# PROBABILISTIC EVALUATION OF A SMART WORK ZONE DEPLOYMENT


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**ABSTRACT**

Smart Work Zones are an emerging technology designed to address the increasing impact of work zones on the safety and mobility of the highway system. Smart Work Zones employ various technologies to monitor current traffic conditions and provide relevant information and guidance to road managers and road users on current traffic flow conditions to promote safer and more efficient navigation of the work zone.

The purpose of this research was to develop a probabilistic analysis framework model for the quantification of benefits and costs related to the deployment of a Smart Work Zone. The performance was quantified in economic terms considering the cost of deployment and potential savings in terms of motorist safety and reductions in user delays, vehicle operating costs, and emissions.

When applied to one specific operating scenario on a case study project on Interstate 95 in North Carolina, the model was found to be capable of providing useful and relevant results that correlated to observed performance. The model results included a sensitivity analysis that identified the sensitivity of the outcome to uncertainty in the input values and a risk analysis that quantified the uncertainty of the predictions. The findings indicated that, at a 95 percent confidence level, the expected benefit / cost (b/c) ratio of deploying a Smart Work Zone system was between 1.2 and 11.9 and the net value (NV) was between $10,000 and $225,000 per month of operation for the defined conditions. The results indicate that when applied under appropriate conditions, Smart Work Zones have the potential to provide significant benefits to road users.

## INTRODUCTION

Intelligent Transportation Systems (ITS) technologies have shown the potential to improve safety and mobility in highway work zones by improving traffic flow, reducing speeds, and directing traffic in a more efficient manner (1). ITS technology applied in a work zone setting, commonly referred to as a "Smart Work Zone", has the ability to measure current traffic conditions approaching the work zone and to use portable roadside signing to advise drivers of reduced speeds ahead and expected delays, as well as suggesting the use of alternate routes. The capability to predict the effects of ITS deployment can lead to better decisions with regards to the application of Smart Work Zone technology and assist transportation agencies in addressing the growing problem of congestion, injuries and fatalities occurring within highway work zones. The ability to reliably predict and quantify in advance the effects of a Smart Work Zone deployment should result in better project selection, better application of the technology, and more successful projects.

While there have been other evaluations of the economic benefits of Smart Work Zones in the past, they have sometimes contained one or more of the following shortcomings:

- Lack of a comprehensive treatment of possible benefits, typically focusing solely on a single measure;
- Simplistic treatment of traffic flow and diversion of vehicles without taking into account the operating characteristics of the system and the dynamic interaction between the system and traffic;
- Failure to acknowledge or quantify the uncertainty of the inputs and the resulting sensitivity of the outputs, and;
- Absence of verification of the predicted results (2).

To support the widespread usage of Smart Work Zones, transportation agencies need improved evidence of the performance capabilities and cost effectiveness of Smart Work Zones. To implement Smart Work Zones, planners and project engineers require an evaluation criterion and a framework to assist them in determining which projects are most suitable for the application of work zone ITS technology and to justify the allocation of funds.

## PURPOSE

The purpose of this paper is to describe the development of a probabilistic Smart Work Zone analysis model with the ability to value and quantify the uncertainty of the expected costs and benefits in terms of reduced user delay, reduced vehicle operating costs, reduced emissions, and improved safety resulting from the deployment of a Smart Work Zone. This development expands on earlier work that described a benefit cost analysis (BCA) and sensitivity analysis for Smart Work Zones (3) by detailing input variables and values including field research and verification, implementing a probabilistic analysis model using DPL, and including a more in-depth sensitivity analysis and risk profile in the outcomes.

In its general form the model is applicable to other transportation projects, but other applications were not explored in this research. Results from traffic modeling, previous research, and project specific characteristics were used as inputs to specifically examine quantitatively the economic benefits from deployment of a Smart Work Zone derived from: 1) mobility benefits in the form of reduced user delay, reduced vehicle operating costs, and reduced emissions, and 2) safety benefits in the form of reduced injury and fatal crashes. Monetary costs included in the economic analysis were the direct agency costs for procurement, mobilization, and operation of a Smart Work Zone. The output of the analysis provided a probabilistic distribution of expected benefit cost (b/c) ratio and expected net value (NV).

## DESCRIPTION OF A SMART WORK ZONE SYSTEM

Smart Work Zone systems can take on numerous variations depending on the application, agency, location, functionality and system vendor. Most systems contain some or all of the elements described below.

Traffic Detection: Traffic data is collected from the roadside on a periodic basis so that informed and relevant decisions can be made for the management of traffic in the vicinity of the work zone. Although permanent sensors can be integrated as part of the system, the short duration and transient nature of work zones necessitates a portable approach to the selection of technologies and systems.

Data Processing: The processing function varies depending on the application, but may include some or all of the following tasks:

- Receiving data from field locations;
- Assembly, analysis, and archiving of data;
- Algorithms and processes to determine roadside information to be displayed;
- Control of information displayed at the roadside;
- Control of website information, and;
- Administration and control access.

The processing function may take place at the roadside, a local base location, or a remote server location.

Roadside Information: The purpose of the roadside information function is to provide motorists with information and guidance to assist them safely and efficiently through the work zone. The relevant guidance is available in several forms depending on the application and may include speed advisories, delay advisories, regulatory speed limit changes, merge control and alternate route guidance.

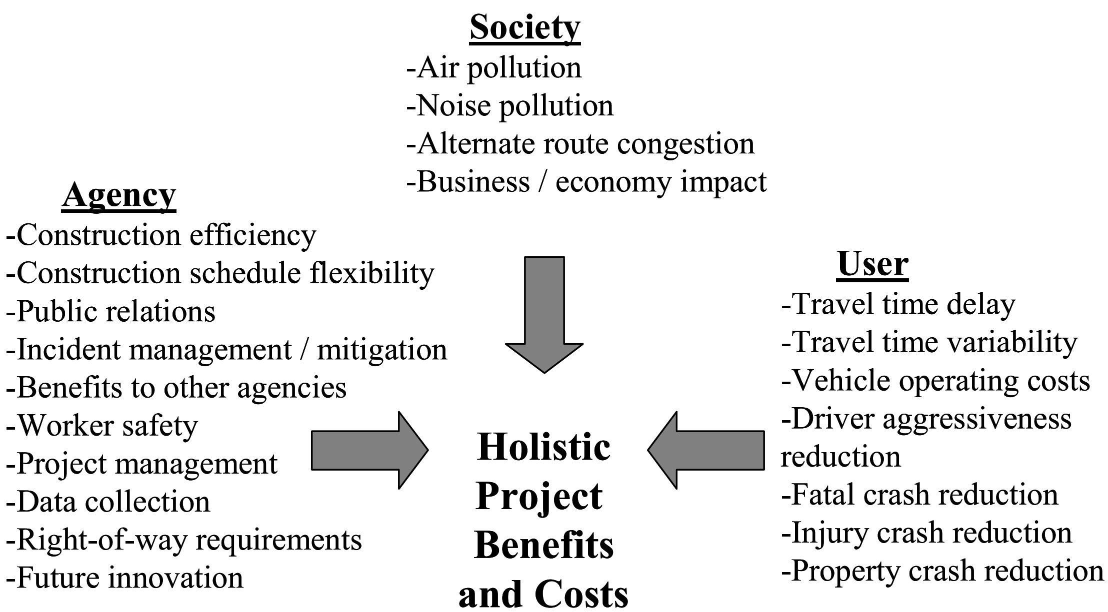
Public website: A public website may be used to provide information to motorists prior to departure on a trip. The website may include delay advisories, alternate route information, and current video images from the site.

Administration: The administration function of the Smart Work Zone provides personnel with the capability to monitor and control the operation of the system.

## EVALUATION OF SMART WORK ZONES

A detailed review of previous research and evaluations of Smart Work Zones has been completed by others (1, 4). As identified by Fontaine and Edera, the body of research as a whole provides evidence that when properly applied, Smart Work Zones can have a positive benefit in traffic management and control in terms of traffic routing and reduction of delays. However, the effects on safety are more difficult to evaluate and are not as conclusive from the research that has been conducted.

There is an increasing emphasis on context sensitive design and holistic transportation analysis. Holistic analysis recognizes that transportation is not an independent entity confined solely to providing capacity and level of service, but rather that it has a much broader influence in social, environmental, economic and political areas (5). Some of the factors that may be considered in a holistic approach are identified in Figure 1.




(6, 7, 8 , 9)

**FIGURE 1 Holistic Costs and Benefits Associated With a Smart Work Zone Deployment**

Some evaluation approaches have attempted to monetize most or all of the benefits and costs of a project, while others treat many of these factors in a subjective and qualitative manner. Guidelines for the evaluation of transportation projects provided by the National Cooperative Highway Research Program (NCHRP) also provide relevant background for determining an evaluation approach. If the broad range of effects of a project are to be considered, attempting to combine them all into a single cumulative index or measure is discouraged. Relatively well-established methods exist for estimating effects, in economic terms, of changes in travel time, safety, and vehicle operating costs. (10). In performing an evaluation, a balance should be pursued between simplicity and comprehensiveness so that important aspects are addressed without becoming impractical.

Many evaluations of transportation projects, including those involving ITS, have been based on some form of a BCA. This has been supported as a valid means of evaluation of ITS projects by most researchers (11). Although a specialized form of transportation system, it is contended that ITS projects must still compete with more traditional construction projects for limited resources. In order to support and justify an ITS project and secure its funding there must be some evidence provided that it will deliver favourable results in terms of social benefits and improved safety in comparison to competing alternatives. A possible bias against ITS applications in favour of hard assets such as asphalt and concrete increases the importance of a credible analysis of expected results to support the deployment of a Smart Work Zone.

The most common approach to Smart Work Zone deployment has been for the agency to pay for the provision of the services from a vendor or contractor on a daily or monthly usage basis without the agency purchasing or owning any equipment. Since the agency owns no equipment at the end of the project, and benefits are received during the actual time of deployment, the time value of money is not a significant factor in assessing this type of project. The term "net present value (NPV)" implies that the time value of money is being calculated which is not the case in this analysis since all major costs and benefits are accrued at the time of deployment and use. To avoid confusion the term net value (NV) is used instead of NPV to describe the summation of all project related costs and benefits that are included in the analysis.

Two issues arise with attempting to use a BCA as the decision making method in the case of Smart Work Zones. First, not all costs and benefits lend themselves to a monetary quantification, which is necessary for a BCA. Second, there is limited available experience and research as to the benefits of work zone ITS, and therefore it is difficult to predict with certainty the benefits that may be realized. Therefore, an analysis approach that addresses uncertainty is desirable.

## PROBABILISTIC APPROACH TO EVALUATION OF SMART WORK ZONES

Given that traffic flow is by nature stochastic and that there is a lack of historic information on system performance and effects of Smart Work Zones, there is an element of uncertainty involved in the analysis which must be considered to allow comparison over the range of possibilities. Uncertainty can be dealt with by applying a probabilistic approach to the evaluation including a sensitivity and risk analysis of the results. FHWA has provided guidance on the use of a probabilistic approach, such as Monte Carlo Simulation, during life cycle cost analysis, but a review of actual practice indicates that most states rely on a simple sensitivity analysis (12).

An example of the application of probabilistic analysis to transportation projects is RealCost, a life cycle cost analysis program developed for the assessment of paving projects (13). The inputs include construction costs, expected life, discount rate, and rehabilitation costs. The output options include a sensitivity analysis plot and a probability profile of the NPV. Other examples of probabilistic analysis tools are microBENCOST and stratBENCOST that provide for evaluation of network and project level options, and include consideration of value of time delay, vehicle operating costs, safety, and emissions in the economic measures (14).

## FORMULATION OF PROBABILISTIC APPROACH

Decision making tools such as the DPL program can provide a similar analysis to that provided by RealCost, including the analysis of sensitivity, risk, uncertainty and expected results. DPL provides the flexibility to define inputs and to formulate the probabilistic calculation of results for a specific application.

The purpose of the analysis framework is to provide a model to evaluate the potential benefits of deploying a Smart Work Zone at a particular site under specific field state conditions to support decision making regarding whether to deploy a Smart Work Zone. Since the decision involves an expenditure of additional funds, some form of economic analysis is anticipated.

The chosen method to quantify the value of a Smart Work Zone project was a probabilistic decision-making model using a BCA approach supported by inputs from modeling of specific aspects of Smart Work Zone operation. A BCA model with the ability to output the estimated incremental b/c ratio and NV was developed as a deterministic model in Excel and as a probabilistic model using Decision Programming Language (DPL) software. DPL facilitates the input of probabilities and distributions for expected input values to determine the probability of possible outcomes considering all variables. The DPL program allows for the definition of each input variable as either a fixed value or as a value with a probability distribution. The results from the Excel analysis were compared to DPL in a deterministic mode and it was verified that the outcome was the same for both calculation methods.

Expected benefits and costs were assigned monetary values for purposes of analysis on an incremental basis as compared to the same case without a Smart Work Zone. Benefits considered in this part of the analysis consisted of mobility effects and safety effects. Mobility effects include reduced user costs (delay and vehicle operating costs) and reduced emissions. Safety effects include reduced injury crashes as well as reduced fatal crashes. This approach facilitates the consideration of the agencies multiple objectives based on monetary values established from analysis of other transportation projects.

Dependent and independent variables were defined and values assigned based on previous research and literature. A sensitivity analysis and validation of the economic model were performed prior to application to the case study site.

Determining appropriate inputs for each model variable requires specific knowledge of the project and relies on the expertise of the practitioner to select appropriate input values. Previous research can be used as a source of information and is supplemented by additional research conducted for this project.

**Defining Mobility Effects**

Three mobility related effects from that could result from the deployment of a Smart Work Zone were considered in the model: user delay, vehicle operating costs, and emissions.

*User Delay*

In order to determine the expected benefits of reducing user delay by deploying a Smart Work Zone, two components are needed; an assigned monetary value for delay time and the amount of delay reduction. In addition to the value of the time lost due to delay, there is also a cost associated with the additional vehicle operating costs and increased emissions that occur when delays occur in a work zone. For clarity in this research, the additional vehicle operating cost and emissions due to delay is explicitly identified and separated from user delay. A number of sources are available to provide reference values for user delay time (15, 16, 17, 18).

The amount of user delay reduction to be expected from the deployment of a Smart Work Zone is not readily apparent without some analysis. In addition, research into the impacts of a Smart Work Zone on user delay is limited. Each application of a Smart Work Zone is unique to a particular set of field state conditions, and previous experiences may not directly apply to the specific case being considered. In the absence of historical information, some form of calculation or modeling is required to determine the expected amount of delay reduction when a Smart Work Zone is deployed.

The BCA model is not dependent on any specific traffic model and can accept inputs from various sources. The focus of the economic analysis is not the traffic model itself, but the outputs from the model. Since the economic analysis incorporates sensitivity and probabilistic analysis it is actually possible to consider several sources of data and a range of possible values.

The traffic model analysis is based on a comparison between a site without a Smart Work Zone and a site with a Smart Work Zone. The "do-nothing" option is considered the base option and includes any typical measures that would normally be applied for traffic control and driver information for the type of project considered. The savings in travel time is the difference between the total travel time for all vehicles on the mainline without a Smart Work Zone and the total travel time for all vehicles on the mainline with a Smart Work Zone, plus the travel time of vehicles that chose to use an alternate route.

*Vehicle Operating Costs*

Vehicle operating costs include fuel, tires, lubricants, repair, and maintenance of the vehicle due to wear and tear. Typically, about 70 percent of the total vehicle operating costs are fuel and oil costs (19). Travel time and the general wear and tear on vehicles from substandard pavement conditions can both have an affect on vehicle operating costs (20). The functional inter-relationship between road condition and road user costs is important and can be developed through econometric methods, but this approach has some inherent drawbacks. The inter-relationship between road condition and road user costs can also be modeled using a first-principles approach to overcome the drawbacks of an econometric approach (21).

In the context of a Smart Work Zone, there are two main effects on vehicle operating costs to be considered. A Smart Work Zone may reduce motorist delays, which could also result in a reduction in fuel and oil consumption. At the same time, if vehicles are diverting to an alternate route, this may change the distance traveled for those vehicles, affecting wear and tear on the vehicle. The effects of increased wear and tear are more significant when the alternate route is significantly longer or is of a poorer quality than the mainline option.

In the scope of this analysis, only the change in fuel consumption due to reduced idling time is considered. Since fuel typically makes up the majority of vehicle operating costs, this assumption is valid provided there is not a significant difference between the travel distance on the mainline and on the alternate route. This is because the wear costs are not the major component of vehicle operating costs and only 5 percent to 15 percent of vehicles are expected to use the alternate route, based on this research and other studies of diversion (22). If there is a significant difference in travel distance the effect on vehicle wear and tear may need to be considered. In the case where the difference between the mainline distance and the alternate route distance is small, the wear related component of vehicle operating cost becomes insignificant.

Detailed estimation of vehicle fuel consumption is a potentially complex task and may include considerations such as vehicle speed, vehicle characteristics, highway slopes, road roughness and temperature. To facilitate the inclusion of vehicle operating costs in the evaluation of a Smart Work Zone without becoming an onerous task, a simplified approach was required. The estimated change in the number of delay hours was multiplied by the idling fuel consumption rate for the assumed mix of vehicles to determine the benefit of reduced vehicle operating cost due to improved traffic flow.

*Emissions*

The implementation of a Smart Work Zone system is expected to result in a change in the traffic flow characteristics at a site by reducing delay time and vehicle speed variability. These changes in traffic flow characteristics may result in a reduction of vehicle emissions. Emissions reduction is important for several reasons including air quality and its effect on personal and environmental health and its contribution to global warming. Many cities and states already have emissions control and monitoring programs in place, and continue to work towards management and reduction of vehicle emissions. In congested urban environments that already experience pollution issues, a system such as the Smart Work Zone that can reduce emissions may be of significant value.

In evaluating mobile source emissions, three emission types commonly considered are carbon monoxide (CO), oxides of nitrogen (NOx), mostly NO and $NO_2$, and volatile organic compounds (VOC). The Environmental Protection Agency (EPA) in the United States provides estimates on vehicle idling rates for these three types of emissions for various vehicle types (23). Vehicle emissions vary depending on the age, condition, fuel type, and technology of the vehicle, and therefore the specific mix of vehicles should be considered in determining emission rates for a given traffic stream. Temperature, speed and acceleration rate can also affect emission rates. (24).

In the context of work zone traffic evaluation, both average speed and acceleration emission rates may be of importance. If a successful strategy for managing traffic can be implemented, the effect on the mainline traffic flow should be more vehicles traveling in the speed range with low emissions and there should also be a reduction in vehicle acceleration events. There is a trade-off as more vehicles are diverted to an alternate route which could possibly be longer in distance than the mainline and may include stops and starts.

Attributing a monetary value to each type of emission is necessary in order to determine the expected benefits from the implementation of a Smart Work Zone. There is no single value that can be assigned to emissions since in general they are not a marketable commodity. As greater emphasis is being placed on emissions reduction clearer values may emerge for vehicle emissions. The value of emissions may also vary based on location and time, such as higher values attributed to emissions in a metropolitan area that is experiencing smog conditions compared to a rural area.

Attempting to define the value of emissions is beyond the scope of this study, but reference values are available from several sources (7, 25, 26, 27). Rather, the scope is to provide a framework wherein emission costs can be input by the user based on the application being considered, the current information available, and the values of the agency.

**Defining Safety Effects**

To determine the expected value in terms of improving safety, the model provides inputs for the expected reduction in injury and fatality crashes and the monetary value of injury and fatality crashes. The model itself does not define how these values are determined but does facilitate the calculation of the value based on a crash improvement rate. The crash improvement rate is the percentage reduction in injuries and fatalities that can be expected by implementing a Smart Work Zone based on research and experience. The reduction rate is applied to the expected crashes that would occur without the presence of a Smart Work Zone.

Several methods can be used to estimate the expected crashes during a construction project:

- Expected crashes can be determined by establishing the crash rate for the construction zone based on similar work zone projects, taking into account relevant adjustment factors for the site under consideration.
- The crash rate for the highway segment prior to construction can provide a base rate to which an adjustment can be applied to estimate the increase in crash rates when a work zone is present. Research has indicated that the increase in the crash rate may typically be from 7 percent to 30 percent (28, 29).
- Research has resulted in models developed to predict work zone crashes, such as a model developed by Tarko that considers a number of variables, including type of work, duration of work, traffic volume, and work intensity (30).

Research and evaluation of the safety effects of the deployment of a Smart Work Zone has been completed on a number of projects and system applications. In some cases positive results have been documented, while others have been inconclusive or negative, although it is unclear if the negative effects are due to the work zone in general or specifically the Smart Work Zone system(1). Both the potential and the uncertainty should be captured in the assessment of safety impacts due to deployment of a Smart Work Zone.

The potential for improvement in work zone safety is also related to traffic exposure at the site. If a work zone is present and operational on a continuous basis, the presence of a Smart Work Zone can influence the entire traffic volume. In some cases a work zone is only present periodically, such as weekdays only, due to high traffic volumes or other concerns. Under these conditions, it is only the traffic volume passing through during work zone operational periods that can benefit from potentially better safety and mobility due to the presence of the Smart Work Zone. The traffic exposure used in determining safety effects must be based on the operating conditions of the site.

**Defining Agency Costs**

The costs to an agency to deploy and operate a Smart Work Zone are the main costs considered in the BCA model. Agency costs are a direct input into the analysis model and therefore a specific formulation for determining agency costs is not required.

Agency costs included in the monetary analysis are the costs for mobilization and operation of the Smart Work Zone system. Currently agencies are typically treating Smart Work Zone systems as a “furnish and operate” turnkey system. The agency does not actually purchase or own any equipment, but rather pays a supplier for each day or month of satisfactory system operation. The duration of a project has been shown to have a significant effect on the expected b/c ratio, and therefore needs to be incorporated into the analysis (1). The performance analysis model includes two agency costs, one for mobilization and the other for ongoing operation. The agency costs for system procurement varies depending on many factors including the complexity of the project, project location, project requirements, and market conditions. The model user should arrive at a reasonable estimate for the system cost based on past experience and knowledge of project specifics.

**FIELD CASE STUDY – INTERSTATE 95**

A Smart Work Zone application on Interstate 95 in Nash County, North Carolina was selected as the case study site to be used for application of the economic analysis. The system in use within the case study site was the Travel Messenger™ TM100 system provided by International Road Dynamics (2). On this project, three message signs were positioned on I-95 upstream of the work area prior to the alternate route exit to provide advisory messages, including suggestions of an alternate route when significant congestion existed. Three additional message signs were positioned to provide route guidance to motorists on the recommended alternate route.

The BCA model was applied to the case study site scenario to determine the range of BCA results considering variations in traffic conditions. The BCA outcome was determined as a b/c ratio and as a NV.

The characteristics of the particular field state conditions can be defined within the model including the type of closure, staging of work, and use of detour routes. The site configuration was obtained using maps, project drawings, and the field locations of Smart Work Zone components, traffic control components, and basic roadway geometry. A field investigation was conducted to obtain additional input values including a survey of local motorists to determine travel shifting, diversion rate by motorists in response to advisory messages, and traffic volume and composition.

Traffic flow volumes through the work zone under congested conditions were obtained from traffic sensors that were a part of the Smart Work Zone and were calibrated by comparison with manual counts from video recorded upstream and downstream of the work zone. Detailed traffic demand data was obtained using a portable video camera trailer positioned upstream of the work zone. The percentage of trucks and cars using the exit ramp leading to the alternate route was also obtained from the video traffic recording.

With inputs for the case study site defined, a model of the Smart Work Zone application was created using VISSIM to estimate vehicle delay time with and without a Smart Work Zone in place. As input traffic volumes increased, the model predicted significant delays and significant reduction of delays by a Smart Work Zone. At the worst condition, it was estimated by the traffic model that delays on the mainline could reach as high as 60 minutes and that the deployment of a Smart Work Zone could save up to 20 minutes per vehicle. While the model results may be accurate for the given conditions, agencies would not normally operate a work zone under these types of conditions and would find alternative methods to keep traffic flowing such as changing work timing or keeping more lanes open. Therefore, the maximum travel time improvement that could be attributed to a Smart Work Zone in the analysis calculation was limited to five minutes per vehicle to avoid over-estimation of the potential benefits in unrealistic conditions.

## APPLICATION OF PROBABILISTIC MODEL TO CASE STUDY SITE

The input parameters were defined for the case study site based on available information from sources such as the literature review, site data, traffic studies, and traffic simulation (31). The input parameters were first defined for the sensitivity analysis and then the most sensitive were used for the risk analysis. For the sensitivity analysis expected, minimum and maximum values were defined. In this process, it is important that the same relative level of uncertainty be used in defining the values. The level of uncertainty can be defined in qualitative terms such as “possible, but highly unlikely” or in quantitative terms such as “5% probability of occurrence”, but they must be consistent. If the level of uncertainty is not consistent, then greater sensitivity might be attributed to a variable than is warranted. The values defined for each of the input parameters are shown in TABLE 1.

The probabilistic approach described in this paper was applied to the North Carolina I-95 case study project, as defined by the input parameters, and was used to perform a sensitivity analysis and a risk analysis.

**TABLE 1: Input Parameters for Performance Analysis of Smart Work Zone Deployment**

| Variable | Description | Minimum | Most Likely | Maximum |
|---|---|---|---|---|
| **Mobility** | | | | |
| **Delay Reduction** | Reduction in user delay (hours/month) | 1063 | 5228 | **7460** |
| **Truck delay value** | Cost of delay for trucks ($/hour) | $25 | $75 | **$125** |
| **Car delay value** | Cost of delay for cars ($/hour) | $10 | $15 | **$25** |
| **Truck operating cost** | Cost of fuel ($/hour) | $1.00 | $1.25 | **$1.50** |
| **Truck emissions rate** | Idling emissions of CO, NOx, and VOC (g / truck idling hour) | VOC = 12.1<br>CO = 109.6<br>NOx = 43.1 | VOC = 12.5<br>CO = 133.6<br>NOx = 36.0 | **VOC = 14.0**<br>**CO = 189.7**<br>**NOx = 26.7** |
| **Car operating cost** | Cost of fuel ($/hour) | $0.50 | $0.75 | **$1.00** |
| **Car emissions rate** | Idling emissions of CO, NOx, and VOC (g / car idling hour) | VOC = 16.7<br>CO = 234.5<br>NOx = 4.9 | VOC = 18.5<br>CO = 262.0<br>NOx = 5.0 | **VOC = 19.3**<br>**CO = 273**<br>**NOx = 5.1** |
| **Emissions value** | Value of emissions of CO, NOx, VOC (US$ / 1000 kg) | VOC = $1802<br>CO = $23<br>NOx = $2,608 | VOC = $3,300<br>CO = $1,150<br>NOx = $4,209 | **VOC = $6700**<br>**CO = $6,360**<br>**NOx = $12,875** |
| **Safety** | | | | |
| **Exposure** | Vehicle Miles Traveled | 439,000 | 690,000 | **1,091,000** |
| **Work Zone Fatal Crash Rate** | Fatal Crashes / 100MVMT | 1.44 | 1.55 | **1.69** |
| **Work Zone Injury Crash Rate** | Injury Crashes / 100MVMT | 24.85 | 27.34 | **29.82** |
| **Safety Improvement Factor** | % Reduction in Crashes | 0% | 5% | **10%** |
| **Non-fatal Injury crash cost** | Average value of injury crash ($ / injury crash) | $19,000 | $32,500 | **$46,000** |
| **Fatal crash cost** | Average value of fatal crash ($ / fatal crash) | $1,300,000 | $2,500,000 | **$3,700,000** |
| **Agency** | | | | |
| **Months** | Duration of operating period (months) | 7 | 8 | **9** |
| **Mobilization** | Cost of system mobilization ($) | $50,000 | $75,000 | **$100,000** |
| **Operating Cost** | **Monthly system cost ($/month)** | **$10,000** | **$12,500** | **$15,000** |

**Sensitivity Analysis**

The purpose of the sensitivity analysis is to determine for which variables a change in the value over its expected range results in a large variation in the outcome. The variation could be due to the magnitude of the variables effect on the calculation, a high level of uncertainty of the variable, or a combination of magnitude and uncertainty. The results of the sensitivity analysis are shown in Figure 2.

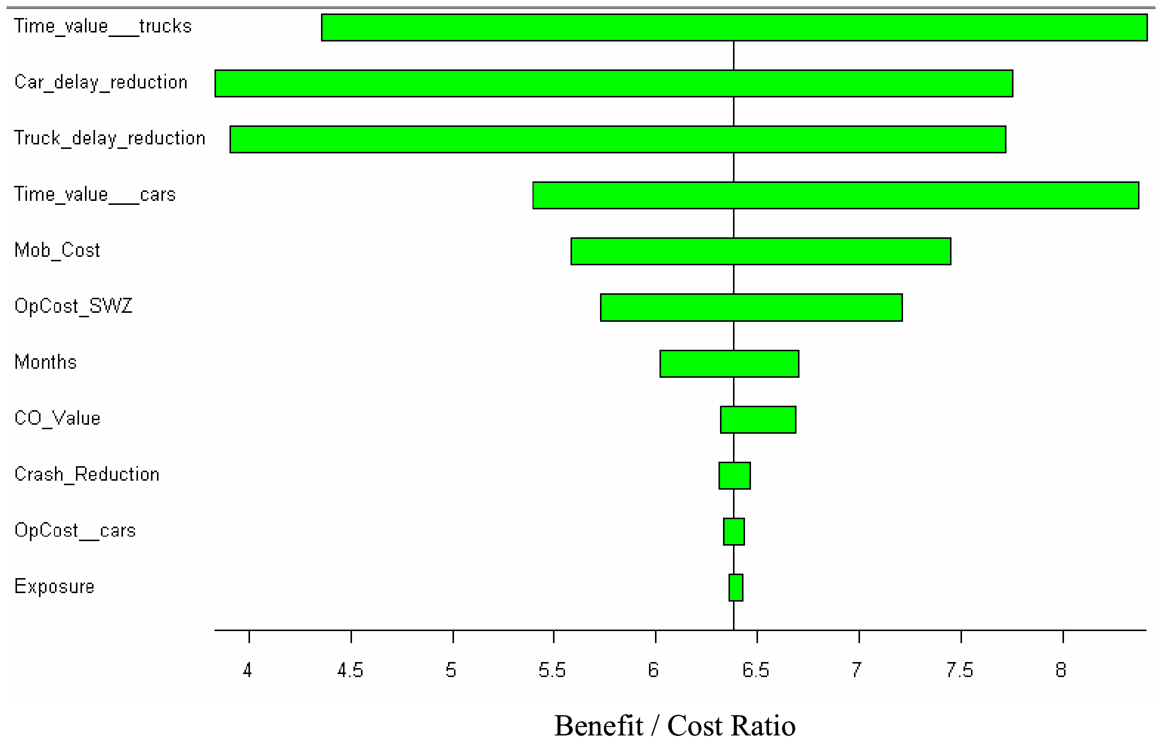



**FIGURE 2: Sensitivity Analysis of Economic Model Independent Variables As Applied To Case Study Site**

The results of the sensitivity analysis show the range of change in the b/c ratio and a ranking of the uncertainty of input variables that are most sensitive when each one is considered individually over its range of expected values. The four most sensitive variables determined in the analysis were all related to the delay caused to drivers: car delay reduction, time value trucks, truck delay reduction, and time value cars. The next three most sensitive variables were all related to the cost of deploying and operating the system. The uncertainty of values for variables related to emissions and safety were the lowest of the measure of effectiveness that were used.

As described in the section on formulation, some simplifying assumptions were made in the determination of vehicle operating costs and emissions. If the sensitivity analysis had identified these variables as sensitive, then a more detailed investigation would be warranted. Since the outcome for this specific application was not highly affected by the uncertainty in vehicle operating costs and emissions, more detailed work was not conducted in this area.

Since the estimates of traffic delay with and without a Smart Work Zone are significant to the final results of the analysis, further investigation of the traffic delay may be warranted. Calibration and validation of the VISSIM model with a larger input set or the comparison of the results with results from other models such as QuickZone may improve the quality of the results.

The expected value of the total estimated benefits of the deployment was $140,000 per month and the estimated costs were $22,000 per month. The expected benefits derived from a reduction in user delay account for 94.3 of the total benefits, attributed approximately equally between savings to cars and trucks. The percentage of total benefits from vehicle operating cost reduction, emissions reduction, and safety improvement are 3.1 percent, 1.4 percent, and 1.2 percent respectively.

**Risk Profile**

The sensitivity analysis identified variables that did not have a significant effect on changing the results of the analysis. These variables can be fixed at their expected values without affecting the results of the analysis. The sensitivity analysis also identified some variables that can have a considerable effect on the outcome if their value changes throughout its expected range. There is some uncertainty with the actual value of these variables, and the variation in value can affect the analysis results. Therefore the uncertainty and range of possible values for those variables should be considered in the analysis. The risk profile provided a method to perform the economic analysis with proper consideration given to the uncertainty of key input variables.

In the risk profile, all variables were fixed at their expected values except for the six variables with the highest sensitivity to uncertainty: car delay reduction, time value trucks, truck delay reduction, time value cars, Smart Work Zone mobilization cost, and Smart Work Zone operating cost. The values for the six most sensitive variables were entered as simple distributions across the range of expected values, as defined earlier. Probabilities were assigned to each value for the most sensitive variables as determined in the sensitivity analysis and defined in TABLE 1. The minimum and maximum values were assigned a probability of 25 percent while the expected value was assigned a probability of 50 percent. The result of the risk profile is a cumulative probability graph, as illustrated in Figure 3.

The x-axis is the estimated b/c ratio for the project under consideration. The y-axis is the cumulative probability of the b/c ratio being less than the value on the x-axis. Based on the analysis, two estimated confidence intervals are indicated on the cumulative probability graph. At a 68 percent confidence interval, the predicted b/c ratio is between 3.3 and 9.1 and at a 95 percent confidence interval, the predicted b/c ratio is between 1.2 and 11.9.

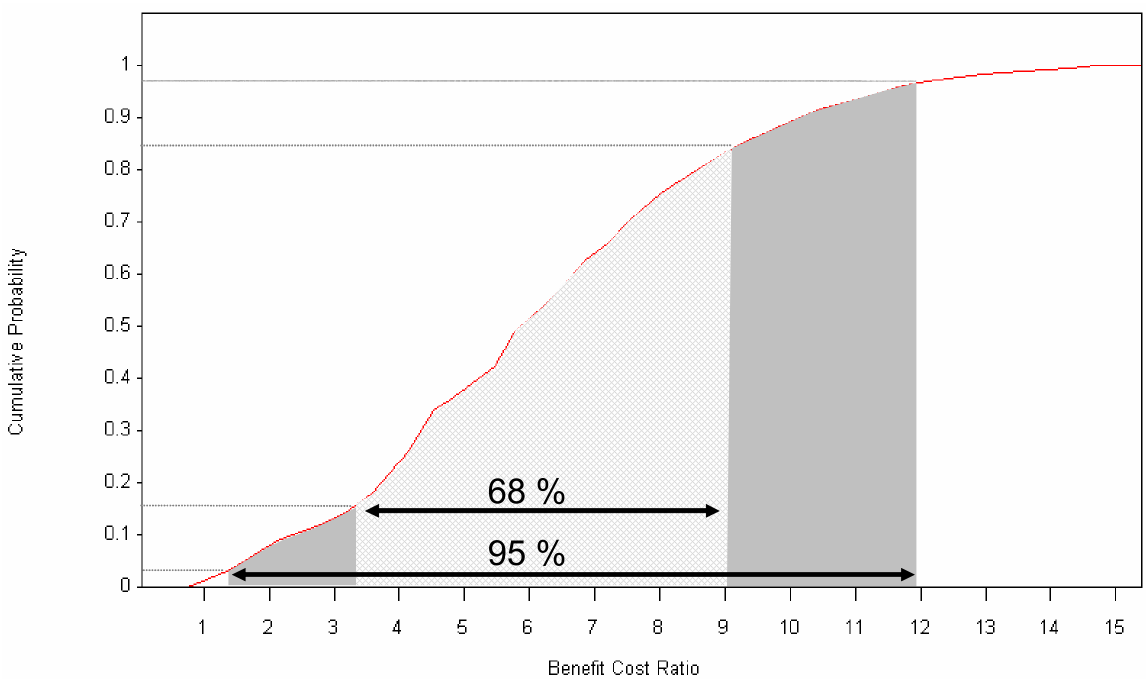



**FIGURE 3: Risk Analysis of Deployment at I-95 Case Study Site, Computed As B/C Ratio**

The risk profile can also be computed in terms of NV. Although b/c ratio is a very common evaluation measure for transportation projects, some analysts may prefer the NV instead. In some cases, NV may also provide additional insight and better decision making information.

The results of the NV analysis are similar to the B/C ratio, since they are based on the same benefit and cost. At a 68 percent confidence level, the predicted NV is between $50,000 and $170,000 per month of operation. At a 95 percent confidence interval, the predicted NV is between $10,000 and $225,000 per month of operation, assuming similar operating conditions for the entire month.

The model provides an analysis for a particular set of conditions that existed at the time of the field research that are not necessarily representative of the entire deployment. Work zone traffic control, traffic flow and other site conditions are often dynamic and a single project may operate under a variety of conditions as traffic volumes, work schedules, and traffic control measures change. In this case, it may be necessary to conduct the analysis several times to cover the expected operating scenarios and develop an assessment that covers all aspects of the entire project.

## CONCLUSION

This research developed a probabilistic evaluation framework for the analysis of a Smart Work Zone deployment and then applied it to a specific case study project on I-95 in North Carolina to demonstrate the economic merits of the deployment. The performance analysis framework that was developed in this research used a probabilistic economic evaluation model to quantify the expected benefits from deployment including reduced user delay, reduced vehicle operating costs, reduced emissions, and improved safety and costs for mobilization and operation.

For the specific case study application, the outcome was positive within the range of expected results. As further research is done in this area, a more comprehensive archive of analyzed conditions may be developed and drawn upon in the future, without the need for detailed investigation of every scenario. The accuracy and confidence level of the analysis can be improved by improving the confidence level of each of the inputs. This framework helps to identify the most significant variables and provides direction for future research in the evaluation of Smart Work Zone deployments.

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