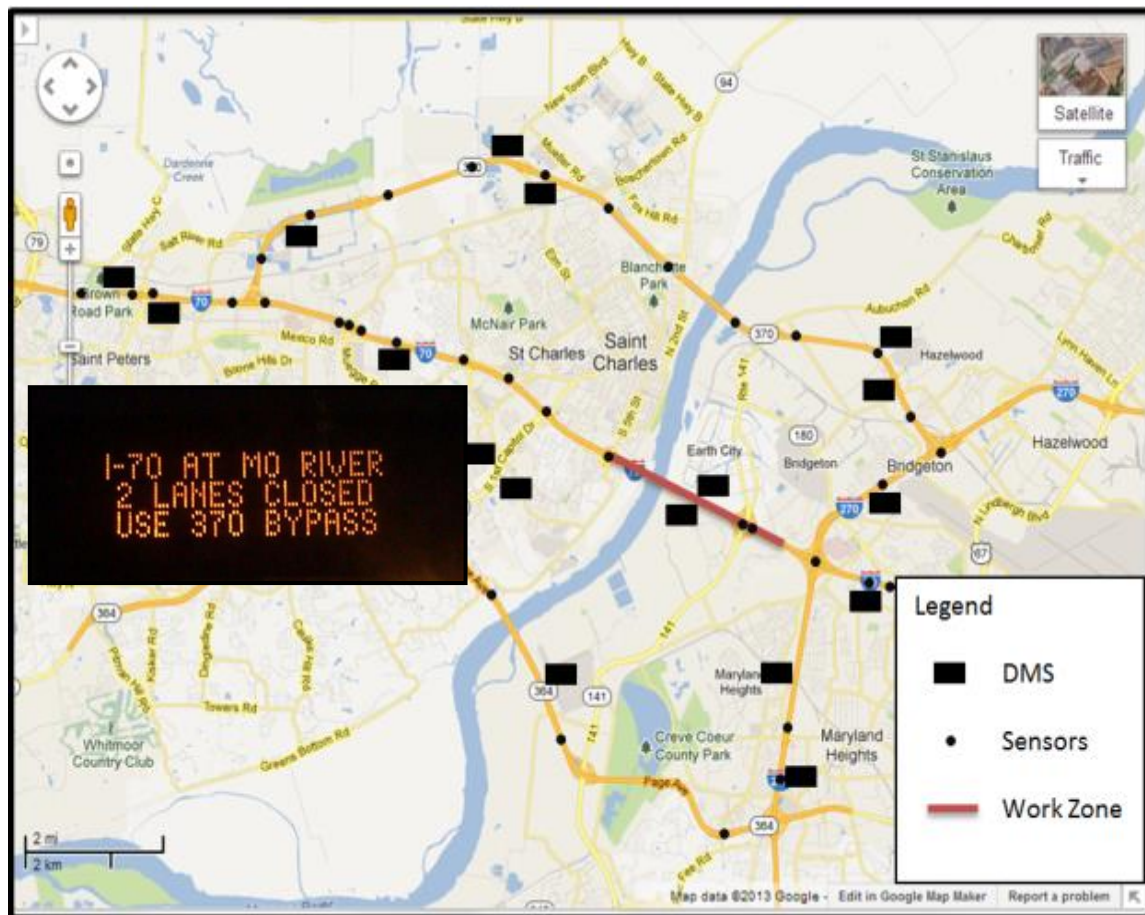
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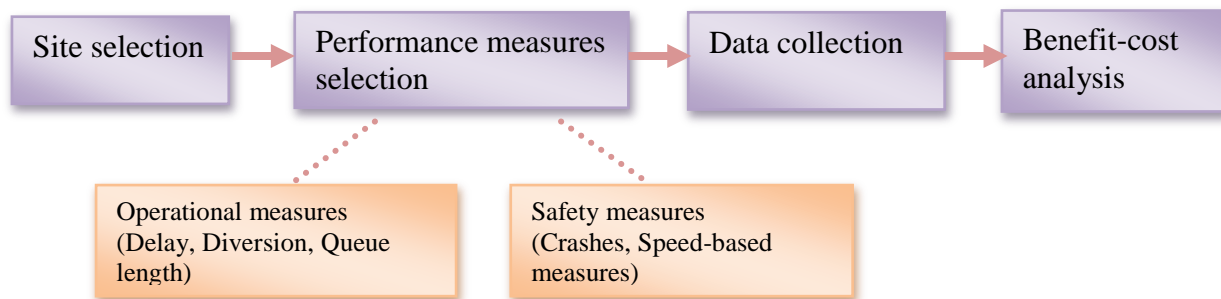
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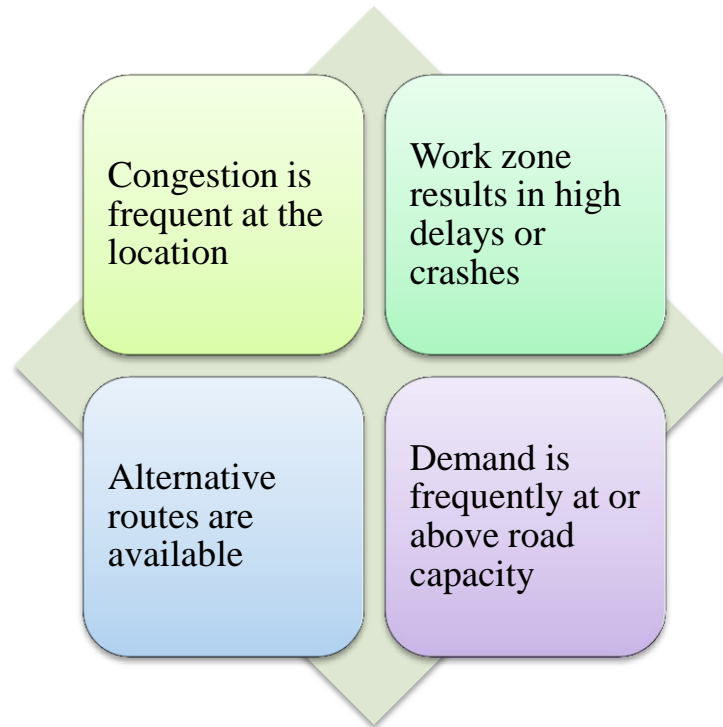
## EXECUTIVE SUMMARY

Intelligent Transportation Systems (ITS) are being increasingly deployed in work zones to improve traffic operations and safety. Also known as Smart Work Zone Systems, these deployments provide real-time information to travelers, monitor traffic conditions, and manage incidents. Despite numerous ITS deployments in work zones, a framework for evaluating the effectiveness of these deployments does not exist. To justify the continued development and implementation of ITS in work zones, there is a need to develop a uniform framework to determine the ITS effectiveness for specific work zone projects. In addition, guidance on the circumstances under which ITS deployment is recommended for a work zone is beneficial to agencies. Such a framework is developed in this report. The framework consists of four steps as shown in Figure E1. In the first step, criteria for selecting work zone sites for ITS deployment are established. The second step consists of selecting operational and safety performance measures for evaluating a deployment. Data needs for measuring and estimating the chosen measures are then determined. The performance benefits are quantified, total costs of ITS deployment estimated, and the benefit-cost ratio is computed in the fourth step.



**Figure E1. Work zone ITS evaluation framework**

The site selection criteria for choosing work zones that offer the greatest potential for traffic and safety improvement through ITS deployment is presented in Figure E2. They are: frequent congestion, high traffic impact at the work zone, availability of alternative routes and over-capacity demand. Depending on the goals of the deployed ITS, one or more of the following five performance measures is recommended: delay, diversion rate, queue length, crash frequency, and speed. These measures were obtained from the synthesis of the existing literature on ITS deployment studies. Using the same measures across ITS deployments will allow for an easier comparison of the results. Traffic sensors that collect traffic flow, speed, and occupancy are key to the chosen performance measures. Additional equipment such as temporary detectors and queue detection trailers may also be needed for accurately measuring queue length. For example, diversion rates can be computed using traffic flow data collected from temporary traffic sensors deployed on the mainline and ramp. Crash data collected by the law enforcement agencies are typically archived by the state DOT. Even though benefit-cost methodology has been implemented in other transportation areas, the application to work zone ITS involves additional wrinkles such as the need to include technology cost factors and the computation of dynamic road user costs.



**Figure E2. Site characteristics warranting ITS deployment**

The proposed work zone ITS deployment framework is illustrated using two case studies. The case study sites are in the St. Louis region in Missouri. The St. Louis urban region has often been ranked approximately twentieth in the U.S. in terms of annual delay according to the Texas Transportation Institute urban mobility report. The first case study, I-70 Blanchette Bridge, is in an urban setting with two major alternative routes. Five lanes were reduced to three lanes in each direction during construction. Only permanent ITS equipment that was already in place was used for the project and no temporary ITS equipment was deployed. The second case study, I-44 Antire Road work zone, is in a rural area with no alternative routes. Three lanes in the eastbound direction were reduced to two lanes. Temporary ITS equipment consisting of four portable DMS signs, eight queue detection trailers, and two Bluetooth travel time sensors, were added to complement the eight existing permanent DMS.

The expected benefit of ITS in the I-70 site was to improve mobility by encouraging traffic to divert to alternative routes. Thus, the benefits of diverting traffic to alternative routes were estimated. A significant field data collection effort was employed using portable surveillance blanketing the entire network, including the major alternative routes. This effort was significant since diversion rates are often not measured in the field but estimated using driver choice models. Diversion rates were measured using traffic data collected before and during the work zone. A traveler survey was conducted to assess the extent to which drivers were influenced by ITS in diverting. The survey revealed that 52% of those that diverted to an alternative route did that due to ITS, specifically DMS. The percentage reliance on DMS was used in a traffic simulation model to estimate the mobility impacts of ITS. Two scenarios were simulated – ‘without DMS’ scenario in which the proportion of traffic diverting to each alternative route was adjusted using the 48% value and ‘with DMS’ scenario in which the

observed diversion rates during the work zone were used. The effect ITS has on delay was then computed by subtracting the delays for 'without DMS' and 'with DMS' scenarios. The permanent DMS equipment in the study corridor serves multiple purposes, and therefore the costs should not be attributed solely to the work zone project. However, the equivalent costs during the work zone period were included in this study in order to estimate the benefit-cost ratio of permanent ITS deployments. The total costs of ITS deployment were estimated to be \$198,530 if equipment costs are included and \$59,130 if only operating costs are included. The delay reduction benefits were estimated to be \$407,694.05 resulting in a benefit-cost ratio of 2.1 to 1 with equipment costs and 6.9 to 1 without equipment costs. The use of ITS in the I-44 Antire Road work zone focused on safety. By warning drivers of downstream traffic speeds and queuing, the potential for rear-end crashes can be reduced. Accordingly, the safety benefits were computed based on the reduction in different types of crashes due to ITS deployment. Fatal, injury, and property damage only crash severities were considered in the analysis. It was estimated that 5.6 property damage only crashes and 0.96 injury crashes were eliminated due to ITS deployment in the work zone. There were no fatal crashes that occurred during the work zone. The safety benefits were then quantified using the AASHTO Red Book unit cost values, which resulted in a total benefit of \$345,900. The benefit-cost ratio was then computed using the actual ITS deployment cost of \$106,700, which produced a benefit-cost ratio of 3.2 to 1.

One recommendation from this study is to encourage state DOTs to collect baseline data at study sites without ITS. This may entail turning off the ITS equipment for a few days while the work zone is deployed. Agencies are usually hesitant to turn off an ITS system when they are available in the field. There is public expectation of receiving traveler information through ITS, and there could be liability concerns associated with available equipment not being used. One possible alternative is to delay the deployment of ITS in the work zone for a few days to collect the 'without ITS' data before turning on ITS. The concern with this approach is that ITS may provide valuable traveler information during the crucial initial period when drivers are unfamiliar with the work zone conditions. Therefore, not having ITS in the initial period could be a concern.





## INTRODUCTION

Ten percent of highway congestion in the U.S. is caused by work zones (1) resulting in an estimated \$700 million lost in fuel each year (2). Traffic safety in work zones is also a concern. For example in Missouri, 57 fatalities occurred in work zones between 2007 and 2011 (3). State departments of transportation (DOTs) strive to improve the safety and mobility in work zones using several approaches, including better scheduling of work activity, better traffic management plans and innovative use of available technologies. The focus of this study is on the use of technology in work zones. In the last decade, Intelligent Transportation System (ITS) have been deployed in work zones by DOTs to improve traffic operations and safety. Also known as Smart Work Zone Systems, these deployments provide real-time information to travelers, monitor traffic conditions, and manage incidents. A review of the existing literature on ITS deployment in work zones revealed several important studies that evaluated their effectiveness. Existing literature focused on one of two focus areas: 1) traffic operations and driver response, and 2) traffic safety. A summary is shown in Table 1 and includes study location, type of ITS deployment, and the key study findings. A more comprehensive review of literature is also provided in Appendix A.

A few interesting trends are evident from these studies. Studies evaluating the benefits of traffic operations outnumber the studies evaluating the safety benefits. This is expected since the intent of most studies was to increase traffic diversion and thereby decrease the congestion on the mainline. In a majority of the studies, the observed diversion rate was less than 10%. There were two sites where the observed diversion was significantly higher (up to 28% in one and 90% in another). Due to short duration and confounding factors such as presence of workers and narrowed lanes, crash analysis may not provide conclusive results for work zone safety evaluations. Surrogate measures including mean speed, 85<sup>th</sup> percentile speed and speed variance have been used for evaluating safety benefits. However, translating the surrogate measures to crash measures (i.e., rate, frequency) and computing societal costs is a major research challenge.

Although there have been numerous ITS deployments in work zones to date, a framework for evaluating the effectiveness of these deployments does not exist. To justify the continued development and implementation of smart work zone ITS, there is a need to develop a uniform framework to determine the ITS effectiveness for specific work zone projects. In addition, guidance on the circumstances under which ITS deployment is recommended for a work zone will be beneficial to agencies. Such a framework is proposed in this report. The framework involves four steps: site selection, performance measure selection, data collection, and benefit-cost ratio computation. The framework is illustrated using two work zone ITS deployment case studies in Missouri: one urban and one rural.

This report is organized as follows. The proposed framework is presented in the next section. A discussion of each of the four steps of the proposed framework is also included. Then the applications of the framework are discussed. They are, the urban I-70 Blanchette Bridge replacement case study, and the rural I-44 and Antire Road case study. The details of a traveler survey administered for the I-70 site, the use of simulation models for assessing the diversion effects, and crash analysis are discussed. Conclusions are drawn and recommendations made in the final section.

**Table 1. Work Zone ITS Deployments****(a) Traffic operations**

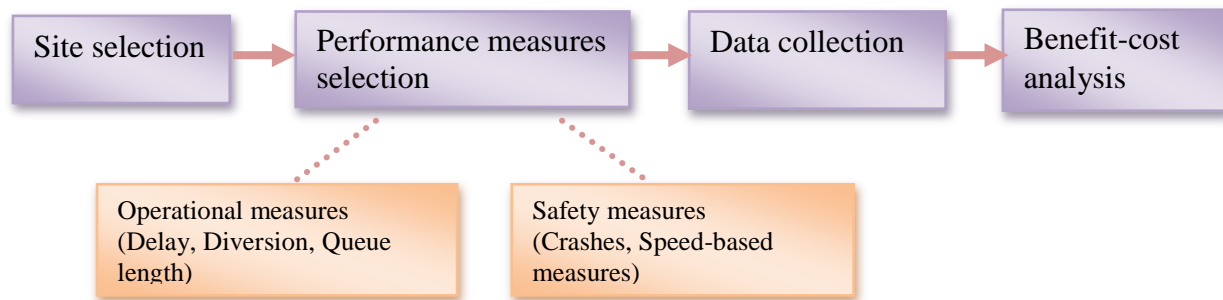
<b>Study location</b>	<b>Type of Work Zone ITS deployment</b>	<b>Main findings (Operations and Driver Response)</b>
I-75 near Dayton, Ohio (4)	Travel time information	71.6 percent of frequent drivers said they diverted
I-95 in North Carolina (5)	Delay and alternate route information on PCMSs	86.4 percent of frequent drivers said they diverted
US 41 in Green Bay, Wisconsin (6)	Speed advisory system	Minimal diversion impacts were achieved as most diversion occurred due to aggressive outreach activity
I-80 in Nebraska (7)	Consider alternate route message on PCMSs	8 to 10 percent increase in traffic diversion
I-80 in Nebraska (8)	Delays-Use Alternate Route was displayed on PCMSs	4 percent increase in traffic diversion
I-680 in Nebraska (9)	Speed advisory system	No significant change in diversion rate
I-94 in Milwaukee, Wisconsin (10)	Travel time information prior to potential diversion points	7 to 10 percent of traffic diverted
I-94 in Milwaukee, Wisconsin (11)	Delay and Travel time information	5 to 10 percent traffic diverted
I-40 in Arkansas (12)	Queue length information and Slow traffic ahead -Be prepared to stop message on PCMSs	When queue exceeded 5 miles, the traffic volume on alternate route was double the normal day volume. Truck traffic diverted more than passenger cars.
I-5 in Santa Clarita, California (13)	Delay advisory system with alternate route information on PCMSs	5.3 to 8.7 percent diversion was observed. Travel time savings of 3 to 4 minutes reported.
I-80 in Nebraska (14)	Speed advisory system	Little to no reduction in mean or 85th percentile speeds during uncongested conditions.
DC-295 in Washington, DC (15)	Delay and speed information (also provided alternate routes via DMSs)	3 to 90 percent traffic diverted from mainline (was not possible to isolate the ITS effect and congestion effect)
I-35 in Waco, Texas (15)	Delay and alternate route information via DMSs	1 to 28 percent traffic diverted from mainline during congested periods
I-30 in Arkansas (15)	Highway advisory radio and DMS alerts for significant delays	82 percent of survey respondents agreed that ITS improved their ability to react to slow or stopped traffic
I-40 in Winston Salem, North Carolina (15)	Delay and alternate route information via DMSs	Inconclusive results due to limitations in the information available for analysis

**(b) Traffic safety**

<b>Study location</b>	<b>Type of Work Zone ITS deployment</b>	<b>Main findings (Traffic Safety)</b>
I-70 in Missouri (King et al.) (16)	Speed advisory system	66.3 percent of drivers slowed down with overall speed reduction of 7 mph near work activity area. Speed variance also decreased.
I-55 in Springfield, Illinois (FHWA) (17)	Travel time information	Crash rates declined and number of citations for moving violations also declined.
I-95 in North Carolina (Bushman et al.) (18, 19)	Delay and alternate route information on PCMSs	22 crashes occurred during 92 days with ITS and 2 crashes occurred during 13 days without ITS.
I-94 in Milwaukee, Wisconsin (Notbohm et al.) (11)	Delay and Travel time information	Observed changes were not statistically significant due to other confounding factors.
I-40 in Arkansas (Tudor et al.) (12)	Queue length information and Slow traffic ahead -Be prepared to stop message on PCMSs	Fatal crash rate was 50% lower than at control sites. No differences in rear-end crash rates.
US-131 in Kalamazoo, Michigan (Luttrell et al.) (15)	Dynamic lane merge system	Significant reduction in number of forced merges and dangerous merges

## FRAMEWORK FOR EVALUATING WORK ZONE ITS DEPLOYMENT

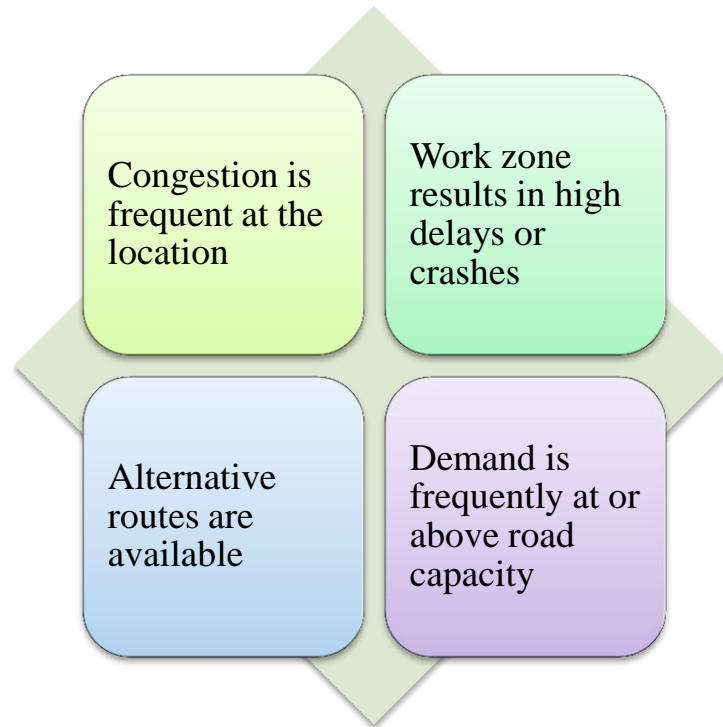
A generic framework for evaluating ITS deployments in work zones was developed. The framework consists of four steps as shown in Figure 1. In the first step, criteria for selecting work zone sites for ITS deployment are established. The second step consists of selecting operational and safety performance measures for evaluating a deployment. Data needs for measuring and estimating the chosen measures are then determined. In the last step, the performance benefits are quantified, the total costs of ITS deployment is estimated, and the benefit-cost ratio is computed.



**Figure 1. Work zone ITS evaluation framework**

### Site Selection

Based on the reviewed literature, guidance was developed on what criteria to use for selecting work zones that offer the greatest potential for traffic and safety improvement through ITS deployment. Figure 2 lists four such site characteristics that may warrant ITS deployment. First, the travel demand at the work zone site should be at or above capacity to derive the greatest ITS benefits. When ITS was deployed at sites with low demand, the evaluation was usually inconclusive or minimally beneficial. Ideally, ITS will help distribute the excess demand on to the alternative diversion routes. Related to the need for high demand is the frequency of congestion at the selected location. If the location witnesses congestion during rush hours or if it is a bottleneck, it may warrant ITS deployment. Studies have also found that drivers unfamiliar with an area are less likely to divert, even with ITS. Thus, one situation where ITS would benefit travelers is in a work zone traveled by drivers that are familiar with the area (e.g., commuters). Freeway work zones in urban areas are an example of such a situation. Thus, the availability of alternative routes and their monitoring are also important while selecting a work zone for ITS deployment. Good traffic management strategies need to be put in place on the alternative routes to handle the additional detouring demand. The operating speeds on alternative routes should be close to that of the mainline so as to avoid any drastic increases in trip travel times. The last site characteristic that could warrant ITS is the likelihood of high delays or frequency of crashes at the work zone.



**Figure 2. Site characteristics warranting ITS deployment**

## **Performance Measures**

Depending on the goals of the deployed ITS, one or more of the following five performance measures is recommended for consideration in the framework: delay, diversion rate, queue length, crash frequency, and speed. These measures were obtained from the synthesis of the existing literature on ITS deployment studies. Using the same measures across ITS deployments will allow for easier comparison of the results. The five measures are defined as follows:

1. *Diversion*: Diversion occurs when a work zone decreases the roadway capacity thus affecting traffic flow. Diversion rate is the increase in volume on the exiting ramp to access the alternative route, divided by the mainline volume before the exit ramp.
2. *Delay Time*: Delay time is the additional travel time experienced by a driver during congestion or slowed traffic resulting from the work zone.
3. *Queue Length*: A queue is a group of vehicles that are traveling very slowly or are stopped. In this study queuing conditions are defined for speeds less than 10 mph similar to Notbohm et al. (11). Maximum and average queue lengths in work zones are then computed based on the extent of the queue during different time periods.
4. *Crash Frequency*: The number of crashes per work zone duration is defined as the crash frequency. Alternatively, crash rate, which includes the traffic exposure, may also be used.
5. *Speed*: Measures such as mean speed, 85<sup>th</sup> percentile speed, compliance rate and speed variability are common speed measures. Mean speed is the arithmetic mean of the vehicle speeds in a given time interval. The 85<sup>th</sup> percentile speed can be computed using the cumulative speed plots and can be compared with the posted speed limit. Some agencies

prefer the use of 85<sup>th</sup> percentile speed than the average speed because speed limits are often based on the 85<sup>th</sup> percentile speed. Speed compliance rate indicates the percentage of drivers traveling below the speed limit. The compliance rate is particularly useful when work zones have lower posted speed limits than normal. Speed variance gives the dispersion of speeds with respect to the mean speed. Speed variance has also been found to be related to safety. All the aforementioned speeds are correlated. It is up to the agency to decide which speed measure best captures the agency's goals.

In addition to these measures, other measures can be evaluated depending on the agency needs. For example, a few studies have used travel time as a surrogate for delay, emissions, emergency response time, changes in demand, and number of forced merges.

## **Data Collection**

Traffic sensors that collect traffic flow, speed, and occupancy are key to the chosen performance measures. Additional equipment such as queue detection trailers may also be needed for accurately measuring queue lengths. In Table 2, a summary of the data needs for each performance measure and the type of ITS communication impacting them are shown. For example, diversion rates can be computed using traffic flow data collected from traffic sensors deployed on the mainline and ramps. ITS technologies such as dynamic message signs (DMS) can be used to communicate the availability of alternative route and the delay on the existing route influencing driver behavior.

To evaluate the effectiveness of ITS in a work zone, there should be a control measurement without the use of ITS. State agencies are usually hesitant to turn off an ITS system after its deployment in the field. This is presumably due to the public expectation of receiving traveler information through ITS. However, turning off ITS equipment is essential in order to accurately assess ITS benefits. Without an appropriate control situation (i.e., without ITS performance) the relative improvement (or worsening) due to ITS deployment cannot be accurately estimated. Thus, state agencies are encouraged to consider not using ITS for a few days during the work zone to provide sufficient control data for evaluating ITS effectiveness.

**Table 2. Data Needs for the Five Performance Measures**

<i>Diversion rate</i>		
<b>Monitoring</b>	Traffic sensors	Gather volume counts at alternative route entrances, and mainline
<b>ITS to communicate with drivers</b>	Pre-trip info: website, news releases, or radio In-route info: DMS, Portable DMS, or HAR Management: ITS system, ITS software, and/or Control center	Messages could include ‘Use alternative route,’ ‘Delay ahead,’ ‘Work zone ahead,’ and ‘Travel time’
<i>Delay time</i>		
<b>Monitoring</b>	Traffic sensors	Gather travel times or speeds along corridor
<b>ITS to communicate with drivers</b>	Pre-trip info: website, news releases, or radio In-route info: DMS, Portable DMS, or HAR Management: ITS system, ITS software, and/or Control center	Messages could include ‘Delay ahead,’ ‘Work zone ahead,’ and ‘Travel time’
<i>Queue Lengths</i>		
<b>Monitoring</b>	Traffic sensors, Queue trailers	Gather queue length or speeds along corridor
<b>ITS to communicate with drivers</b>	In-route info: DMS, Portable DMS, or HAR Management: ITS system, ITS software, and/or Control center	Usually queue lengths are not reported with other pre-trip info. Messages could include ‘Slowed traffic ahead,’ ‘Reduced speeds ahead,’ ‘Crash ahead,’ and ‘Delay ahead’
<i>Crash Frequency</i>		
<b>Monitoring</b>	Crash reports	Gather crashes occurring along corridor
<b>ITS to communicate with drivers</b>	Pre-trip info: website, news releases, or radio In-route info: DMS, Portable DMS, or HAR Management: ITS system, ITS software, and/or Control center	Only communications directly related to safety are expected to affect crash rates. Messages could include ‘Crash ahead,’ ‘Reduced speeds ahead,’ and ‘Crash rate statistics’
<i>Speed-based measures</i>		
<b>Monitoring</b>	Traffic sensors	Gather speeds along corridor
<b>ITS to communicate with drivers</b>	Pre-trip info: website, news releases, or radio In-route info: DMS, Portable DMS, or HAR Management: ITS system, ITS software, and/or Control center	Messages could include ‘Reduced speeds ahead,’ ‘Crash ahead,’ ‘Work zone ahead,’ ‘Travel time,’ and ‘Delay ahead’

## Benefit-Cost Analysis

Even though benefit-cost methodology has been implemented in other transportation areas, the application to work zone ITS involves additional considerations such as the need to include technology cost factors and the computation of dynamic road user costs.

### Cost Calculations

The total cost of the deployed ITS system includes the cost of equipment, the cost of operation, and the cost of set up. The total cost is represented as

$$C_{Total} = C_{Equipment} + C_{Operations} + C_{Setup}$$

where,

$C_{Equipment}$  = permanent ITS equipment cost per single work zone application duration + costs of any temporary ITS equipment deployed for the application

$C_{Operations}$  = number of office personnel \* hourly wage \* duration of work zone in hours

$C_{Setup}$  = number of field personnel \* hourly wage \* duration of work zone in hours

### *Benefit Calculations*

The total benefit of the ITS system consists of delay reduction benefits and crash reduction benefits. Delay reduction benefit is computed using the difference of delay with and without ITS multiplied by the unit cost of value of time. These benefits do not include the savings resulting from fuel savings and emissions reduced, since such benefit estimations are very complex. The total benefit is represented as

$$B_{Total} = B_{Delay\ Reduction} + B_{Crash\ Reduction}$$

where,

$$B_{Delay\ Reduction} = (total\ delay\ without\ ITS - total\ delay\ with\ ITS) * unit\ cost\ of\ value\ of\ time\ of\ private\ vehicles + (total\ delay\ without\ ITS - total\ delay\ with\ ITS) * unit\ cost\ of\ value\ of\ time\ of\ commercial\ trucks$$

The benefits resulting from reduction in crashes is quantified using the unit costs provided in Table 5-17 of AASHTO's Red Book, i.e. User and Non-User Benefit Analysis for Highways (24). The computation of crash benefits consists of all crash severities – fatal, injury, and property damage only (PDO) crashes. The total crash reduction benefits can then be computed as follows:

$$B_{Crash\ Reduction} = (fatal\ crashes\ without\ ITS - fatal\ crashes\ with\ ITS) * cost\ per\ fatal\ crash + (injury\ crashes\ without\ ITS - injury\ crashes\ with\ ITS) * cost\ per\ injury\ crash + (PDO\ crashes\ without\ ITS - PDO\ crashes\ with\ ITS) * cost\ per\ PDO\ crash$$

After determining the costs and benefits for the ITS deployment, benefit-cost ratio are computed by dividing the benefits over the costs. Benefit-cost ratios greater than 1.0 indicate that the benefits derived from ITS outweigh deployment costs.

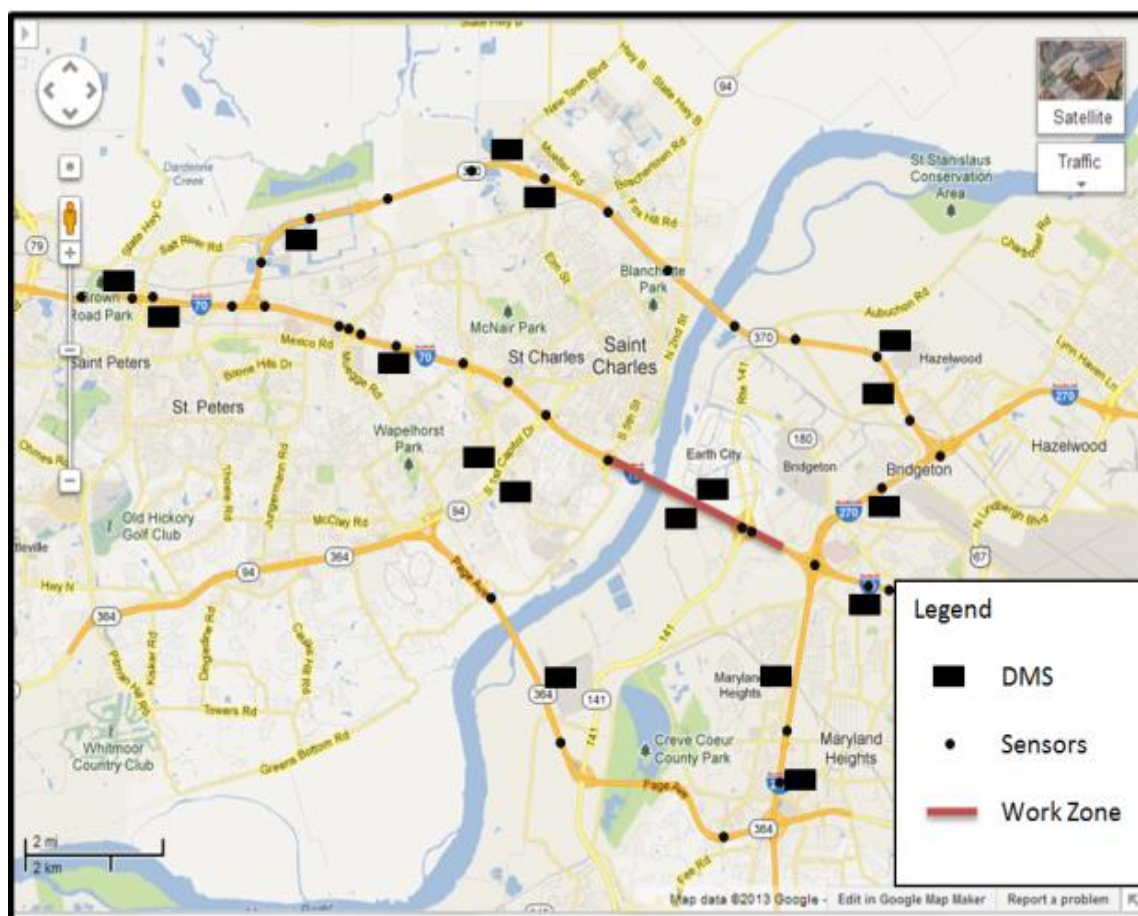
## **APPLYING THE FRAMEWORK TO TWO WORK ZONE ITS DEPLOYMENTS**

Two case studies were chosen to illustrate the framework developed in the previous section. These sites are in the St. Louis region in Missouri. The first case study, I-70 Blanchette Bridge, is in an urban setting with two major alternative routes. Five lanes were reduced to three lanes in each direction during construction. Only permanent ITS equipment that was already in place was used for the project. The second case study, I-44 Antire Road work zone, is in a rural area with no alternative routes. Three lanes in the eastbound direction were reduced to two lanes. Temporary ITS equipment consisting of four portable DMS signs, eight queue detection trailers, and two Bluetooth travel time sensors, were added to complement the eight existing permanent DMS.

### **I-70 Blanchette Bridge Case Study**

The I-70 Blanchette Bridge work zone is a \$63 million rehabilitation project of a 54 year old bridge. On November 2, 2012, the westbound bridge over the Missouri River was closed for a yearlong reconstruction project. The eastbound bridge currently is used by both directions of traffic. Since the westbound bridge is closed, five lanes per direction were reduced to three lanes per direction on the eastbound bridge by striping the lane to accommodate six new lanes in the footprint of five lanes. Two highways, Rt. 364 and Rt. 370, served as alternative routes across the Missouri River. The average annual daily traffic (AADT) as of 2011 was 121,220 including 14,187 commercial trucks (11.7% of the AADT). The original speed limit of 60 mph was reduced to 45 mph within the work zone. Each of the four site characteristics warranting ITS deployment was met: congestion is frequent at the location, the duration of the work zone resulted in consistent delays and potential for crashes, alternative routes are available, and the demand is frequently at or above road capacity. Figure 3 shows the I-70 network with DMS and locations for traffic sensors.





**Figure 3. I-70 Blanchette Bridge work zone network map**

ITS was used at the Blanchette Bridge work zone site to promote traffic diversion during congested periods, warn drivers of lane closures, narrow lanes and reduced speed limits, and provide travel times. DMS was the main component of ITS used to provide en-route information to drivers while the pre-trip information was provided using newspaper, radio, television, and traveler information websites.

## Data Collection for I-70 Case Study

Existing traffic sensors in the study area provided traffic data on the main roadways only (I-70, Rt. 364, and Rt. 370). They did not provide data on ramps. Ramp flows were necessary to obtain the diversion rates. Thus, ramp flows at several key decision points in the area was collected using portable video cameras deployed at the locations. A map of the data collection locations is shown in Figure 4 as red circles. Cameras were deployed strategically to capture the diversion volumes to each alternative route. Video data was collected during AM peak (7:00-9:00), PM off-peak (1:00 – 2:00), and PM peak (4:00 – 6:00). Two datasets were collected: before data without work zone and during work zone data. The before and during work zone data were both collected on the same day of the week on a Wednesday. Traffic studies are usually conducted between Tuesday and Thursday because they represent the typical work day traffic. The before data was collected on October 24, 2012 and the during data on November 7, 2012.

[illegible]

Figure 5 shows the diversion towards each detour route and time periods recorded for the AM peak hours (blue arrows), pm peak hours (black arrows), and an off-peak hour in the afternoon (red arrow). Table 3 shows the percentage of mainline traffic accessing each alternative route before and during the work zone. The diversion rate is then calculated by subtracting the before and during percentages and is reported in the final column of Table 3.



Figure 5. Network map of I-70 network diversion

Table 3. Diversion Rates for Before Construction and During Construction

	Time	Before WZ, Day 1 (10/24/12)	During WZ, Day 2 (11/7/12)	Diversion
EB I-70 to EB I-370	AM peak, 7-9am	30.6%	36.1%	+5.5%
EB I-70 to NB Rte 94		7.7%	10.0%	+2.3%
EB I-70 to SB Rte 94		3.5%	4.9%	+1.4%
WB I-70 to NB Earth City Expy	Off- peak, 1-2pm	11.9%	13.8%	+1.9%
WB I-70 to NB I-270	PM peak, 4-6pm	9.2%	11.9%	+2.7%
WB I-70 to SB I-270		22.2%	28.7%	+6.5%
NB I-270 to WB I-370		19.8%	24.5%	+4.7%
NB I-270 to Missouri Bottom Rd		5.0%	5.1%	+0.1%
SB I-270 to WB Rte 364		17.7%	21.9%	+4.2%



With the diversion rates measured for I-70, the next step was to find the portion of the diversion caused by ITS. The researchers did not have permission to turn off the DMS during the duration of the work zone in order to measure the diversion in the absence of DMS. Thus, a traveler survey was used to capture the effect of the DMS on diversion rates.

### **Survey of Motorists for the I-70 Work Zone**

The primary objectives of the survey were to assess the extent to which drivers were influenced by DMS, how much delay drivers typically perceived to experience through the work zone, and what DMS information the drivers viewed to be the most valuable. The ITS survey was created using an online survey creation website and distributed to the St. Louis area via the Missouri Department of Transportation's social media outlets.

It was important to analyze each question in the survey for appropriate wording. The main question of the survey was "What percent of a driver's decision to choose an alternative route was based on DMS." Past surveys concerning DMS only asked about drivers preferences on DMS, if DMS made an effect on their behavior, or if DMS messages were understandable. This survey asked if they used an alternative route based on DMS messages. By concentrating on DMS with diversion rates, the benefits of DMS could be acquired. The other survey questions help explain the differences in drivers' choices and habits. The survey questionnaire as it appeared on the website is presented in Appendix B.

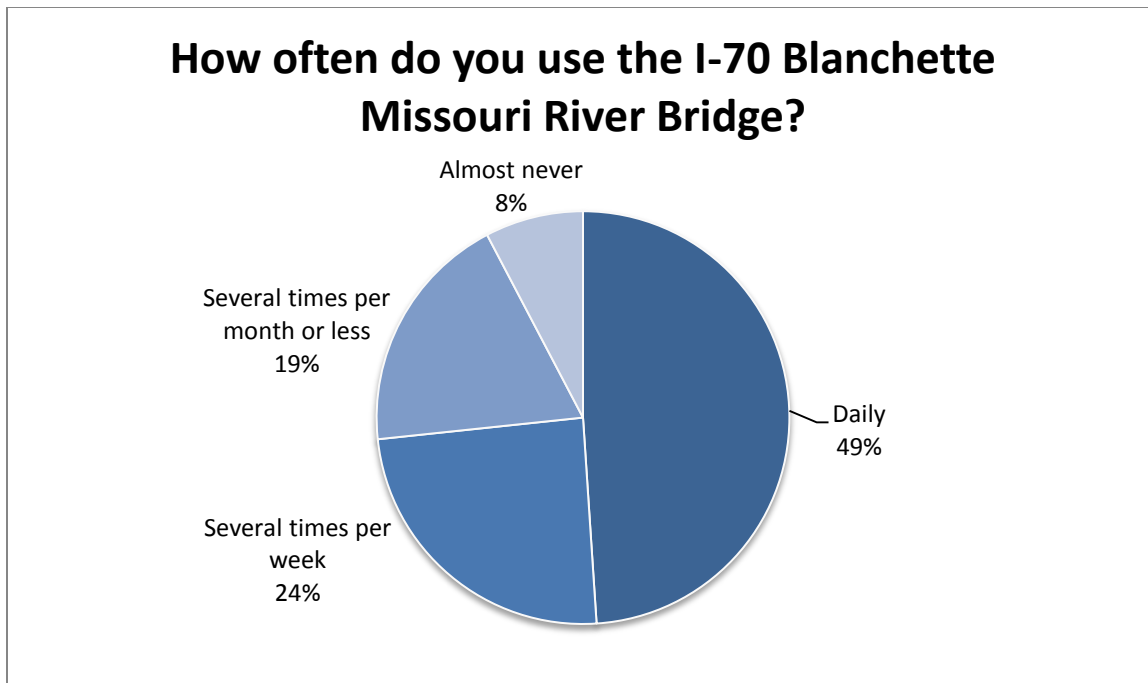
The survey was distributed to the St. Louis area via the Internet from March 1, 2013 4:59PM until April 1, 2013 3:53PM. The number of complete surveys is 492 out of 496 respondents (99.2% completion rate). The responses to the questions are organized below.

### *Key Findings*

- 1) In comparing responses between morning and evening commutes, it was found that the percentage use of alternative routes is higher for evening travel.
- 2) 98% of drivers said they were aware of the I-70 work zone before they began their trips. This means that MoDOT was successful in disseminating the traveler information through various media outlets advising the travelers about the work zone.
- 3) 52% of drivers in the AM and PM said they used an alternative route due to DMS.
- 4) Awareness of the work zone led to increased use of alternative routes in the AM and PM.
- 5) According to delays reported by drivers, there are longer delays (over 15 min) if drivers were not aware of the work zone or if they were not influenced by DMS.
- 6) The DMS signs had the greatest influence on drivers within the age group of 46 to 65 years.

### *Frequency of Use*

The survey responses indicate frequent use of the I-70 Blanchette Missouri River Bridge. As shown in Figure 6, about 50% use the bridge on a daily basis. This means that around half of the traffic has adjusted to traveling through the work zone. About 8% almost never use the bridge. This means that the remaining 92% of travelers are familiar with the work zone conditions.



**Figure 6. Frequency of driver usage of the I-70 Blanchette Missouri River Bridge**

#### *AM and PM Peak Travelers*

When asked about their morning commute, 77% of the travelers responded that their trip consisted of crossing the Blanchette Bridge going Eastbound and 76% of the travelers responded that they commuted during the hours of 6-9am. When morning travelers were asked if they used an alternative route, 13% stated using Route 370, 20% using Route 364, and 3% using I-64.

When travelers were asked about their evening commute, 79% responded that their commute consisted of crossing the Blanchette Bridge and 80% responded that their evening commute occurred in the hours of 3-6pm. When travelers were asked if they used any alternative routes when commuting in the evening, 15% stated using Route 370, 26% using Route 364, and 3% using I-64. Comparing the responses for morning and evening commutes, it can be inferred that the stated use of alternative routes increased for evening travel.

#### *Awareness of the Work Zone*

When travelers were asked if they were aware of the work zone before they began their trip, 98% of drivers said they were aware of the work zone. This result shows that MoDOT was successful in disseminating the traveler information through various media outlets advising the travelers about the work zone.

#### *Influence of DMS on Alternative Route Usage*

Forty seven percent of the surveyed population stated that the DMS signs influenced their decision to use an alternative route. The responses to the influence of DMS and the use of

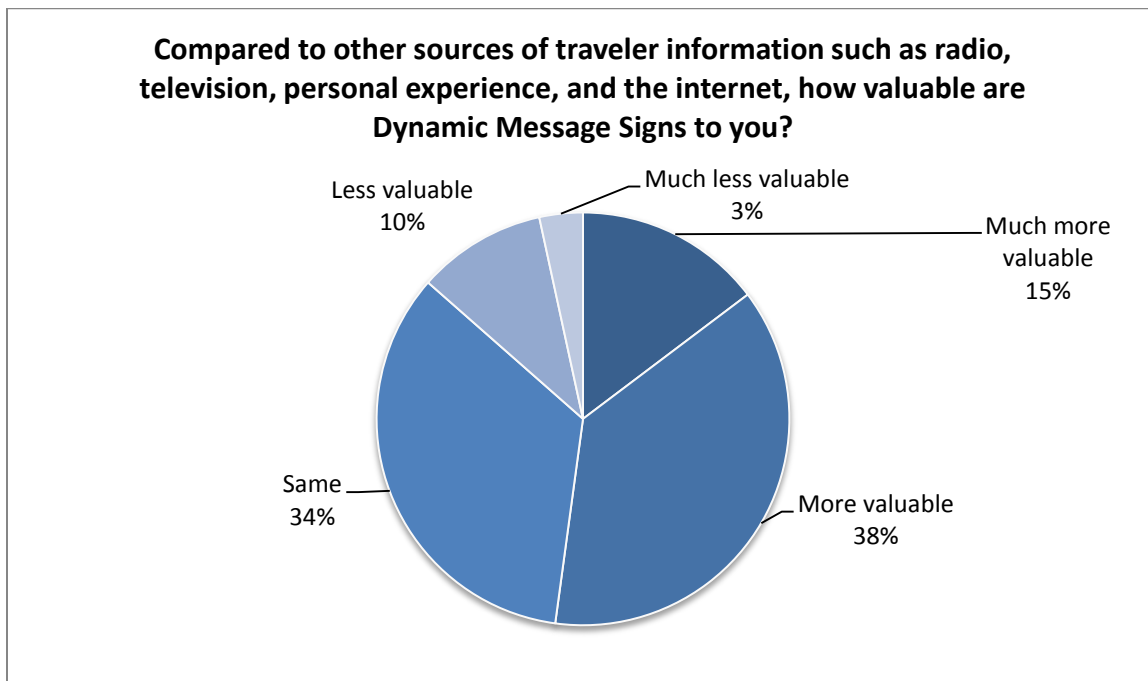
alternative route questions were cross-referenced to determine what portion of drivers that detoured was due to DMS. Table 4 cross-references the two questions for the AM peak period. From the table the total number of respondents that answered yes to being influenced by DMS and to using an alternative route is 93 (8 using I-64, 43 using I-370, and 42 using Rt. 94.) +43+42). The total number of respondents using an alternative route is 179. Thus, 93/179 or 52% of those that detoured were influenced by DMS.

**Table 4. Cross-Reference Table of AM Alternative Route Usage and DMS Influence**

Do the Dynamic Message Signs influence your decision to use an alternative route?	In the mornings (AM), do you use an alternative route around the I-70 Blanchette Missouri River Bridge?				
	No	Yes, I use I-64	Yes, I use Route 370	Yes, I use Rt. 94/Rt. 364 (Page Avenue)	Grand Total
No	176	7	21	58	262
Yes	135	8	43	42	228
Blank response	1	1			2
Grand Total	312	16	64	100	492

#### *DMS Compared to Other Traffic Information Sources*

When travelers were asked the value of DMS compared to other sources, 87% said they were equal or more valuable than other sources, 15% thought that the DMS were much more valuable, 38% thought that the DMS were more valuable, and 34% thought the DMS were equal in value to other sources (see Figure 7).



**Figure 7. Compared value of DMS to other traveler information sources**

### *Demographics of survey respondents*

Ninety nine percent of the responses came from residents local to the St. Louis area and the remaining 1% came from visitors. Eighty five percent of the trips were work-related while 15% were for recreation. Ninety nine percent of the responses came from private vehicle travelers with the remaining 1% being from commercial truck operators or public transportation travelers. Both genders were well represented with 54% of the responses coming from females and 46% from males. In terms of age distribution of respondents, 58% were between the ages of 46 and 65, 33% were between the ages of 26 and 45, and 9% were either below 25 or above 66 years old.

### **Performance Measures for the I-70 Case Study**

Three performance measures were used to evaluate the I-70 case study: diversion rate, delay time, queue length. As previously described, field data and a survey were used to obtain diversion rate. Traffic simulation was used to determine the delay and queue length measures, similar to a previous study by Fontaine and Edara (20) that used simulation to evaluate ITS deployments in work zones.

The performance measure values extracted using simulation are described next. The study network was simulated using the VISSIM software program. There were six original simulations: before period AM-peak, off-peak, and PM-peak; and during work zone AM-peak, off-peak, and PM-peak. Road geometry, including number of lanes and entrances and exits, were modeled to scale. Traffic volumes and speed distributions were entered using field sensor data. A screenshot of the road network in VISSIM is shown in Figure 8.



**Figure 8. VISSIM geometry of the I-70 Blanchette Bridge network**

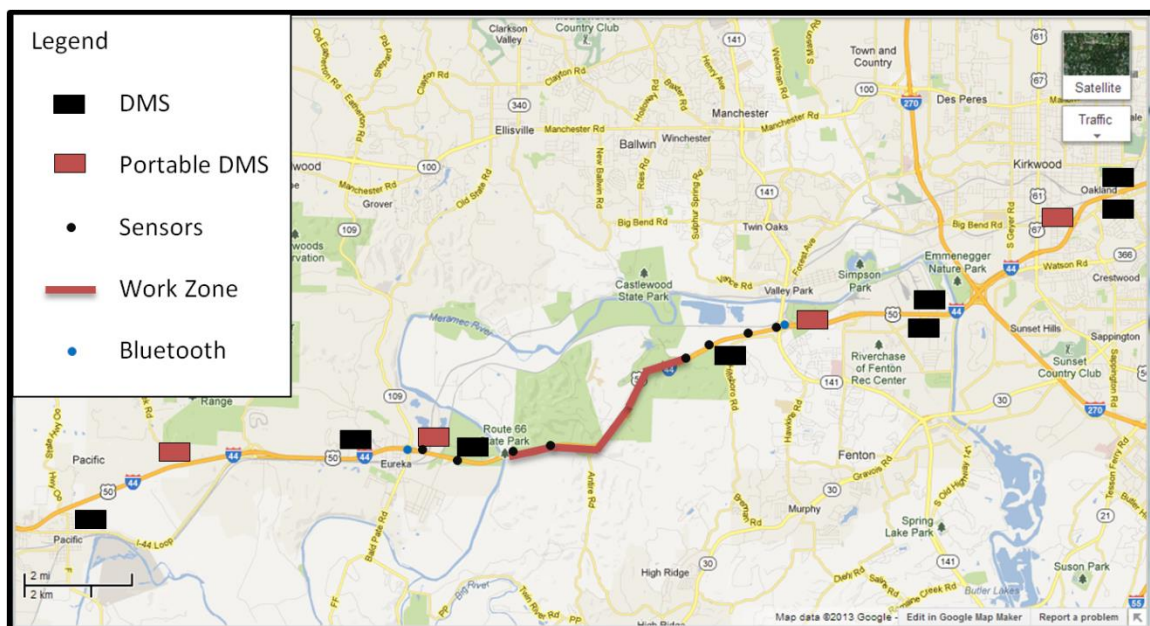
Travel times found from recorded DMS displays were used to validate the simulation model. The travel time between the two eastbound DMS chosen was 7.44 min for the time before the work zone and 7.75 min during the work zone, for the 8.3 miles segment. The travel time between the westbound chosen DMS was 9.00 min for the time before the work zone and 10.21 min during the work zone, for the 9.1 mile segment. The minor increases in travel times with the work zone were possibly due to the reduction in traffic volumes - some travelers switched to alternative routes, a 9% diversion was observed during peak hours, and some travelers shifted their departure times. The travel times for the AM period simulations were within 9% of the reported DMS travel time while the PM period simulations were within 3%. Each simulation was run 20 times to account for the random nature of simulation.

The survey revealed that 52% of drivers that diverted relied on DMS, fully or partially, to receive detour information. Thus, 48% of drivers who diverted knew about the work zone and detour routes through sources other than DMS. Two scenarios were simulated – ‘without DMS’ scenario in which the proportion of traffic diverting to each alternative route was adjusted using the 48% value and ‘with DMS’ scenario in which the observed diversion rates during the work zone were used. The effect ITS has on the delay was then computed by subtracting the delays for ‘without DMS’ and ‘with DMS’ scenarios. For the AM period, without ITS resulted in a total delay of 13.37 hours and with ITS resulted in 11.82 hours. For the off-peak period, without ITS resulted in a hourly delay of 2.14 hours and with ITS resulted in 2.08 hours. And for the PM period, without ITS resulted in a total delay of 73.41 hours and with ITS resulted in 36.13 hours.



## I-44 Work Zone Case Study

The I-44 work zone site involved road resurfacing from June 1, 2012 to October 19, 2012, a total duration of 140 days. The location was southwest of St. Louis between Antire Road and Lewis Road. No alternative routes were available due to its rural setting. The average annual daily traffic as of 2011 was 68,181 including 8,020 heavy vehicles (11.8%). The original speed limit of 65 mph was reduced to 55 mph in the work zone. Two of the four criteria of high ITS benefits were met: congestion is frequent at the location and the work zone produces consistently high delays or frequent crashes. Re-routing traffic was not a goal of the ITS deployment since alternative routes were not available. The major truck usage at night and heavy commuter traffic prompted the use of ITS to improve safety by warning drivers of the work zone and of any queuing. Figure 9 shows the I-44 network with 12 DMS and 10 sensor locations.



**Figure 9. I-44 Antire Road work zone network**

The equipment used in the ITS deployment include: eight queue detection trailers, two Bluetooth sensors, eight permanent DMS in the area, and four temporary DMS. New data was gathered every minute per lane. Messages on the DMS depended on the average traffic speeds computed from the 1-minute data. For speeds greater than 40 mph, the portable DMS displayed “Stay Alert, Do Not Text and Drive.” For speeds between 15 mph and 40 mph, it displayed “Slowed traffic Y Miles Ahead, XX Mins 109 to 141.” The 109 and 141 values refer to the exit numbers on I-44. And, for speeds less than 15 mph, it displayed “Stopped traffic Y Miles Ahead, XX Mins 109 to 141.” Unfortunately, the Bluetooth sensors were placed too far upstream and downstream of the work zone to capture the delays caused by the work zone. Vehicles often sped up after they passed the work zone to make up for lost time, thus vehicles did not experience delay over the entire Bluetooth segment. One recommendation for future Bluetooth sensor deployments is to position them closer to the work zone boundaries to capture work zone delays.

The I-44 ITS deployment was primarily targeted at improving safety by preventing queuing-related crashes by warning drivers of any downstream queues. Thus, the main

performance measures were related to safety, i.e., the crash frequency and speed-based measures. Speed-based measures were extracted from the traffic sensors and the queue trailers. However, since there was no control period where the ITS was not operational, the effect of ITS on speeds could not be estimated. Although the crash frequency measure had the same problem, other studies have quantified the effect of ITS on queuing related crashes. Thus, by determining the total crash frequency one could use the reduction rates from literature to quantify the safety benefits at the I-44 site. The analysis of crash frequency and related benefits for both case studies are presented in the next section.

## **Crash Analysis**

The objective of analyzing the crash frequency was to ascertain the effect of ITS on crashes. Neither site allowed the suspension of ITS for any amount of time in order to collect ‘without ITS’ data. The type of ITS used in the I-44 site, queue warning trailers and temporary DMS, focused on improving safety at the work zone. It was similar to the deployment on I-55 in southern Illinois as reported in Nemsky (21). Nemsky reported a 13.8% reduction in queuing related crashes in a work zone due to the use of ITS. This reduction rate was applied to quantify the effect of ITS at the I-44 work zone site. During the work zones period, a total of 35 PDO crashes and 6 injury crashes were reported in the MoDOT crash database. The without ITS crash frequency was estimated to be 40.6 PDO crashes ( $35/(1-0.138)$ ) and 6.96 injury crashes ( $6/(1-0.138)$ ) during the work zone period. Such reduction rates were not applicable to the type of ITS used in the I-70 site and therefore the effect of ITS on safety was not quantified for the I-70 site. The main purpose of ITS at the I-70 site was to improve mobility by encouraging diversion to alternative routes.

## **Computing Benefit-Cost Ratios**

The benefits and costs of ITS deployments at the two work zone sites were estimated. The following assumptions and computations were made to quantify the benefit-cost ratios:

1. The I-70 work zone lasts for 1 year and the I-44 work zone lasts for 140 days.
2. There is one office staff personnel for monitoring operations of the work zone and two field staff for ITS set up.
3. Office staff earned \$20.25 per hour and field staff earned \$14 per hour according to average MoDOT salaries in Missouri (22). For estimating annual salary, a full 365 calendar days were used instead of 235 days (subtracting weekends and holidays) to account for critical support outside regular hours.
4. Actual MoDOT costs of ITS equipment were used when available. If actual costs were not available then the USDOT ITS website values were used instead (23).
5. Permanent ITS equipment has an operating life of 10 years.
6. The duration of setting up 4 Portable DMS, 8 Queue trailers, and 2 Bluetooth sensors is 8 hours.
7. Traveler wage related information was obtained from the AASHTO Red Book (24) while the vehicle mix was obtained from the MoDOT website for the St. Louis region (25).

These values are:

- a) Average wage = \$16.84/hr for passenger cars and \$18.56/hr for trucks
- b) Total compensation as a percentage of average wage = 120% for passenger cars and 50% for trucks

- c) Occupancy = 1.5 for passenger cars and 1.05 for trucks
- d) Vehicle mix = 88.3 for passenger cars and 11.7 for trucks
- 8. Costs of injury and PDO crashes obtained from Table 5-16 of the AASHTO Red Book (24) were for the year 2000 which were discounted to the work zone year 2012 at a 4% annual rate. The 4% rate is used by the highway safety manual (26) for economic analysis. After discounting, the cost for an injury crash was \$323,888 and a PDO crash was \$6,244.

### **Cost calculations for I-70 Case Study**

$$C_{Equipment} = 17 \text{ Permanent DMS at } \$82,000 \text{ each}/10 \text{ years} * 1 \text{ year work zone duration} \\ = \$139,400$$

The permanent DMS equipment in the study corridor serves multiple purposes, and therefore the costs will not necessarily be borne by the work zone project. However, the equivalent costs during the work zone period are included in this study in order to estimate the benefit-cost ratio of permanent ITS deployments.

$$C_{Operations} = 1 \text{ Office Staff} * \$20.25/\text{hour} * 365 \text{ days} * 8 \text{ hours per work day} = \$59,130$$

$$C_{Setup} = 0 \text{ (since only permanent ITS equipment was used)}$$

$$C_{Total} = C_{Equipment} + C_{Operations} + C_{Setup} = \$198,530$$

### **Cost Calculations for I-44 Case Study**

The actual costs of deploying the smart work zone system used at the I-44 work zone site were provided by MoDOT as \$106,700. The deployment costs include equipment cost and the operating support cost. Although permanent DMS were also present within the study area, their costs were not included since the safety benefits were primarily drawn from the temporary smart work zone system deployed in the project.

### **Benefit Calculations for I-70 Case Study**

The total delay estimates for the AM Peak, Off-peak, and PM Peak were obtained from the calibrated simulation models as discussed earlier. The delay reduction benefits for each period are presented as follows:

#### *AM Peak Benefits*

$$B_{Delay Red.} = (13.37 \text{ hours} - 11.82 \text{ hours}) * \$16.84/\text{hour} * 1.2 * 1.5 * 0.883 + (13.37 \text{ hours} - 11.82 \text{ hours}) * \$18.56/\text{hour} * 0.5 * 1.05 * 0.117 = \$43.25$$

#### *Off-Peak Benefits*

$$B_{Delay Red.} = (2.14 \text{ hours} - 2.08 \text{ hours}) * \$16.84/\text{hour} * 1.2 * 1.5 * 0.883 + (2.14 \text{ hours} - 2.08 \text{ hours}) * \$18.56/\text{hour} * 0.5 * 1.05 * 0.117 = \$1.67$$

### *PM Peak Benefits*

$$B_{Delay Red.} = (73.41 \text{ hours} - 36.13 \text{ hours}) * \$16.84/\text{hour} * 1.2 * 1.5 * 0.883 + (73.41 \text{ hours} - 36.13 \text{ hours}) * \$18.56/\text{hour} * 0.5 * 1.05 * 0.117 = \$1040.32$$

Thus the benefits are composed of the reduction in delay from ITS, the average wage, the total compensation as a percentage of average wage, the vehicle occupancy and the vehicle mix.

The delays for AM and PM peak periods were computed for the entire peak period durations, 2 hours each, whereas the off-peak delays were only computed for 1 hour. Thus, the off-peak benefits were extrapolated for 20 hours. The total daily benefits are then computed as follows.

$$B_{Total} = B_{Delay Red.} = \$43.25 \text{ for AM peak} + \$1.67 \text{ for off-peak} * 20 \text{ hours of off-peak} + \$1040.32 \text{ for PM peak} = \$1,116.97 \text{ per day} * 365 \text{ days} = \$407,694.05$$

The benefits of I-70 case study did not include safety benefits due to insufficient data from the short deployment time frame. It is likely that the estimated benefits would be higher if crash savings could have been quantified.

### **Benefit Calculations for I-44 Case Study**

The benefits resulting from ITS use in I-44 work zone were estimated from the reduction in crash frequency for injury crashes and PDO crashes. These were the only two types of crashes that occurred during the work zone period.

$$B_{Crash Reduction} = 5.6 * \$6,244 + 0.96 * \$323,889 = \$345,900$$

The benefit-cost ratios (b/c) were computed for the two case studies. The I-70 ITS deployment resulted in a cost of \$198,530, a benefit of \$407,694 and a b/c ratio of 2.1 to 1. The I-44 ITS deployment resulted in a cost of \$106,700, a benefit of \$345,900 and a b/c ratio of 3.2 to 1. For the I-70 site one could argue that the equipment cost should not be included, since the permanent ITS already existed at the location. If the equipment costs were ignored and only the operating costs of \$59,130 were included, then the b/c ratio increases to 6.9 to 1. Recall that the I-44 b/c ratio did not include mobility benefits and the I-70 one did not include safety benefits. If a work zone experiences both mobility and safety benefits, then the b/c ratio could be much larger than the ones reported here.

## CONCLUSIONS

A framework for evaluating the effectiveness of ITS deployments in work zones was developed. Four critical site characteristics that may warrant ITS deployment were identified: frequent congestion, high traffic impact at the work zone, availability of alternative routes and over-capacity demand. The framework recommends using one or more of the five uniform performance measures to facilitate comparisons across different ITS studies. These measures are: diversion rate, delay time, queue length, crash frequency, and speed. The monetary benefits and costs of ITS deployment in a work zone are then computed using the performance measure values. The developed framework was illustrated using two case studies, one urban work zone on I-70 and one rural work zone on I-44, in Missouri.

One main recommendation of this study is that state DOTs interested in evaluating the effectiveness of work zone ITS deployments collect data without ITS. This can be accomplished by turning off the ITS equipment for a few days during the work zone deployment. However, agencies might be hesitant to turn off functioning equipment due to liability issues or concerns over the public's expectation of benefiting from such equipment. One possible alternative is to delay the deployment of ITS in the work zone for a few days to collect the 'without ITS' data before turning on ITS. Thus, the without ITS data is collected before the public has experienced the ITS system. But ITS may have provided valuable traveler information during the crucial initial period when drivers are least familiar with the work zone conditions. Therefore, not having ITS in the initial period could also be undesirable.



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## APPENDIX A. COMPREHENSIVE LITERATURE REVIEW

This comprehensive literature review will examine previous research on the effectiveness of ITS equipment in work zones. Many aspects of smart work zones are documented which show what, why, where, and when of ITS deployment, and how the benefits of ITS deployment can be measured. While the following reports provide vital information on work zones, the use of a common procedure for measuring ITS effectiveness is consistently absent.

The following information was extracted from each reviewed article: 1) the characteristics of the work zone ITS deployment, 2) the performance measures (diversion, delay, queues, accident rates, and speeds), 3) the intended benefits to be achieved by the deployment (e.g., increasing traffic diversion, or improving safety), 4) the methodology used and data collected to evaluate the deployment, 5) findings of the evaluation and lessons learned. A tabular format shown in Table A1 will be used to present the results of each article.

**Table A1. Format for Presenting Reviews of Articles in Literature**

<b>Characteristics</b>	<ul style="list-style-type: none"><li>• Location</li><li>• Equipment</li><li>• Details</li></ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"><li>• Diversion, Delay, Queues, Accident rates, and Speeds</li><li>• Details</li></ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"><li>• Increasing Traffic Diversion</li><li>• Improving Safety</li><li>• Other Intended Benefits</li></ul>
<b>Methodology</b>	<ul style="list-style-type: none"><li>• Type of Data</li><li>• Procedure</li></ul>
<b>Findings</b>	<ul style="list-style-type: none"><li>• Results</li><li>• Lessons Learned</li></ul>

### ITS Use to Improve Traffic Operations

Time Prediction System (TIPS) was evaluated by Zwahlen and Russ (2002). The travel times of I-75 were displayed using changeable message signs to influence driving choices. By comparing measured travel times with TIPS estimations of travel times, the accuracy of TIPS could be determined. Estimated travel times came from 5 microwave sensors while measured travel time came from personnel driving through the work zone with recording equipment. The system had an overall accuracy of 88% when one considers that the system rounds the displayed travel times to the nearest 4 mph. The recommendation was to improve the placement of sensors.

**Table A2. Zwahlen and Russ (2002) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-75 near Dayton, Ohio, 13 miles</li> <li>• July to November, 2000</li> <li>• Travel Time Prediction System (TIPS)</li> <li>• 3 changeable message signs (CMS), 5 microwave radar sensors, control center, and radios</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Speeds</li> <li>• Recorded with microwave sensors</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Determine accuracy of TIPS predicted travel times</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Data collected by sensors and sent to control center via radio signals</li> <li>• 119 trial runs to find measured travel time</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• 88% of predicted travel times were within 4 minutes of measured travel time</li> <li>• Maximum error was 18 minutes</li> </ul>

A survey was conducted by Bushman and Berthelot in conjunction with NCDOT (2005). The survey focused on driver perception of portable changeable message signs (PCMS) along the work zone on I-95 in North Carolina. The overall response from the public was very good 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 with highly traveled work zones.

**Table A3. Bushman and Berthelot (2005) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-95 in North Carolina</li> <li>• Travel Messenger System</li> <li>• 3 portable changeable message signs (PCMS), 3 sensors, 3 more message signs on alternative routes, and website</li> <li>• Survey of 333 local residents</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Only survey performed</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Improve safety</li> <li>• Provide information to drivers to promote diversion</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Surveys were mailed out and returned by local residents</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• 90.9% of drivers had seen the PCMS</li> <li>• 42.6% of drivers thought signs were always accurate</li> <li>• 40.5% of drivers were influenced regarding alternative routes</li> <li>• Near 100% for readability</li> <li>• 95.3% recommended continued use of ITS</li> <li>• 93% of drivers do not use the website</li> </ul>

Horowitz and Notbohm (2003) reviewed Intellizone, which provides a warning message on freeways of slowed traffic ahead. If speeds were below 50 mph, detectors average the highway speeds every three minutes and display a 10 mph range of speeds. Below 20 mph, the warning message denotes stopped traffic. Compared to TIPS, Intellizone is cheaper yet detectors are less accurate. It is recommended that multiple detectors accompany a portable message sign

to provide improved accuracy.

**Table A4. Horowitz and Notbohm (2003) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"><li>• US 41 in Green Bay, Wisconsin</li><li>• Intellizone by Highway Information Systems</li><li>• Wireless detectors and portable message signs</li><li>• Data from detectors and Survey</li></ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"><li>• Diversion, Delays, and Speeds</li><li>• Preexisting diversion rates were high</li><li>• Average delay time was around 8.9 minutes</li></ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"><li>• Warn drivers of slowed speeds to increase diversion</li></ul>
<b>Methodology</b>	<ul style="list-style-type: none"><li>• 3 Days of field data collected</li><li>• Detectors average speeds every 3 minutes and display a range of speeds</li></ul>
<b>Findings</b>	<ul style="list-style-type: none"><li>• Drivers were satisfied with speed signs</li><li>• Diversion was high due to driver awareness, not necessarily advisory signs</li><li>• Delay was approximately the same for diverted and non-diverted traffic</li><li>• The posted delay times on the message boards did not match delay times described by drivers</li></ul>

McCoy (2000a) reviewed a Portable Traffic Management System (PTMS), which uses variable message signs to provide details of downstream congestion. If three consecutive vehicles had speeds less than 25 mph, then an alternative route recommendation message was displayed. 73% of the surveyed drivers saw the VMS. The optimum time to view a VMS is considered to be 7 seconds. There was not enough time for drivers to adequately read the interchangeable messages with a 1.5 second time difference. The survey indicated that drivers question the usefulness of VMS if the cause of the delay was missing or an alternative route was not specified.

**Table A5. McCoy (2000a) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"><li>• I-80 in Nebraska between Lincoln and Omaha, speed limit was 55mph</li><li>• PTMS by Brown Traffic Products, Inc.</li><li>• Video Detection, Nu-Metrics NC-97 counters, and variable message signs</li><li>• Survey of 135 drivers</li></ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"><li>• Diversion and Speeds</li><li>• Diversion was calculated using ramp volumes</li><li>• Mean speed, standard deviation, 85<sup>th</sup> percentile speed, 10 mph pace, mean of highest 15<sup>th</sup> percentile speed, and speed compliance were calculated</li></ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"><li>• Increase diversion during congestion</li></ul>
<b>Methodology</b>	<ul style="list-style-type: none"><li>• Data was collected for passenger and larger vehicles</li></ul>
<b>Findings</b>	<ul style="list-style-type: none"><li>• Maximum of 4% diversion</li><li>• Nu-Metrics NC-97 counters malfunctioned so data was unusable</li><li>• No evidence that the system affected speeds</li></ul>

McCoy (2000b) reviewed the ADAPTIR system for using radar sensors and variable message signs (VMS) to advise drivers of congestion at a work zone. Performed on I-80 in Nebraska, four VMSs were used with one increasing the diversion rate by 3%. Speeds were affected by the posted messages; however, there was no effect on forced merges or decreased accident rates. A survey was conducted, which indicated that messages with specific alternative route were preferred, while posted delay times were understood but prone to inaccuracy.

**Table A6. McCoy (2000b) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-80 in Nebraska between Lincoln and Omaha, speed limit was 55mph</li> <li>• Automated Data Acquisition and Processing of Traffic Information in Real-time (ADAPTIR) by Scientex Corporation</li> <li>• Radar sensors with central system control computer with 4 Variable Message Signs and Highway Advisory Radio communications</li> <li>• Survey of 264 drivers</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion, Delays, Accident Rates, and Speeds</li> <li>• Diversion was calculated using ramp volumes</li> <li>• Mean speed, standard deviation, 85<sup>th</sup> percentile speed, 10mph pace, mean of highest 15<sup>th</sup> percentile speed, and speed compliance were calculated</li> <li>• Also recorded were forced merges, within 500ft of taper</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Warn drivers of slowed speeds and delays to increase safety</li> <li>• Promote increased diversion</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Roadside remote stations collect data every 4 minutes during peak volume, and 8 minutes otherwise</li> <li>• Speeds and lane geometry recorded during summer of 1999</li> <li>• Forced merges were measured at the work zone taper</li> <li>• Diversion volumes recorded</li> <li>• Accident rate examined with regression model</li> <li>• Autoscope, automated video detection, applied to video to process speeds</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Measuring HAR effectiveness was outside scope of work</li> <li>• There is no evidence that ADAPTIR affected lane distribution or forced merges due to low volumes</li> <li>• Congestion density was found to be &gt; 25 vehicles/mile</li> <li>• One VMS caused 3% diversion while another was not significant</li> <li>• Accident rates were higher due to work zone presence</li> </ul>

A study performed on I-680 in Nebraska reviewed a Work Zone Speed Advisory System (Pesti et al., 2002). Video detection recorded speeds and volumes. Speeds slower than 55 mph were posted on the changeable message signs. When speeds dropped below 15 mph, Nebraska Department of Roads (NDOR) was notified of a possible incident. Due to the low levels of demand in the area, the system was inefficient in decreasing speeds or increasing diversion. Only 35 people responded to the survey. The website usage was considered a success as well as the accuracy of the changeable message signs.

**Table A7. Pesti et al. (2002) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-680 in Nebraska, work zone speed limit was 55mph</li> <li>• Work Zone Speed Advisory System (WZSAS)</li> <li>• 2 video detectors, control system at NDOR, 2 changeable message signs (CMS), and traffic website</li> <li>• Online survey conducted, 35 responses</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion and Speeds</li> <li>• Accuracy of speeds was established for the system</li> <li>• Change in demand was also a performance measure</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Warn drivers of slowed speeds</li> <li>• Decrease traffic demand on I-680</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Video data collected every minute and sent to the NDOR control building</li> <li>• Recorded two 4-week periods in winter</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• High number of diversion routes also let other traffic onto highway without seeing messages</li> <li>• High levels of demand occurred about 15 minutes per day</li> <li>• The system did not significantly decrease speeds, increase diversion, or decrease demand</li> </ul>

TIPS was evaluated by Horowitz et al. (2003). In this study, diversion and delay were focused on as the performance measures. The portable changeable message signs (PCMS) displayed delay times. To increase driver diversion, static signs were used which decreased the amount of messages to be displayed on the PCMS. High volumes resulted in longer delay times displayed, but no direct correlation can be made of TIPS effect on diversion. A recommendation would be to apply a simulation to find the benefits of TIPS.

**Table A8. Horowitz et al. (2003) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-94 in Milwaukee, Wisconsin, 12 miles</li> <li>• Travel Time Prediction System (TIPS) \$179,000</li> <li>• 4 portable changeable message signs (PCMS), 5 microwave detectors, alternative route static signs, and base station</li> <li>• 65mph reduced to 55mph for work zone</li> <li>• Urban</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion and Delay</li> <li>• Only delay messages were displayed</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Reduce accident rates by providing warning messages of traffic ahead</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Volume recorded from detectors or tube counters for alternative routes every 15 minutes</li> <li>• TIPS recorded data every 30 seconds</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Diversion between 7-10%</li> <li>• Maximum delay was 32 minutes</li> </ul>

The Travel Time Prediction System (TIPS) uses changeable message signs which show work zone travel times to drivers (Notbohm et al., 2001). By displaying travel times, TIPS

promoted diversion rates. There were only two scenarios where travel time exceeded 40 minutes. In this case, there was no evidence that the displayed travel times affected traffic diversion or safety. A major problem was the message signs rounding travel times to the nearest four minutes. The recommendation was to not rounding travel time estimates for message signs.

**Table A9. Notbohm et al. (2001) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-94 in Milwaukee, Wisconsin</li> <li>• Travel Time Prediction System (TIPS)</li> <li>• 4 changeable message signs (CMS) and 5 roadside microwave radar sensors</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion, Accident rates, and Speeds</li> <li>• Two evaluation phases to find volume of diverted traffic due to TIPS, tube counters used</li> <li>• Accidents were compared to opposite side of freeway</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Provide travel times to drivers who would choose to divert or not</li> <li>• Reduce rear-end collisions</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Data collected in June to August 2001</li> <li>• Data recorded every 30 seconds</li> <li>• 210 measured travel times where compared to predicted value from TIPS</li> <li>• Time messages were displayed for at least 3 minutes</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• TIPS travel times vary an average of 2-3 minutes from field recorded values</li> <li>• No evidence of significantly increased safety, low number of crashes</li> <li>• Injury accident frequency was lower during use of TIPS, deemed inconclusive</li> <li>• Diversion ranged from 7-10%</li> <li>• Diversion with or without TIPS is about equal</li> </ul>

Tudor et al. (2003) compared ADAPTIR and CHIPS using work zones on I-40 in Arkansas. The focus was to reduce queue lengths 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, although more expensive, had a better accuracy of the messages displayed on the changeable message signs. Recommendations were made to display queue lengths rather than delay times.

**Table A10. Tudor et al. (2003) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"><li>• I-40 in Arkansas</li><li>• Automated Data Acquisition and Processing of Traffic Information in Real-time (ADAPTIR) by The Scientex Corporation \$322,500</li><li>• 5 changeable message signs (CMS), highway advisory radio (HAR), 5 Doppler radar sensors, and radio central control</li><li>• Computerized Highway Information Processing System (CHIPS) \$490,000</li><li>• 2 changeable message signs (CMS), highway advisory radio (HAR), 15 traffic sensors, and radio central control</li></ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"><li>• Queuing and Accident Rate</li><li>• Accident rates compared to a similar location</li></ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"><li>• Reduce rear-end collisions by warning drivers about queues</li></ul>
<b>Methodology</b>	<ul style="list-style-type: none"><li>• Data collected by sensors and sent to control station</li><li>• ADAPTIR had a 10 minute interval which was deemed inefficient while CHIPS had a 5.8 minute interval</li></ul>
<b>Findings</b>	<ul style="list-style-type: none"><li>• ADAPTIR messages were made more generic because estimates were off</li><li>• CHIPS had communication problems due to equipment but still had a 90% accuracy of delay time messages</li><li>• ADAPTIR had a longer response time then CHIPS</li></ul>

Chu et al. (2005) performed an evaluation of the CHIPS which is an automated work zone information system. The study was performed on I-5 in California and included diversion, delay, queuing, and speed performance measures. The portable message signs were updated when a queue formed. The messages suggested a specific alternative route. Due to the high volume of traffic for the holiday weekend, 5.3 to 8.7% of the mainline vehicles diverted therefore saving 3 minutes off their delay time. A postcard survey was used to identify the utility of the message signs. 78% of exiting vehicles diverted onto alternative routes due to traffic conditions while only 36% responded that CHIPS improved safety.



**Table A11. Chu et al. (2005) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-5 in Santa Clarita in Southern California</li> <li>• 1.3 miles in length</li> <li>• 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</li> <li>• Survey used</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion, Delay, Queue length, and Speed</li> <li>• Diversion rate is calculated using the change in the diverting volume over the total volume</li> <li>• Maximum delay was 33 minutes</li> <li>• The detectable maximum queue length is 2.4 miles</li> <li>• Mean speed and speed variance were used in safety analysis</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Evaluate the efficiency of the implemented systems</li> <li>• Determine if issues, such as calibration, power failure, or inapt algorithms, decrease efficiency</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Command center communicates with the trailers using wireless antenna and radio frequencies</li> <li>• Only weekend and holiday data collected to ensure high demand</li> <li>• 100 surveys responses were obtained</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• 78% of exiting vehicles diverted due to traffic conditions</li> <li>• Only 36% responded that CHIPS improved safety</li> <li>• 5.3-8.7 % diversion rates therefore around 3 minutes were saved from delay time</li> </ul>

The Federal Highway Administration (2008) provided a helpful review of ITS benefits in work zones in a report following the earlier 2002 study. There were five key hypotheses for the report which were that the ITS information will be timely and accurate, ITS will divert traffic during congestion, ITS will decrease delay, ITS will decrease congestion, and ITS will improve safety. Three of the results of the field studies are as follows: In Washington, D.C., there was a 52% reduction in mainline volume during congestion due to ITS. In Waco, TX, there was an average of 10% diversion of traffic during congestion due to ITS with a 28% maximum diversion. In Kalamazoo, MI, the implemented Dynamic Lane Merge system, flashing lights on signs which denote when to merge early, reduced forced merges by a factor of seven and dangerous merges by a factor of three. More results are listed below. Lessons learned include having enough time to allow instruction of construction leadership, set up, testing, right-of-way procurement, and recording of conditions prior to construction, agencies considering ITS should be aware of the need for system maintenance and the increased impact on alternate routes, and deploying ITS only when traffic demand is adequate.

FHWA made several recommendations on the use of ITS which are useful for this study. When flashers are on at a lane closure, last-minute merges decrease. Using appropriate messages in congested traffic increases diversion rates and allows better management of incidents at a work zone. Surveyed drivers felt that messages concerning stopped traffic ahead are helpful and add to the safety of work zones. The use of ITS may not decrease delays for low volumes because drivers show greater compliance with speed limits when ITS is used.

**Table A12. Federal Highway Administration (2008) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• DC-295 in Washington, D.C., urban</li> <li>• November 2006 to August 2007</li> <li>• Real-Time Work Zone System (RTWS)</li> <li>• 8 traffic sensors, 13 DMS, 2 remote traffic microwave sensors, 3 pagers, and 2 cameras</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion and Delay</li> <li>• 52% average diversion</li> <li>• Diverging messages work best during congested traffic</li> <li>• Holiday weekends increase the diversion rates</li> <li>• Specific delay times can better aid driver choices</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Reduce congestion</li> <li>• Provide travel information</li> <li>• Increase public confidence in ITS</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Traffic Base processed data, compared with construction schedule</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Maximum occurring diversion rate of 90%, average of 52%</li> <li>• Managing reoccurring congestion combined with work zones is possible</li> </ul>
<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-35 South of Waco, Hillsboro, Texas</li> <li>• October 2006 to February 2007</li> <li>• 6 microwave detection trailers, 6 message signs, 3 cameras, internet website, and system software</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion and Queues</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Reduce congestion</li> <li>• Provide travel information</li> <li>• Determine public confidence in ITS</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Traffic Base processed data, staff compared with camera views</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Average diversion rate of 10%</li> <li>• The agency in charge of data should coordinate equipment early and communicate to construction personnel early</li> </ul>
<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-131 in Kalamazoo, Michigan</li> <li>• September to October 2004</li> <li>• Dynamic Lane Merge (DLM) System</li> <li>• 5 trailers spread out by 1500 feet with lighted no passing signs</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Delay and Speeds</li> <li>• Early merge systems do not always mean less delays, but safety is improved since late merges are decreased</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Reduce dangerous merges</li> <li>• Determine effects on safety and mobility</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Time trial runs performed</li> <li>• Count data collected by staff in the field</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Dynamic Lane Merge (DLM) system works in reducing late merges</li> <li>• Evidence inconclusive for decreased delays</li> <li>• Communicate with the police department early to avoid additional variables in data</li> </ul>

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-30 Little Rock to Benton, Arkansas</li> <li>• May to June 2004</li> <li>• Automated Work Zone Information System (AWIS)</li> <li>• 47 vehicle detector sensors, 4 radio transmitters, 15 DMS, 8 stationary video, HAR, and internet website</li> <li>• Survey</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Delay and Crashes</li> <li>• Only 1/3 of drivers feel less bothered by construction when delay times are given</li> <li>• Accident reports only available in hard copies so no analysis is provided</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Improving Safety</li> <li>• Advise public on trip planning</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Data collected and advisory messages displayed on DMS and website, HAR reported traffic</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• 49% drivers agree that system works regarding safety</li> <li>• 95% drivers use DMS, 24% for HAR, and 5% for website</li> <li>• Portable closed circuit video was a hindrance in the work zone</li> </ul>
<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-40 Winston-Salem, North Carolina, rural</li> <li>• 10 DMS, 10 traffic sensors, and internet website</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion and Delay</li> <li>• Alternative routes should be accessible and able to handle increased traffic flow</li> <li>• Lane drops and slow-moving work zone vehicles both cause delays</li> <li>• Multiple delay messages should remain consistent until delay is gone</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Reduce congestion</li> <li>• Advise drivers to diverge in real-time</li> <li>• Increase public confidence in ITS</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Traffic volumes and speeds, historical accident data, and construction schedules used</li> <li>• Computers automatically updated DMS and website</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• The volume was never past the threshold value to activate the ITS system</li> <li>• Agencies should evaluate data output to see if field adjustments are necessary</li> </ul>

Benekohal, Avrenli, and Ramezani (2009) studied how ITS, specifically speed photo enforcement (SPE), can reduce speed thus reducing probability of rear end collisions due to speed differentials. According to their research, the type of ITS equipment plays a large role in determining the driver's preferred speed through work zones. When one considers the limited space of a work zone combined with the presence of workers and recording sensors, the speeds are significantly reduced. The authors proceeded to find the speed-flow relationship to accurately measure the road capacity in a work zone. By estimating capacity, the diversion rates and overall traffic flow characteristics could be reasonably determined thus revealing the effects of ITS.

**Table A13. Benekohal, Avrenli, and Ramezani (2009) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"><li>• I-64 in Illinois near St Louis, I-55 in Illinois near Chicago, rural</li><li>• June and July 2007</li><li>• Speed photo enforcement (SPE) van and detectors</li><li>• Only off-peak hours recorded, all 55 mph</li></ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"><li>• Speeds</li><li>• Reduce speeds mean reduced capacity</li></ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"><li>• Find speed-reducing effects of SPE</li></ul>
<b>Methodology</b>	<ul style="list-style-type: none"><li>• Base data without speed enforcement vs. SPE data</li><li>• 2 Data sets near St. Louis and 1 near Chicago</li><li>• Data collected several hundred feet downstream of the SPE van</li><li>• Free-flow vehicles only</li></ul>
<b>Findings</b>	<ul style="list-style-type: none"><li>• Speed of 50 mph means a reduction of 4.5 mph using SPE</li><li>• Speed of 65 mph means a reduction of 8.4 mph using SPE</li></ul>

In a similar paper on ITS equipment, Chan (2009) performed a field study of four types of Automated Speed Enforcement (AES) equipment and made recommendations for deployment. The four types were 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 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 recommendations include using devices which use redundant measurements, using tracking radar equipment instead of conventional radar, and accounting for the natural errors which occur when using radar.

**Table A14. Chan (2009) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"><li>• State Highway SR-12 in Northern California</li><li>• Rural, mostly 2 lane highway, 55 mph</li><li>• 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 Technology</li><li>• Control was SR-12 Caltrans Traffic Station</li></ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"><li>• Accidents and Speeds</li><li>• Speeding caused most accidents for location historically</li><li>• Altered lanes and poor visibility add to speeding risk</li></ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"><li>• Compare ASE Equipment</li></ul>
<b>Methodology</b>	<ul style="list-style-type: none"><li>• Historical accident data (2002-2006), Surface traffic sensors counts, speeds, and vehicle class distribution data (2007), and ASE equipment data (2008)</li><li>• RWASS and EVT-300 were roadside, Trans-Q was roadside mounted on a pole angled at 45° towards downstream, and 4 NC-200s were dispersed on the middle of near side lane</li></ul>
<b>Findings</b>	<ul style="list-style-type: none"><li>• SR-12 Caltrans Traffic Station, most reliable</li><li>• RWASS, underestimates vehicle count due to low position</li><li>• EVT-300, model out-of-date so it was used to compare data</li><li>• NC-200, closest results to control, not all positions credible</li><li>• Trans-Q, underestimates speeds</li><li>• Radar has natural errors, use redundant measurements, and use tracking radar equipment</li></ul>

Jackson's (2010) report on "Dynamic Work Zone Traffic Management" explained how to determine work zone scheduling on a highway. Threshold values are set depending on the construction site and maximum free flow characteristics. When volumes are higher than the site specific threshold, lanes should not be closed. By recording travel times and speed, advance warning systems associated with smart work zones can be updated to increase driver awareness.

**Table A15. Jackson (2010) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• State of Oregon</li> <li>• Bridge construction, primary routes were broken into segments</li> <li>• Side-fire radar</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Delay, Queue, Crashes, and Speeds</li> <li>• Define acceptable and not acceptable delays and build strategies based on those values</li> <li>• Queue length measured using side-fire radar</li> <li>• Speed and volume data can identify queues</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Preserve safety</li> <li>• Restrict lane closure hours</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Radar equipment recorded volumes and speeds for 12 months</li> <li>• Free-flow maximum threshold was determined</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Construction times linked to ITS system provides less delay and greater safety</li> </ul>

Edara et al. (2011) performed a study of dynamic message signs (DMS) effects on rural roadways. Cameras recorded changes in volumes due to a bridge closure, and VISSIM simulation calculated the diversion rates. Resulting benefits for three days of DMS usage ranged from \$5,163 to \$55,929 with an average of \$21,365. The accident rates performance measure was not used in the analysis since necessary details were not available from the data. A survey showed that the public, especially commercial truck drivers, use the DMS, and the messages do promote diversion and speed reductions.

**Table A16. Edara et al. (2011) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-55 in southeast Missouri, 2 locations</li> <li>• I-57 Bridge fully closed for 3 days</li> <li>• One site had a permanent dynamic message sign (DMS) and the other had a portable changeable message sign (PCMS)</li> <li>• 2 cameras, DMS, static signs, and VISSIM simulation</li> <li>• Survey of 198 drivers</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion, Accident rates, and Speed</li> <li>• Full route diversion</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Divert traffic by use of DMS</li> <li>• Determine driver perception of DMS</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Before, during, and after data collected and compared</li> <li>• Accident rates for the one year of data with DMS compared to 5 years without</li> <li>• 2 cameras recorded speeds</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Accident rates increased for the one year of data with DMS</li> <li>• 94% of drivers followed directions displayed on DMS</li> <li>• 98% of truck drivers followed directions</li> <li>• 41% of drivers only receive traffic details from DMS</li> <li>• 3.6 and 1.25 mph speed reductions observed</li> </ul>

Fontaine and Edara (2007) assessed the benefits of work zones using simulations to determine impacts of smart work zones (SWZ). The benefit to cost ratio increases with increasing congestion; however, the initial costs are higher than the benefits for scenarios with a short timeframe and a peak volume greater than the capacity of the road. Furthermore, the study supported 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.

**Table A17. Fontaine and Edara (2007) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• Simulated location for 24 hour period</li> <li>• VISSIM simulation software</li> <li>• 8-mile mainline route, 65 mph, one alternative route</li> <li>• Rural route used since urban drivers could have many accessible alternative routes and could be more familiar with seeking alternative routes in the area</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion, Delay, and Speeds</li> <li>• Diversion ranges from 4 to 20% but depends on volume</li> <li>• Diversions increase when an alternative route is clearly identified rather than identifying slower speed ahead</li> <li>• Displaying diversion routes is more useful than displaying delay times since drivers are likely to complain when delay times are incorrect</li> <li>• Effect of congestion may have larger impact on speeds than speed advisory signs</li> <li>• Lower speeds on alternative routes can decrease system performance if too many drivers divert</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Benefits exceed costs when speed advisory messages or travel time or delay messages are implemented</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Simulation data, Washington, D.C. traffic volume data</li> <li>• Use of peak hour volume, diversion %, alternate route speed, and daily travel time savings</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Table results show the number of days until the benefit/cost is <math>&gt; 1.0</math> or benefit/cost could be found given a specific number of days</li> <li>• Use of a SWZ may result in a higher benefits than cost depending on said variables</li> </ul>

In regards to why simulation is used for this study, Kushto and Schofer (2011) used simulation to measure the impacts of construction zones on drivers regarding delay. By using VISSIM, they simulated a 1.1 mile stretch of freeway with a 0.5 mile work zone using input data from the Chicago area. Diversion routes were implemented on several but not all scenarios. Measuring performance on an individual, disaggregate basis can lead to new conclusions about work zone management. One of the results found was that flow can recover faster by lowering the frequency and length of interruptions compared to just working during the off-peak period. Work zones have the lowest delays when construction interruptions are minimized compared to adding a diversion route. Because work zones have a large affect on individual drivers and delay times, this simulation approach can aid in providing guidance on when to apply ITS better manage construction practices.



Garber and Ehrhart (2000) developed mathematical equations to find accident rates. The equation incorporates average speed, speed variance, geometrics of the roadway, and traffic volumes. The required data to find the accident rate included mean speed, standard deviation of speed, lane width, shoulder width, and lane flows. Multivariate ratio of polynomials outperformed the other deterministic models which were multiple linear regression and robust regression. A recommendation was made to apply stochastic models to accident rate equations since accidents occur randomly.

**Table A18. Garber and Ehrhart (2000) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• 52 locations in Virginia, 55 mph or 65 mph freeways</li> <li>• Model system, Number Crunching Statistical Systems</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Accident rates and Speeds</li> <li>• Accident records obtained from North Carolina DMV</li> <li>• Average speeds and standard deviation were used</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Provide best mathematical approach to link accident rates and lane geometrics</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Data collected from speed monitor stations and police records</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Multivariate ratio of polynomials had best results</li> <li>• Statistical evidence that if speed standard deviation increases, the accident rate increases</li> <li>• Slight increase in lane flow decreases accident rates</li> <li>• Urban freeways with flow ranging from 1000 vph and 1200 vph have lowest accident rates</li> </ul>

Sun et al. (2011) evaluated the use of sequential lights during a nighttime work zone. Taper cones have lights which flash in sequential order to aid in guiding drivers into the open lane. Lower speeds resulted from sequential light deployment. Overall, more merges occurred farther from the work zone taper; however, the area closest to the work zone taper saw an increase of merges compared to when sequential lights were not used. The benefit/cost ratio value for sequential lights was between 5 to 1 and 10 to 1.

**Table A19. Sun et al. (2011) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-70 in Missouri, 3 sites, 60mph</li> <li>• Sequential Lights, cameras, and a radar gun</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Speeds</li> <li>• Merging locations determined the safety value</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Determine benefits and costs of sequential lights</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Data collected by cameras</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Mean speed reduced 2.21mph and 85<sup>th</sup> percentile speed reduced by 1mph</li> <li>• More effective towards rural areas and commercial trucks</li> </ul>

A highway construction project with Bluetooth readers and portable changeable message signs were evaluated by Brydia, Poe, Voigt, and Ullman (2013). Construction of I-35 was



supplemented with ITS for 5 years. A survey was distributed before construction began to identify the preferred ITS by the local residents. The results showed that drivers prefer to have images of the freeway or to know the current speeds of the road before they travel. End of queue monitoring and identifying alternative routes were key to meeting the objectives of minimizing traffic congestion. Bluetooth stations were distributed along the highway. Bluetooth range is 5-8 miles for a rural setting and 2-3 miles for an urban setting. The study concluded that lane closure information is 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.

**Table A20. Brydia, Poe, Voigt, and Ullman (2013) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-35 from San Antonio to Hillsboro</li> <li>• 21 portable changeable message signs, Bluetooth readers, Wavetronix traffic counters and Closed Circuit Television</li> <li>• Lane Addition</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion, Delay, Queues, and Speeds</li> <li>• Performance measures monitored by Waco District Public Information Officers</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Track traffic congestion</li> <li>• Improve communications to drivers</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Bluetooth data</li> <li>• Anonymous Wireless Address Matching stations monitored travel time</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Maximum queue length exceeded 3.5 miles during an incident</li> <li>• Speeds reduced by 40 mph during an incident</li> <li>• Traffic recovery took 3.5 hours following an incident</li> <li>• Bluetooth showed that lane closures did not significantly decrease speeds</li> </ul>

The effectiveness of portable changeable message signs with graphics was evaluated by Huang and Bai (2013). Graphics are quicker to interpret by drivers and cause a greater reduced mean speed. The chosen locations in Kansas were rural, two-lane highways. These sites were ideal because a flagger, or, in this case, an image of a flagger, was necessary. Graphics of flaggers and construction workers were compared to messages with only text and a combination of graphics and text. Text-Graphics were then compared to two alternative graphics. Graphics reduced mean speeds between 13-17%.

**Table A21. Huang and Bai (2013) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• Phase 1, K-13 in Kansas, 65mph</li> <li>• Phase 2, US-75 between Burlington, KS and I-35, 65mph</li> <li>• 5 JAMAR TRAX Apollyon speed sensors and portable changeable message signs</li> <li>• Rural, two lane needed for image of flagger to be evaluated</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Speeds</li> <li>• Speed reduction measured using speed sensors</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Improve changeable message sign displays</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Speed Data</li> <li>• Gap time between sensors were recorded</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Phase 1</li> <li>• 8 mph reduction, Text only = 13%</li> <li>• 6 mph reduction, Text and Graphic = 10%</li> <li>• 11 mph reduction, Graphic only = 17%</li> <li>• Phase 2</li> <li>• 8 mph reduction, Text-Graphic 1 = 13%</li> <li>• 8 mph reduction, Text-Graphic 2 = 13%</li> <li>• 7 mph reduction, Text-Graphic original = 11%</li> <li>• Graphics are significantly more effective than using only text on portable changeable message signs</li> </ul>

McCanna (2013) presented on work zone ITS at the Transportation Research Board conference. From 2005-2011, the State of Oregon replaced 365 bridges which significantly decreased highway mobility. Oregon followed the example of other State's Department of Transportation by applying ITS in work zones starting in 2010. ODOT developed a Qualified Products List allowing them to consistently compare vendor's equipment. Oregon will evaluate their fourth vendor starting in summer of 2013. Recommendations include increasing law enforcement at construction zones in an overtime program and replacing out-dated signs as soon as possible.

**Table A22. McCanna (2013) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• 3 ITS vendor demonstrations in State of Oregon</li> <li>• 4<sup>th</sup> vendor demo to be on I-84 at US 97 interchange</li> <li>• 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</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Diversion, Delays, Queues, Accident rates, and Speeds</li> <li>• Drivers warned of downstream conditions using message signs</li> <li>• Overall reduction in delay</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Improve traffic safety</li> <li>• Optimize traffic management</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Data collected on construction sites</li> <li>• System communicated traffic conditions to DOT personnel</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Traffic communications need to be specific about either traffic operations or safety</li> <li>• Products need to be tested on large construction project with a long-term duration</li> </ul>

Davis and Labrum (2013) presented on management of traffic at the Transportation Research Board conference. Using 10 Bluetooth units with GPS and real-time monitoring, speeds and travel times were recorded. The project overcame challenges including slow communication of alerts and multiple facilities closing at the same time. Recommendations include a two week test period for equipment and to maintain a high level of communication between the DOT and the contractor.

**Table A23. Davis and Labrum (2013) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• 7800 South and Bangerter, Salt Lake City, Utah</li> <li>• ICone radar units, Sensys sensor network, and Traffax Inc. Bluetooth units were investigated</li> <li>• 10 Bluetooth units (4 solar and 6 battery powered)</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Speeds</li> <li>• Speeds in mph monitored at the Bluetooth positions</li> <li>• Current, predicted, and historical travel times monitored as well</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Provide real-time data to maximize DOT efforts</li> <li>• Increase the speed of construction projects</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• 48 traffic movements were monitored</li> <li>• 3 alert levels occurred: Warning, Tier 1 with a penalty, and Tier 2 with a second penalty</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Monitor only the critical movements</li> <li>• Signal timing must make model timing for micro-simulation</li> <li>• Both peak and off-peak hours needed for micro-simulation</li> </ul>

## ITS Use to Improve Traffic Safety

The number of reports on ITS improving traffic operations outnumbers the reports on improving safety. Safety is equally important as operations in smart work zones, but safety can be a challenge to measure. Safety depends on communications. The main performance measures concerning safety are accident rates and speed. Accident rates can be determined by historical data, lane change distributions, forced merges, and mathematical models. One report mentioned a maximum reduction in accidents by 10%. Speeds can be measured using mean, standard deviation, 85<sup>th</sup> percentile, mean of highest 15<sup>th</sup> percentile, 10 mph pace, and speed compliance. One report showed the maximum speed reduction was 8.4 mph and others had an average speed reduction of 2.21 mph and 7 mph. Reduced speeds mean reduced capacity but increases safety. Low volumes usually mean greater compliance with speed limits.

King et al. (2004) evaluated IntelliZone for its use in measuring safety. Only 2 variable message signs (VMS) were used to display traffic warning to drivers ahead of the work zone. Performance measures included speed averages and variances which were gathered from detectors. 2 of 20 days had congested data. Without a lane closure, the congestion never reached a point where the VMS messages were displayed. Speeds were effectively reduced by about 7 mph. The survey showed that more drivers understand the meaning of the messages on VMS even if the entire message was not read. Recommendations were to use more cameras and VMS for similar studies.

**Table A24. King et al. (2004) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"><li>• I-70 in Wentzville, Missouri</li><li>• IntelliZone</li><li>• 2 variable message signs (VMS), 6 magnetic and video detectors, and a mobile command unit</li><li>• Survey of 101 drivers; 62 face-to-face and 39 returned by mail</li></ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"><li>• Speeds</li><li>• Mean speed and speed variance were the performance measures</li><li>• Mean headway and vehicle conflict data were collected but not analyzed</li></ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"><li>• Improve safety on freeway work zones</li></ul>
<b>Methodology</b>	<ul style="list-style-type: none"><li>• Speed, volume, and headway data collected by detectors and sent wirelessly to command unit</li><li>• Due to sight restrictions of the video cameras, conflict data was limited</li><li>• Data collected before and after system deployment</li></ul>
<b>Findings</b>	<ul style="list-style-type: none"><li>• From survey, 63% slowed down and 3.6% diverted due to VMS</li><li>• On average, speeds reduced by 7 mph</li></ul>

The Federal Highway Administration (2002) preformed a study on ITS in work zones to provide an overall guide for smart work zones in four case studies and the lessons learned from those experiences. ITS is normally used for managing traffic which involves providing real-time messages to the public, improving accident response time, tracking behavior changes, and even enforcement of traffic law. The main operations of the studies were to detect traffic congestion and send messages to the public via dynamic message signs along the road, the radio, and/or the internet. From the four case studies, the lessons learned were to test ITS equipment for reliability

in processing data and sending out appropriate messages, increase awareness of the public about the work zone traffic plan, allow portability of equipment if the work zone consistently moves, allow associated staff to have discretion on what information is displayed because an automated system could malfunction, and provide ease of access to equipment because of a need for a reset, realignment, or manual override.

**Table A25. Federal Highway Administration (2002) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-55 Springfield, Illinois</li> <li>• Automated Portable Real-Time Traffic Control System (RTTCS)</li> <li>• 17 DMS, 8 sensors, 4 closed circuit television (CCTV) cameras, Internet website</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Queue and Speeds</li> <li>• Queue lengths begin alert system</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Manage and monitor traffic</li> <li>• Provide travel information</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Data collected wirelessly, data processed by traffic station</li> <li>• Volume and speed calculated</li> <li>• Advisory messages displayed on DMS and website</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• No significant queues</li> <li>• Communicate well between engineers, construction personnel, and emergency response</li> </ul>
<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-496 Lansing, Michigan</li> <li>• Fully closed highway sections, all traffic was diverted</li> <li>• Temporary Traffic Management System (TTMS)</li> <li>• 17 cameras, 12 DMSs, six queue detectors, and National Sign and Signal's 'ITSworkzone' software, Internet website, Management Staff</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Queue and Speeds</li> <li>• Advanced warning of queue can reduce back of queue crashes</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Manage and monitor traffic</li> <li>• Provide travel information</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Data collected wirelessly, data processed by software at Construction Traffic Management Center (CTMC)</li> <li>• Staff managed queues based on CCTV and Advisory messages displayed on DMS and website</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Advance information provided to drivers, police, and emergency response</li> <li>• Clearly define capabilities of the vendor in the beginning</li> </ul>
<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-40/I-25 Albuquerque, New Mexico</li> <li>• Intersection reconstruction, permanent equipment installed</li> <li>• 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</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Delay</li> <li>• Measure reduction of incident clearance time</li> <li>• To reduce ITS set up time one could use the Advanced Cone Machine and the Quick Change Moveable Barrier</li> </ul>

<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Manage and monitor traffic</li> <li>• Manage incidents</li> <li>• Increase Safety</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Staff managed queues based on CCTV and Advisory messages displayed on DMS and website, HAR reported traffic</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Incident clearance time reduced from 45 minutes to 25 minutes</li> <li>• Portability and access to ITS equipment is necessary</li> <li>• 60% of survey agreed with the data accuracy</li> </ul>
<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-40 West Memphis, Arkansas</li> <li>• Central location for travel and surrounding bridges</li> <li>• Automated Work Zone Information System (AWIS)</li> <li>• 12 queue detectors, 5 remotely controlled DMS, 3 highway advisory radio units, 5 pagers, and an email alert system</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Delay, Queue, and Speeds</li> <li>• Length of queue is easier to measure than delay in minutes</li> <li>• Advanced warning of queue can reduce back of queue crashes</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Manage and monitor traffic</li> <li>• Provide travel information</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Before and After data used</li> <li>• Data collected wirelessly, data processed by traffic station</li> <li>• Advisory messages displayed on DMS while HAR reported traffic</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Delay decreased</li> <li>• Faster response time to incidents</li> <li>• Needed to allow for an override to the system</li> </ul>

Bushman and Berthelot (2004) analyzed accident rates in smart work zones. In the study, trailer sensors recorded speeds and volumes which triggered messages on the portable changeable message signs. Accident rates were the main performance measure. The days when ITS was used was compared to a control, i.e. the days when the system was down. There were low numbers of accidents when ITS was not in operation. Because of the short amount of time and low number of accidents when ITS was not in operation, no significant conclusions could be made. Recommendations were to have more days to record accidents with a balanced amount of with and without ITS deployment.

**Table A26. Bushman and Berthelot (2004) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-95 near Rocky Mount in North Carolina</li> <li>• April to November, 2003</li> <li>• Portable changeable message signs (PCMS), static signs, and 3 sensor trailers</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Accident Rates</li> <li>• Accident records obtained from North Carolina DMV</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Reduce accident rates by providing warning messages of traffic ahead</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Data collected by trailers and number of accidents recorded</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• 22 accidents total</li> <li>• Due to short amount of time the work zone did not have ITS, no conclusions can be made about accident reduction</li> </ul>

McCoy and Pesti (2002) evaluated the effect of portable changeable message signs (PCMS) on reducing speeds. The field study was at the same location as the other I-80 ITS deployments. 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. A survey was likewise performed. 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 congestions, the speed was only slightly reduced. The survey demonstrated driver confusion regarding messages displayed.

**Table A27. McCoy and Pesti (2002) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-80 in Nebraska between Lincoln and Omaha, speed limit was 55mph, recorded for 16 days</li> <li>• Automated Data Acquisition and Processing of Traffic Information in Real-time (ADAPTIR) by Scientex Corporation</li> <li>• 3 portable changeable message signs (PCMS), radar sensors, cameras, and arrow board</li> <li>• 264 drivers surveyed</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Speeds</li> <li>• Speeds recorded using cameras</li> <li>• Mean speed, 85th percentile speed, and average of speeds higher than 85 percent determined the speed reduction</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Warn drivers to reduce speeds</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Data was recorded every 8 minutes and 4 minute during the peak</li> <li>• Reduced speeds of 10mph triggered messages</li> <li>• Data collected before, during, and after ADAPTIR was used, yet no congestion occurred</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Slightly reduced speeds during high density</li> <li>• Not as efficient due to low traffic volumes</li> <li>• PCMS signs would be more efficient if separation was less</li> </ul>

Maze, Kamyab, and Schrock (2000) performed a survey with multiple variables to control vehicle speeds in work zones. The preferences concerning strategies to decrease speeds of each U.S. state are listed providing a good basis for comparison. Consequently, in Missouri, there is no information provided in the survey for the effectiveness of the 12 strategies, i.e. 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 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 have an existing speed limit of 55-65mph with an advanced speed limit of 35mph. For all other scenarios, including multiple lanes with or without concrete barriers, lane shifts, or a median crossover, the existing speed limit is 65-70mph for rural and 60mph for urban roads with an advanced speed limit reduction of 10-20mph. 10mph is used in protected areas with concrete barriers or other safety devices while 20mph is used for completely unprotected areas. The lowest reduced speed in Missouri is 35mph.



**Table A28. Maze, Kamyab, and Schrock (2000) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"><li>• Survey</li></ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"><li>• Diversion, Delay, and Speeds</li><li>• State of Tennessee recommends that alternative routes should have speeds at least 10mph below normal speeds</li><li>• Trucks get advanced warning of events from Wizard work zone alert and information radio by TRAFCON Industries, Inc.</li><li>• Reducing speed variance could reduce number of crashes</li><li>• Signs and optical speed bars do not greatly affect driving speed</li><li>• Narrowing lanes can reduce speeds</li><li>• Drone radar, rumble strips, and speed monitoring displays reduce speeds slightly</li></ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"><li>• Increase safety and manage speeds</li></ul>
<b>Methodology</b>	<ul style="list-style-type: none"><li>• Compare state practices</li></ul>
<b>Findings</b>	<ul style="list-style-type: none"><li>• A majority of state agencies use regulatory reduced speed limit signs in work zones; however, only 7 percent of states consider the signs to effectively reduce speeds</li><li>• No single ITS equipment provides significant speed reductions alone, therefore, a combination of equipment is preferential</li></ul>

In a study on traffic safety, Nilsson (2004) addresses safety performance measured without use of a case study. Accident rates and changes in average speeds were the main performance measures. Level of exposure was used to find the level of risk for all people traveling on roadways. By applying the power model, the number of injured drivers in a accident as well as number of accidents was well represented. The number of fatalities was consistently underestimated. The main area for application of the model is rural roads. The model produced a 3-dimensional graph of performance measures to be used instead of a table of values. While the figure can be a good representation of the safety on a roadway, most transportation experts normally use tables; therefore, it will take time for the industry to adjust.

Lyles, Taylor, and Grossklaus (2004) evaluated variable speed limits (VSL) in a study in Michigan. The optimum result of VSL is to decrease speed variance by applying a realistic speed limit. VSL have 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. Data results showed that speeds were slightly better managed and that accidents were not directly caused by VSL. Recommendations were made to reevaluate VSL were no freeway ramp speeds could affect VSL deployment.



**Table A29. Lyles, Taylor, and Grossklaus (2004) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-96 southwest of Lansing, Michigan, 18 mile</li> <li>• 4 deployments, the first deployment had the best results</li> <li>• The VSL included microwave traffic detectors, speed display message boards, pneumatic tube sensors, and 7 communication trailers</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Accident rates and Speeds</li> <li>• Average speed, display speed, difference of average speed and display speed, 85<sup>th</sup> percentile speed, percent of vehicles over 60 or 70 mph, variance, and travel time</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Improve compliance with speed limits</li> <li>• Improve traffic flow and safety</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• VSL were spaced between a few hundred feet to 1 mile</li> <li>• Data was aggregated into 6 minute intervals</li> <li>• Trailers recorded data before and after VSL use</li> <li>• Police officers who were enforcing the areas received a message after 1 minute when VSL were changed</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Average speeds were slightly higher with VSL present</li> <li>• Travel times were reduced up to 6%</li> <li>• Changes to the 85<sup>th</sup> percentile speeds and speed variance were inconclusive</li> <li>• Percent of vehicles over 60 or 70 mph decreased to some degree</li> <li>• Speeds were more consistent during off-peak and nighttime use</li> <li>• VSL did not contribute to accident rates</li> </ul>

### **Benefit-Cost Analysis of ITS Deployments**

Costs are a major hindrance to deploying ITS. On the other hand, justifying the deployment of ITS is easy when one considers the costs of staff, accident damages, fatalities, and delay which has the most impact on costs. A review of the following reports showed benefit/cost ratios of 1.2 to 11.9, 2.1, and 18 to 36, respectively.

Bushman, Berthelot, Taylor, and Scriba (2007) developed a benefit/cost model for ITS deployment in work zones. Benefits included quantified values for higher safety and a lower level of traffic delays. Costs included deployment labor, operational costs, and emissions. Some input parameters were defined in the most likely scenario as follows, reduction in user delay = 5228 hr/month, vehicle delay cost = \$15/hour for car and \$75/hour for truck, accident rate = 1.55 fatal accidents per 100 million vehicle miles traveled and 27.34 injury accidents per 100 million vehicle miles traveled, duration = 8 months, mobilization cost = \$75,000, and operation cost = \$12,500/month. The model calculated the benefits to outweigh the cost with a ratio from 1.2 to 11.9. The average benefit is \$140,000/month and the average cost is \$22,000/month. Note that these values are calculated to a specific site in North Carolina and that the analysis produces a range because of the uncertainties associated with a lack of previous research and the large number of variables within a work zone study.

**Table A30. Bushman, Berthelot, Taylor, and Scriba (2007) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"><li>• I-95 in North Carolina</li><li>• Travel Messenger TM100 system by International Road Dynamics</li><li>• 3 message signs next to exits, traffic sensors, cameras on exit ramps</li><li>• Simulation and Survey</li></ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"><li>• Delay and Accident rates</li><li>• Delay time and delay reduction</li><li>• Simulation estimated maximum of 60 minute delay while 20 minute delay reduction due to ITS</li><li>• Accident rate for work zone should be compared to accident rate for work zone with ITS, Fatal crashes/100MVMT or Injury crashes/100MVMT</li></ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"><li>• Improving mobility</li><li>• Increase safety</li><li>• Calculate Benefits/Cost</li></ul>
<b>Methodology</b>	<ul style="list-style-type: none"><li>• Camera trailer collected data</li><li>• VISSIM simulator used to estimate results</li></ul>
<b>Findings</b>	<ul style="list-style-type: none"><li>• Average benefit of \$140,000/month, average cost of \$22,000/month</li><li>• When more research is available, the estimations to find a benefit/cost for a scenario will be clearer</li></ul>

Ford et al. (2011) developed a useful cost-benefit analysis structure for IT management tools. Many of the systems were databases with geographic information while others were analytical tools for construction. While not directly measuring ITS equipment with the previously mentioned performance measures, the use of many different variables within the benefit and cost categories is applicable to this study. It was found that larger benefits are closely linked with proper coordination, contracts, and management. Since four of the nine tested tools did not have a greater benefit to cost ratio of one, it is recommended using multiple ITS equipment in tandem.

**Table A31. Ford et al. (2011) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• Oregon State Bridge Program</li> <li>• Tested systems: Geographic Information System Infrastructure (GISI) 2004, Environmental Baseline Report Online (EBRO) 2004, EBRO Mobile Data Collection (MDC), Engineering Drawing System (EDS) 2004, Electronic Document Management System (EDMS) 2005, Bridge Reporting System (BRS) 2006, Construction Engineering/Inspection tool (CEI) 2007, Pre-Construction Assessment tool (PCA) 2007, Work Zone Traffic Analysis tool (WZTA) 2009</li> <li>• Monte Carlo Simulation used</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Benefits and Costs</li> <li>• Benefits included Overall time saved, Staff time saved, Data reliability, and Work efficiency savings</li> <li>• Costs included Billing per time, Computing requirements, Licensing requirements, and System development</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Evaluate the benefits/cost ratio of the implemented systems</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Only post analysis preformed</li> <li>• Emphasis on Bridge Program, timing, interest, and uncertainties</li> <li>• Systems compared with equivalent systems or systems without certain benefits</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• Cost percentages were Staff 82%, Licenses 10%, Data storage 7%, and Hardware 1%</li> <li>• The combined benefits/cost was 2.1 using a conservative approach</li> <li>• Benefits were greatly higher when data retrieval was fast or if staff time was reduced likely due to ease of operation</li> </ul>

Bushman and Berthelot (2004) used QuickZone to estimate 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 off of Daniels et al. *Techniques for Manually Estimating Road User Costs Associated with Construction Projects* (1999). Emission costs of \$3731/ton CO, \$3889/ton NOx, and \$1774/ton VOC were used based off of the Federal Highway Administration's *ITS Deployment Analysis System User's Manual* (2000). Accident rate costs of \$59,719 per injury accident and \$3,000,000 per fatal accident were used based off of Federal Highway Administration's *ITS Deployment Analysis System User's Manual* (2000) and a United States Department of Transportation guideline (2003). User delay has the greatest impact on benefit/cost ratio 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. Recommendations were had to valid QuickZone software under a variety of traffic and weather conditions.

**Table A32. Bushman and Berthelot (2004) Summary**

<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• I-95 in North Carolina, 19 miles</li> <li>• 17 months</li> <li>• QuickZone software</li> <li>• Portable changeable message signs (PCMS), traffic sensors, and website</li> </ul>
<b>Performance Measures</b>	<ul style="list-style-type: none"> <li>• Delay, Queuing, and Accident rates</li> <li>• Emissions is another performance measure including CO, NOx, and VOC</li> </ul>
<b>Intended Benefits</b>	<ul style="list-style-type: none"> <li>• Determine benefits of ITS deployment in work zones</li> <li>• Reduce demand by promoting diversion routes</li> </ul>
<b>Methodology</b>	<ul style="list-style-type: none"> <li>• Data collected by sensors</li> <li>• Costs found through literature review</li> <li>• Data inputted into QuickZone software</li> </ul>
<b>Findings</b>	<ul style="list-style-type: none"> <li>• ITS reduced maximum queue length by 1.64 miles</li> <li>• User delay reduced by 8.2 minutes</li> <li>• Emissions is calculated to be \$0.90 per hour of delay</li> <li>• Accidents were reduced by 2.5% to 10%</li> </ul>

Table A33 is the averaged results from the literature review. A “-” represents that a result is applicable to the cell but the literature review provided no corresponding values while an “X” represents a result that is not applicable for the performance measure.

**Table A33. Averaged Results from Literature Review**

	<b>Diversion (%)</b>	<b>Delay (minutes)</b>	<b>Queue Length (miles)</b>	<b>Accident Rate (%)</b>	<b>Speeds (mph)</b>
<b>Average</b>	12.07	8.90	-	X	-
<b>Max</b>	-	41.67	2.40	X	X
<b>Average Reduction</b>	X	10.57	-	3.19	4.52
<b>Maximum Reduction</b>	X	-	1.64	-	40.00
<b>85th Percentile Reduction</b>	X	X	X	X	1.00

## APPENDIX B. BLANCHETTE BRIDGE WORK ZONE MOTORIST SURVEY

This survey was developed by the Civil Engineering department at University of Missouri-Columbia in consultation with the Missouri Department of Transportation. The intent of the survey is to gather data on the use of the I-70 Blanchette Bridge which crosses the Missouri River. Data will be used to find the effectiveness of transportation information systems in work zones. The survey has 19 questions and takes approximately 5 minutes. See the figures below to be familiar with the subject matter. On the map, the I-70 Blanchette Bridge Work Zone appears in red and Dynamic Message Signs appears in black.

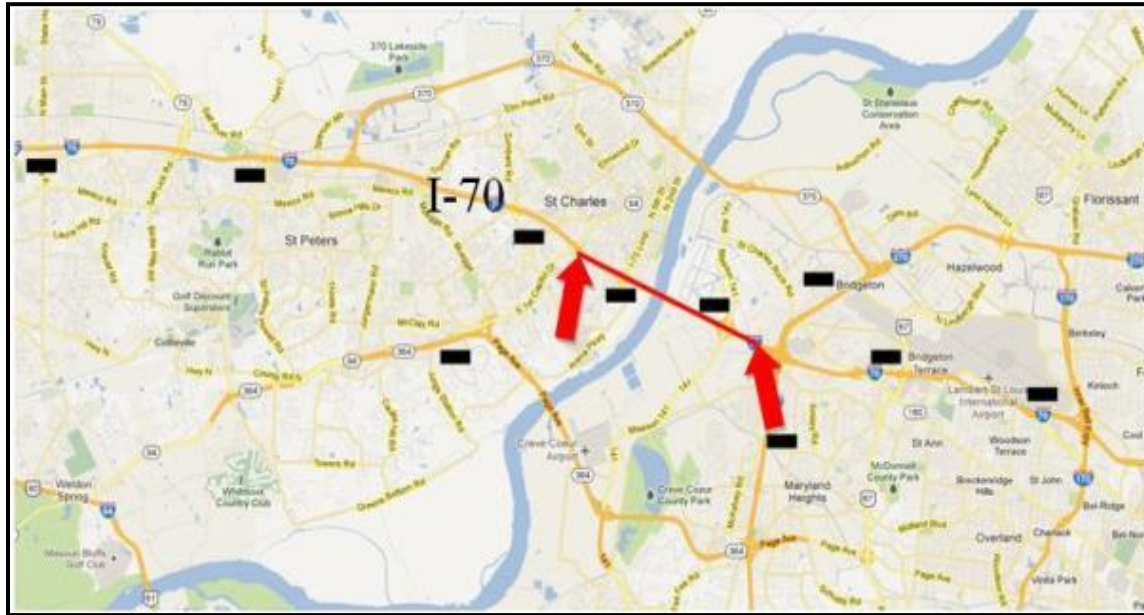


Figure B1. I-70 Blanchette Missouri River Bridge work zone between two arrows, Google 2013



Figure B2. Sample dynamic message sign

**1. How often do you use the I-70 Blanchette Missouri River Bridge?**

- ☒ Daily      ☐ Several times per week      ☐ Several times per month or less      ☐ Almost never

**2. In the mornings (AM), does your trip cross the Missouri River?**

- ☒ Yes, I travel east      ☐ Yes, I travel west      ☐ Yes, I travel both east and west      ☐ No, I do not cross the river

**3. In the mornings (AM), do you travel during the rush hour of 6-9 AM?**

- ☒ Yes      ☐ No

**4. In the mornings (AM), do you use an alternative route around the I-70 Blanchette Missouri River Bridge?**

- ☒ Yes, I use Route 370      ☐ Yes, I use Rt. 94/Rt. 364 (Page Avenue)      ☐ Yes, I use I-64      ☐ No

**5. In the evenings (PM), does your trip cross the Missouri River?**

- ☒ Yes, I travel east      ☐ Yes, I travel west      ☐ Yes, I travel both east and west      ☐ No, I do not cross the river

**6. In the evenings (PM), do you travel during the rush hour of 3-6 PM?**

- ☒ Yes      ☐ No

**7. In the evenings (PM), do you use an alternative route around the I-70 Blanchette Missouri River Bridge?**

- ☒ Yes, I use Route 370      ☐ Yes, I use Rt. 94/Rt. 364 (Page Avenue)      ☐ Yes, I use I-64      ☐ No

**8. Were you aware of the Blanchette Bridge work zone's impact on the traffic before you began your trip across the Missouri River?**

- ☒ Yes      ☐ No

**9. Do the Dynamic Message Signs influence your decision to use an alternative route?**

- ☒ Yes      ☐ No

**10. Compared to other sources of traveler information such as radio, television, personal experience, and the internet, how valuable are Dynamic Message Signs to you?**

- ☒ Much more valuable      ☐ More valuable      ☐ Same      ☐ Less valuable      ☐ Much less valuable

**11. Due to the I-70 Blanchette Bridge work zone, what is the average delay you have experienced on top of normal commute delay?**

- ☒ 0-5 minutes      ☐ 5-10 minutes      ☐ 10-15 minutes      ☐ Over 15 minutes

Dynamic Message Signs commonly display the following:

Travel times to major cross streets

Expected delays

Average speeds

Lane closures

Incident information

Construction detour information

**12. How valuable do you find travel times posted on Dynamic Message Signs compared to other messages? For example: "I-270 15 min".**

- ☒ Much more valuable      ☐ More valuable      ☐ Same      ☐ Less valuable      ☐ Much less valuable

**13. How valuable do you find incident messages posted on Dynamic Message Signs compared to other messages? For example: "Accident Rt Lane Closed Ahead".**

- ☒ Much more valuable      ☐ More valuable      ☐ Same      ☐ Less valuable      ☐ Much less valuable

**14. How valuable do you find construction detour messaging posted on Dynamic Message Signs compared to other messages? For example: "I-70 at MO River/ 2 Lanes Closed/ Use 370 Bypass".**

- ☒ Much more valuable      ☐ More valuable      ☐ Same      ☐ Less valuable      ☐ Much less valuable

**15. Residency: Are you a local or a visitor?**

- ☒ Local      ☐ Visitor

**16. Trip Purpose: Was the purpose of the trip for work or recreation?**

- ☒ Work      ☐ Recreation

**17. Vehicle Type: What type of vehicle did you use?**

- ☒ Commercial Truck      ☐ Public Transportation      ☐ Private Vehicle

**18. Gender: Are you male or female?**

- ☒ Male      ☐ Female

**19. Age Group: Which of the following age groups do you belong to?**

- ☒ 16-25      ☐ 26-45      ☐ 46-65      ☐ 66+

Thank you for completing the survey! Your assistance will help transportation engineers improve traffic flow and safety in work zones. We sincerely appreciate your time.