PROBABILISTIC PERFORMANCE MODEL FOR EVALUATION OF A SMART WORK ZONE DEPLOYMENT

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Abstract

A safe and efficient highway infrastructure is a critical component and a valuable asset in terms of its monetary value, as well as supporting the way of life and economic activities of the people it serves. In North America, performing maintenance, repair, and expansion of an aging highway infrastructure to a target level of performance while dealing with ever-increasing traffic demands creates a significant challenge in terms of road user safety and mobility. Much of the current highway infrastructure was built several decades ago and it is therefore requiring increasing levels of maintenance and rehabilitation.

The cost of delays resulting from traffic congestion induced by work zones is estimated to be more than $6 billion per year. Work zone related traffic fatalities exceed more than 1000 lost lives per year in North America. Work zone related fatalities account for approximately 2.8 percent of highway fatalities in United States and 1.3 percent in Canada. While overall fatal crash rates have been steadily decreasing in both Canada and United States, work zone related fatalities have not been decreasing.

Smart Work Zones are an emerging technology designed to improve the safety and mobility within work zones on highways. Smart Work Zones employ various technologies to monitor current traffic conditions and provide relevant information to road managers and road users on current traffic flow conditions and automatically provide guidance to motorists for safer and more efficient navigation of the work zone.

This research examined the effects of a Smart Work Zone deployment by modeling traffic flow with and without a Smart Work Zone at the case study site in North Carolina to provide inputs into a performance analysis framework. The quantification of benefits and costs related to the deployment of a Smart Work Zone was developed in a probabilistic analysis framework model. The performance was quantified in economic terms of expected benefit cost ratio and net value realized from the deployment of a Smart Work Zone. The model considers the cost of deployment and potential savings in

terms of motorist safety (fatal and injury crash reduction) as well as improvements in traveler mobility including reductions in user delays, vehicle operating costs, and emissions.

The model output is a risk profile that provides a range of expected values and associated probabilities of occurrence to quantify the expected benefits while also taking into consideration the uncertainty of the most sensitive input variables. The uncertainty of input variables determined to be the most sensitive were those associated with the amount of user delay and the valuation of user delay. The next most sensitive inputs are those associated with the cost of deploying and operating the Smart Work Zone system.

The model developed in this research concurs with the approach and analysis used in other models for the analysis of transportation projects. The model developed in this research provides a tool that can be used for decision making regarding the deployment of a Smart Work Zone and comparison with other transportation project alternatives. The model employs a user definable approach that enables it to be adapted to the specific conditions of a diverse range of field state conditions and has the ability to interface with several traffic flow models.

When applied to 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 case study represented one of many operating scenarios on the project, and is not necessarily representative of all the field state conditions occurring over the period of the entire deployment.

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 ratio of deploying a Smart Work Zone system was between 1.2 and 11.9 and the net value was between $10,000 and $225,000 per month of operation. Approximately 94 percent of the expected benefits were from savings in user delay and the remainder from savings due to improved safety, reduced emissions, and reduced vehicle operating costs. The results indicate that when applied under appropriate conditions, Smart Work Zones have the potential to provide significant benefits to road users. Under heavily congested conditions, the diversion of even a small amount of traffic to a more efficient route can provide sizable travel time improvements for all traffic.

In summary, the model developed in this research was specifically developed to apply to Smart Work Zones, but in its general form could also be applied to other work zone traffic management applications. In the case study the model was applied to a single rural work zone, but the framework could be extended for an integrated analysis of multiple work zones and network analysis in an urban setting. The research provides a fundamental framework and model for the analysis of Smart Work Zones and a method to determine the sensitivity of the uncertainty of input values. The research also identifies areas for continued examination of the effects of Smart Work Zone deployment and the prediction of expected benefits.

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List of Symbols and Abbreviations

AADT	Average Annual Daily Traffic
B / C	Benefit Cost Ratio
BCA	Benefit Cost Analysis
CO	Carbon Monoxide
DPL	Decision Programming Language software
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
HERS	Highway Economic Requirements System
IDAS	ITS Deployment Analysis System
IRR	Internal Rate of Return
ITS	Intelligent Transportation Systems
NCHRP	National Cooperative Highway Research Program
NCDOT	North Carolina Department of Transportation
NHS	National Highway System
NOx	Oxides of Nitrogen
NPV	Net Present Value
NV	Net Value
PCMS	Portable Changeable Message Sign
SWZ	Smart Work Zone
TMC	Traffic Management Centre
USDOT	United States Department of Transportation
VOC	Volatile Organic Compounds

1 Introduction

1.1 Background

Intelligent Transportation Systems (ITS) technologies have shown the potential to improve safety and mobility in highway work zones (FHWA[1], 2002). However, there are limited reliable models to predict the effects of ITS deployed in work zones. 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.

Highway work zones decrease safety and mobility on the highway system. Work zones are an increasing factor in inducing traffic delays and less safe driving behaviour because of increasing need for pavement rehabilitation. Work zones often require additional driving manoeuvres such as lane changes, crossovers and speed reduction which are made more difficult by driver unfamiliarity with the new traffic patterns. A reduction in capacity can also result from the presence of a work zone due to lane closures, lane narrowing, lane shifts, and other factors. Changes due to a work zone result in a disruption of normal traffic flow, leading to a reduction in traffic flow capacity, increased delays, and increased crash potential.

Improving safety and mobility in work zones can be addressed through a variety of approaches. One of the solutions being utilized by transportation agencies to help minimize safety and mobility concerns in work zones is the use of ITS technology. 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. Smart Work Zones can be used to monitor and manage traffic, provide traveler information, manage incidents, enhance safety, increase capacity, plan future work zones, and enhance traffic enforcement (FHWA [1], 2002).

Traffic volumes and the amount of highway preservation work are both increasing, while there has been limited growth in highway capacity to accommodate the increased traffic. In the United States vehicle miles traveled increased by 82 percent between 1980 and 2001 while lane miles increased by only 4.2 percent (FHWA [2], 2004). The transportation infrastructure is a vital asset and as it ages, more effort and resources must be focused on the preservation of the road infrastructure. The share of capital funds used for preservation in 2000 was 52.0 percent, up from 47.6 percent only a few years earlier in 1997 (FHWA [3], 2002).

It is estimated that 26.5 percent of the National Highway System (NHS) in the United States experienced at least one day of work zone activity in 2001 and that on the peak activity day, July 25th, 4.8 percent of the NHS experienced an active work area. In terms of exposure, an estimated 12 billion vehicle miles traveled were through an active zone and an additional 61 billion vehicle miles traveled were past an inactive work zone in 2001 (Ullman, 2004). The additional activity required to preserve the highway infrastructure, often in areas with high traffic volumes, contributes to localized long term congestion problems on the highway system.

Traffic management is further complicated in urban areas where multiple projects may be occurring simultaneously, especially in jurisdictions with constraints on the length of the construction season. Non-recurring conditions such as weather, incidents, and special events are responsible for an estimated fifty percent of all highway congestion, of which nearly 24 percent is attributed to work zones (Chin, 2002). Based on the estimated total cost of congestion on United States highways, the cost of congestion due to work zones is more than $6 billion per year (Lomax, 2005).

In addition to the safety and mobility concerns expressed above, many rural freeways have a high percentage of unfamiliar travelers. As an example, 57 percent of motorists on rural sections of Interstate 95 in North Carolina reside out-of-state (North Carolina Department of Transportation, 2003). Therefore, unfamiliar drivers are frequently unaware of upcoming work zones, resulting in an increase in crash potential and a corresponding need for better advance traveler information.

1.2 Need

Measures of traffic safety such as crashes and fatalities per distance traveled have shown long term improvement in North America. In Canada, from 1984 to 2001, fatalities resulting from traffic collisions decreased by 33 percent despite substantial increases in population (26 percent), motor vehicles registered (26 percent), and licensed drivers (34 percent) (Transport Canada, 2002). Despite the progress in overall safety, fatalities associated with work zones are not decreasing. In the United States, work zone related fatalities increased for a period of 5 years from 693 in 1997 to 1181 in 2002, an increase of 70 percent. From 2000 to 2005 work zone related fatalities have exceeded 1000 per year in the United States (National Work Zone Information Clearinghouse, 2004). In Canada, work zone related fatalities varied between 38 and 41 annually over the period of 1998 to 2001 with no apparent long term trend. Overall, work zone related crashes account for approximately 2.8 percent of all highway fatalities in United States and 1.3 percent in Canada (Bushman[1], 2004).

Maintaining mobility of traffic while undertaking road preservation work is an increasing concern of many agencies. In 2004 the *Rule on Work Zone Safety and Mobility* was published in the Federal Register. The purpose of the rule is to "*facilitate the systematic consideration and management of work zone impacts throughout project development and implementation*". One of the reasons for this approach is the growing frustration of travelers with delays associated with work zones (FHWA[4], 2004). To address the mobility needs of road users, more than 100 possible strategies are identified in the FHWA *Rule on Work Zone Safety and Mobility* for improving work zone safety and mobility in categories of control, traffic control devices, project coordination, public awareness, motorist information, demand management, network management, safety management, incident management and enforcement strategies. Smart Work Zones are one of the strategies identified that can be used to address safety and mobility issues associated with work zones

The application of ITS technology to work zones has the potential to improve safety and mobility. While some implementations of Smart Work Zones have been very successful in meeting safety and mobility objectives, other implementations have not had the desired results due to poor system performance, poor project selection, or poor planning (Fontaine, 2001). The ability to reliably predict 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.

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. Addressing traffic related issues, such as safety and mobility, are of primary importance in work zones and therefore it is necessary to be able to understand and predict the effect of a Smart Work Zone on traffic conditions.

1.3 Research Goal

The goal of this research is to demonstrate the merits of ITS based work zone traffic management systems and provide a performance evaluation framework to make informed decisions on the deployment of Smart Work Zones.

1.4 Research Objective

The objective of this research is to develop a probabilistic Smart Work Zone analysis model with the ability to value the expected costs and benefits and quantify the uncertainty in terms of reduced user delay, reduced vehicle operating costs, reduced emissions, and improved safety resulting from the deployment of a Smart Work Zone.

1.5 Research Scope

This research evaluated the effect that the deployment of a Smart Work Zone may have on road users, the agency, and society. Both safety and mobility are of primary importance as they may be most affected by traffic flow through the work zone.

This research focused on one particular type of Smart Work Zone technology and application. The Smart Work Zone, as considered here, is a traffic management system that measures current traffic conditions and provides advisories to motorists on a public information website and at the roadside via portable changeable message signs (PCMS). The system employed in the case study site on I-95 in North Carolina was the Travel Messenger™ TM100 system provided by International Road Dynamics (Bushman[2], 2004). The analysis framework could be applied to other types of systems such as lane merge guidance or speed advisory systems, but application to other systems is beyond the scope of this study. This study examined the application of a fully portable system consisting of roadside traffic sensors, roadside message signs, and a public website including a graphical map displaying traffic conditions.

A probabilistic performance analysis model was developed for the evaluation of Smart Work Zone applications and evaluated for that purpose. 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 ratio and expected net value.

Estimates of the changes in traffic flow and traffic delay were investigated using two commercially available traffic models to perform the traffic flow analysis of vehicles through a Smart Work Zone. The two models considered in this study were the QuickZone macroscopic analysis tool and the VISSIM microsimulation software.

The models were applied to a field deployment case study that took place in 2003 on a rural portion of Interstate 95 in North Carolina. The models were evaluated based on their ability to predict queue development as compared to actual field conditions as observed at the study site in North Carolina. The modeling and analysis was restricted to a specific set of conditions that occurred during the field investigation of the case study site and may not necessarily reflect the variety of conditions that occurred throughout the entire deployment. Therefore, the results should not be considered as typical or representative of the entire project.

1.6 Methodology

The methodology followed in the research, as illustrated in Figure 1, included a literature review, formulation of the analysis framework, validation of the framework, and application of the analysis to a case study scenario from I-95 in North Carolina. The methodology is described in more detail in the following subsections

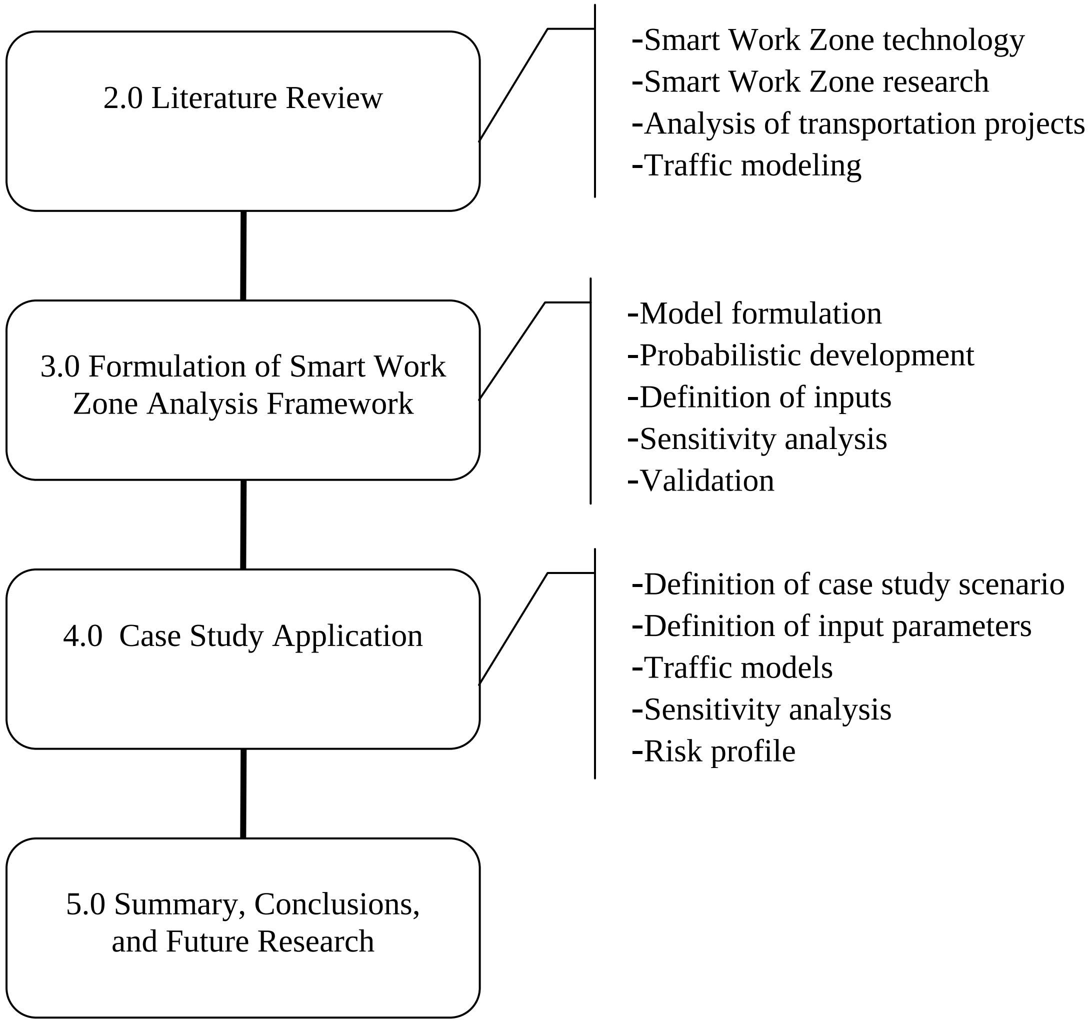


Figure 1: Diagram of Research Methodology

1.6.1 Literature Review

The main subjects of the literature search were Smart Work Zone technology, Smart Work Zone evaluations and research, traffic flow modeling, analysis of transportation projects, user delay, traffic safety, vehicle operating costs, and emissions. Potential sources were identified including a search using the University of Saskatchewan Engineering library system, the Transportation Research Board online database, the Work Zone Safety Information Clearinghouse, FHWA work zone publications, and networking with industry professionals. Relevant results from the literature search were compiled and are summarized in Chapter 2.

1.6.2 Development of Smart Work Zone Analysis Framework

A framework was developed for the assessment of Smart Work Zone deployments and the benefits and costs associated with the deployment. Approximately 20 benefits and costs were identified with a variety of measures to quantify their value. To facilitate the common comparison, economic units were chosen for the Benefit Cost Analysis (BCA) framework. The defined requirements of the BCA were to produce quantifiable results of deploying a Smart Work Zone, address uncertainty and risk in the analysis and application, and balance need for confidence in results with time for performance of analysis. A broad range of possible agency, user, and social effects were identified for consideration. The scope for this study was defined to include safety (injury and fatal crashes) and mobility (user delay, vehicle operating, and emissions) benefits and costs.

A BCA model with the ability to output the estimated incremental benefit cost ratio and net value was developed as a deterministic model in Excel and as a probabilistic model using Decision Programming Language (DPL) software. DPL was created by Applied Decision Analysis and facilitates the creation of decision making models and analysis of complex problems. 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.

The results from the Excel analysis were compared to DPL in a deterministic mode to ensure that both provided comparable results. Probabilistic analysis was then introduced through DPL to determine the sensitivity of the results to uncertainty in the input variables and to develop a risk profile to address the uncertainty in the analysis and application of Smart Work Zones.

1.6.3 Application of Work Zone Analysis Framework to Field Case Study

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

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 benefit / cost ratio and as a net value.

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 field location 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.

To analyze the effects of a Smart Work Zone on traffic flow, two traffic flow models were evaluated during the formulation process to represent two basic approaches to the modeling process. The two models considered were QuickZone 2.0, a commercially available macroscopic traffic model developed specifically for work zones, and VISSIM, a microscopic traffic simulation model. 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. Vehicle arrivals and percentage trucks in the traffic stream were manually tabulated at one minute intervals. 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 each of the two modeling methods, using identical project phasing, traffic volumes, capacity and traffic behaviour. The sensitivity of each model was analyzed considering variations in the capacity, demand, and traffic behaviour variables. To evaluate the outputs being produced by each of the two traffic models, results from the field case study site were compared with the predicted model results. A comparison of the predicted results from each of the models was compared to actual field results to determine the reliability of each model to represent typical real life conditions. Input parameters were varied to determine the sensitivity of the model results to changes in typical field state conditions of work zones.

The I-95 case study values were used as inputs into the economic analysis model and a sensitivity analysis and risk analysis were performed to estimate the expected results of applying a Smart Work Zone under the specified site and traffic conditions.

1.7 Layout of Report

Chapter 1.0 includes the introduction and background, need, goal, research objectives, scope, and methodology of this research.

Chapter 2.0 provides a summary of the literature review regarding Smart Work Zone deployment, evaluation of intelligent transportation systems, and the valuation of traffic safety, travel time delay, vehicle operating cost, and vehicle emissions.

Chapter 3.0 describes the formulation of the analysis framework for deterministic and probabilistic benefit cost analysis of a Smart Work Zone deployment and the validation of the framework.

Chapter 4.0 presents the application of the traffic model and economic analysis to a case study site on I-95 in North Carolina. The process of obtaining model input values, including field investigation and traffic modeling, is described. A probabilistic economic analysis of the effects of Smart Work Zone deployment is presented including sensitivity analysis and risk analysis.

Chapter 5.0 provides a discussion of the results of the study, identifying validity and limitations of the approach, and future research and enhancements to the framework.

2 Literature Review

Since Smart Work Zones are a relatively new application of ITS, research regarding Smart Work Zones is not yet extensively documented in the available literature. There is a larger body of applicable research and reference literature available for more common applications of ITS as well as transportation projects as a whole (PIARC, 2000). A literature review was conducted to identify the existing research and information related to the deployment and evaluation of Smart Work Zones.

The first section of the literature review provides an overview of the history, technology and evaluation of Smart Work Zones. The second section of the literature review covers the various elements related to the performance analysis model that was developed in this research. Each of the main components of the model illustrated in Figure 2 is addressed in the literature review. Traffic modeling is an important subset of traffic delay analysis, and therefore this research. As a result, traffic modeling as it pertains to Smart Work Zone analysis is presented as an additional subsection in the literature review.

Several of these topic areas are quite broad, so the literature review was restricted to information closely related to the objective of the study – evaluating the use of Smart Work Zones. Sources of information include agency crash statistics data, evaluation guidelines and technical advisories from government agencies such as Transport Canada, FHWA, and the Environmental Protection Agency (EPA). Information from relevant Smart Work Zone research projects are also documented in the literature review

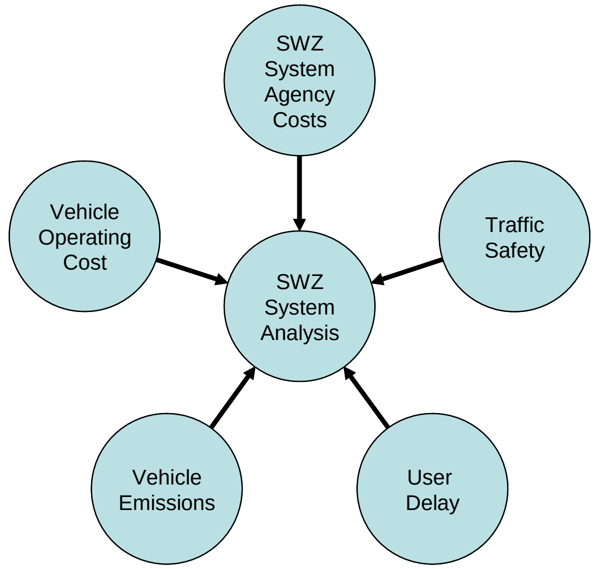


Figure 2: Smart Work Zone Performance Analysis Model Components

2.1 Review of Smart Work Zone System Technology

2.1.1 History of Smart Work Zone Development

Smart Work Zones are a relatively new development for the management of work zone traffic. In 1996 Minnesota Department of Transportation was one of the first agencies to begin experimentation with this type of technology, but with less automation than currently available systems (SRF Consulting Group, 1997). The system used semi-portable field units to provide traffic data back to a traffic management center (TMC). At the TMC, the traffic data was manually reviewed and messages were selected by an operator to be displayed on permanent and portable message signs in the vicinity of the work zone. The primary purpose of the Smart Work Zone system was to provide advisories of traffic delays due to a work zone. In 1996 Maryland also experimented with an automated Smart Work Zone system. Between 1996 and 2006, some form of work zone ITS has been applied in approximately 20 States and Provinces.

Additional applications of Smart Work Zones have been developed to address other traffic control and guidance needs such as reduced speed advisories, dynamically adjusted speed limits and lane merge control and guidance (FHWA[1], 2002). The predominant application still remains providing relevant delay advisories and alternate route guidance. Advancements in the technology have led to increased functionality of the travel information system including improved portability, public websites, and video images, but the primary purpose of improving safety and mobility remains unchanged.

2.1.2 Smart Work Zone System Operation

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 illustrated in the system architecture diagram shown in Figure 3.

Each of the Smart Work Zone components is described in their general application and then specifically how they were applied to the case study project on I-95 in North Carolina considered in this research.

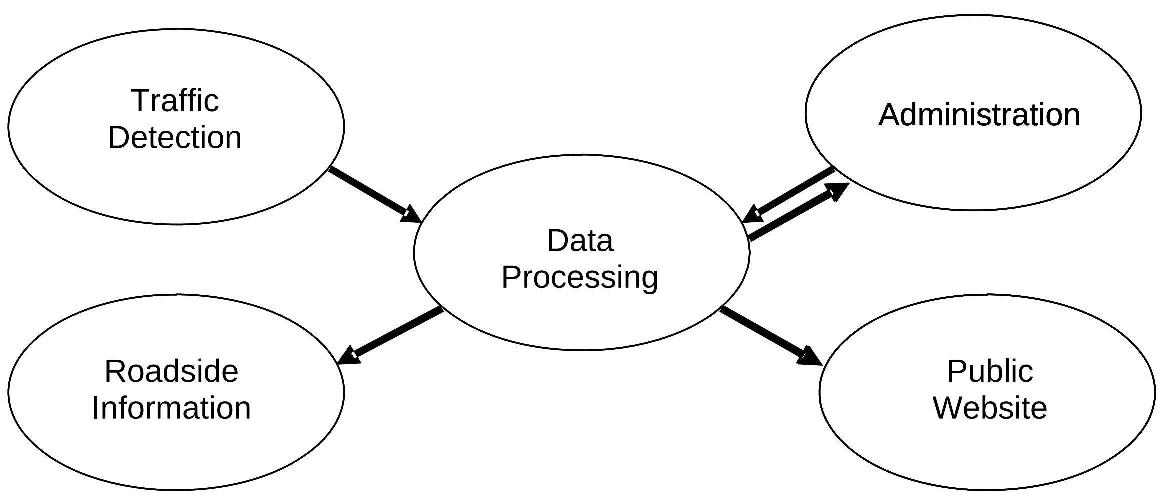


Figure 3: Typical Smart Work Zone System Architecture

Traffic Detection: Traffic detection data is collected from the roadside on a periodic basis so that informed and relevant decisions can be made on 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 many work zones necessitates a portable approach to the selection of technologies and systems. Detection technologies include acoustic, Doppler radar, microwave and video technology. For the specific application under consideration in this thesis a radar based true-presence microwave traffic sensor was used at three detection locations. The microwave traffic sensor is capable of measuring speed, volume, and occupancy over one to eight lanes.

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. In the specific application under consideration, the processing function was split between a roadside microprocessor and a server computer stationed at a remote location. The roadside electronics for data processing are shown in Figure 4.

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.

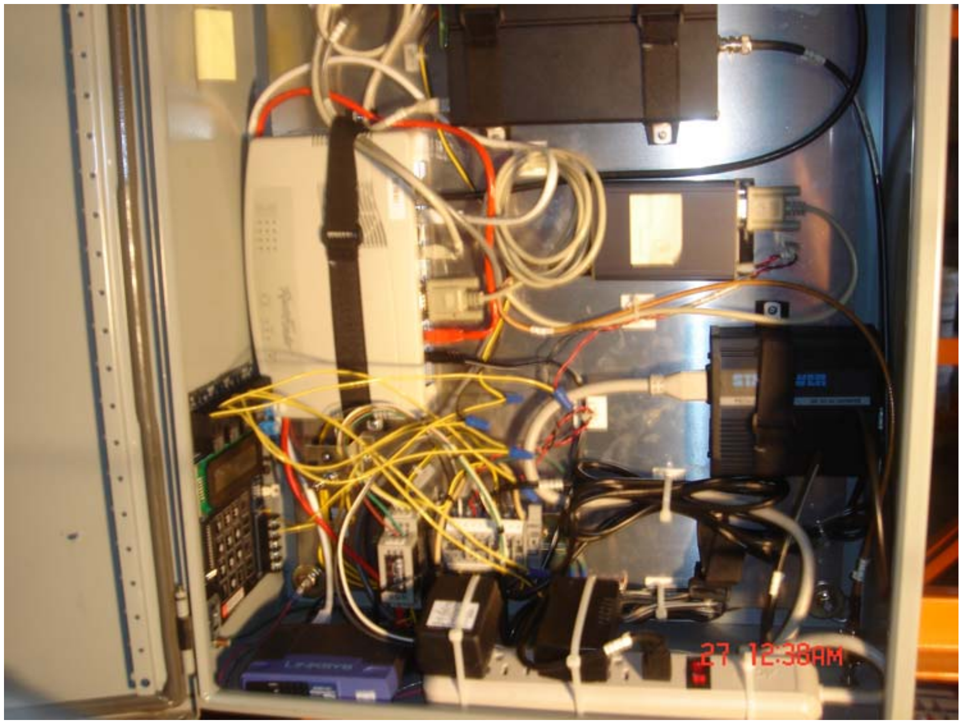


Figure 4: Smart Work Zone Road Side Electronics for Data Processing

The application that is the subject of this thesis was designed to provide delay time advisories and alternate route guidance to motorists. PCMS equipped with wireless communication were used to receive advisory messages from the central processor and post them for motorists to see. The display message was updated every two to three minutes as new traffic data was processed. Three levels of messages were provided to motorists based on current traffic conditions. Messages were displayed on three lines of eight characters and up to three frames in sequence. A PCMS with current travel information is illustrated in Figure 5.

Generic messages informing motorists of a work zone ahead, such as “Traffic Slowing Ahead / Prepare To Merge” and “Current Traffic Info / No Delay Exits 150-141”, were displayed when no delays were detected. When short delays were detected, but not long enough to warrant the use of the alternate route, the current delay estimate was displayed with a message such as “Traffic Stopped Ahead / 15 Minute Delay”.

Figure 5: Road Side Message Sign Advising Motorists of Delay Ahead

When delay time reached the point where the alternate route offered a shorter travel time, the amount of delay and the suggested alternate were displayed using a message such as “Traffic Stopped Ahead / 20 Minute Delay / Use Exit 141 As Alt”. Travel time on the alternate route was estimated based on the existing site conditions and was not monitored in real time. There was sufficient capacity available on the alternate route so that the additional traffic from the mainline was not expected to cause any traffic delays on the alternate route.

<u>Public website</u>: A public website is used to provide information to motorists prior to departure on a trip. The website may include advisories of delay, alternate route information, and current video images from the site. A typical webpage including a color coded map of a construction site is illustrated in Figure 6.

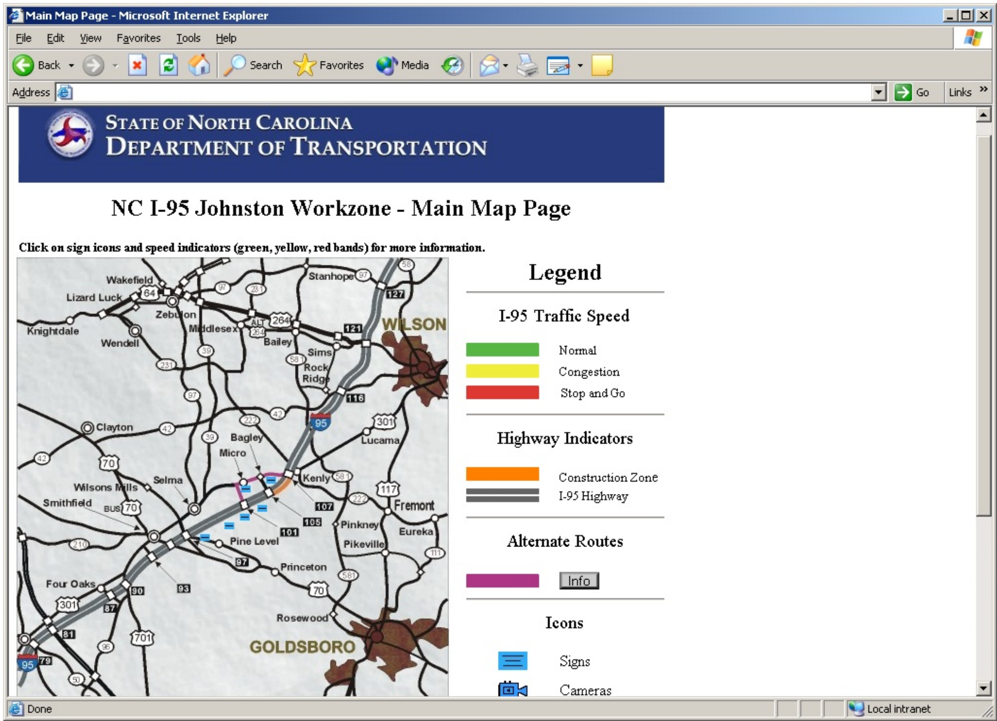


Figure 6: Public Website Showing Current Conditions

The availability and usage of the public website is relevant for the system performance analysis since it may alter motorist behaviour. Given travel information in advance of departure, motorists may decide to alter the timing of their trip, the trip route, and the final destination. Trip alteration results in a reduction or shift in demand at the site which could alter the analysis of safety and user delay.

<u>Administration</u>: The administration function of the Smart Work Zone provides the capability to monitor and control the operation of the system. The most recent traffic information and video images are made available and current system functions are monitored and reported. System control parameters can be adjusted and information being distributed can be overridden by authorized personnel. For example, in the case of a traffic crash specific messages may be posted to the roadside signs.

2.1.3 Smart Work Zone Research

A detailed review of previous research has been completed by others (Fang, 2006). Only the most relevant sources as they pertain to the economic evaluation goals of this study are cited here. Much of the early research was inconclusive due to technical difficulties, unsuitable test locations, and a focus on the ability of systems to meet the functional requirements, and not on the operational effectiveness (Fontaine, 2003). Studies have been conducted that indicate potential benefits in traffic control and safety with the deployment of a Smart Work Zone. To illustrate, one study in Nebraska showed that the percentage of vehicles using alternate routes increased from eight percent without signing in place to eleven percent when the system was in operation. This particular system did not give any guidance to actually use alternate routes, only advisories of the expected delay, and it was proposed that the increase in alternate route usage may have been greater if directive messages were used. Research in Wisconsin on a system which provided delay messages, but no directive to use alternate routes, indicated that diversion rates of ten percent were achievable during peak hour traffic (Horowitz, 2003).

Previous research was conducted in Arkansas on a system similar to the one deployed in Nebraska (Tudor, 2003). The crash rate at the site with the Smart Work Zone was compared with two other control sites with similar characteristics, using number of crashes per 100 million vehicle miles traveled as the measure. The fatality rate was 2.2 for the site with a Smart Work Zone, compared to 3.2 and 3.4 at the sites without a Smart Work Zone, an average reduction of 33 percent. The rate of rear-end crashes was 33.7 for the site with a Smart Work Zone, compared to 29.5 and 43.2 at the sites without a Smart Work Zone, an average reduction of seven percent. Traffic counts taken on an alternate route showed an increase in traffic when a back-up advisory message without identifying an alternate route was displayed. The increased traffic on the alternate route was estimated to represent in the range of two to six percent of the mainline traffic.

A study in Missouri examined the use of an automated system which advised drivers when delays and reduced speeds were occurring at a work zone site. Analysis showed that the system had a positive effect on the reduction of mean speed and speed variance as the traffic neared the work zone. This is considered to be an indication of improved safety of the work zone (King, 2004).

The research conducted to date provides an indication that Smart Work Zones can have a positive effect in managing traffic. Many of the studies are for specific projects and often focus on a limited number of effectiveness measures. The objective of this study was to bring together the pieces of information from previous research work that has been performed and supplement it with additional research to lay the groundwork for a more comprehensive assessment of Smart Work Zone benefits.

2.2 Economic Analysis Applied to Smart Work Zone Projects

The stated objective of the study was to develop a model and framework for determining the suitability of Smart Work Zone technology for a specific project. If the use of Smart Work Zones is to become a common practice rather than limited to experimental projects, Smart Work Zones will need to be evaluated against other transportation improvement projects. Therefore, it is reasonable to consider the use of established decision criteria such as an economic benefit-cost analysis.

When transportation infrastructure projects such as road and bridge construction and maintenance are being considered there is typically well documented historic information on which to base the analysis. With ITS projects, especially Smart Work Zones, the history of benefit and cost data is limited. Progress is being made in this regard, as available information from ITS projects is gathered and made available by the United States Department of Transportation (USDOT) through the FHWA ITS benefit / cost database (USDOT[1], 2004) and other initiatives.

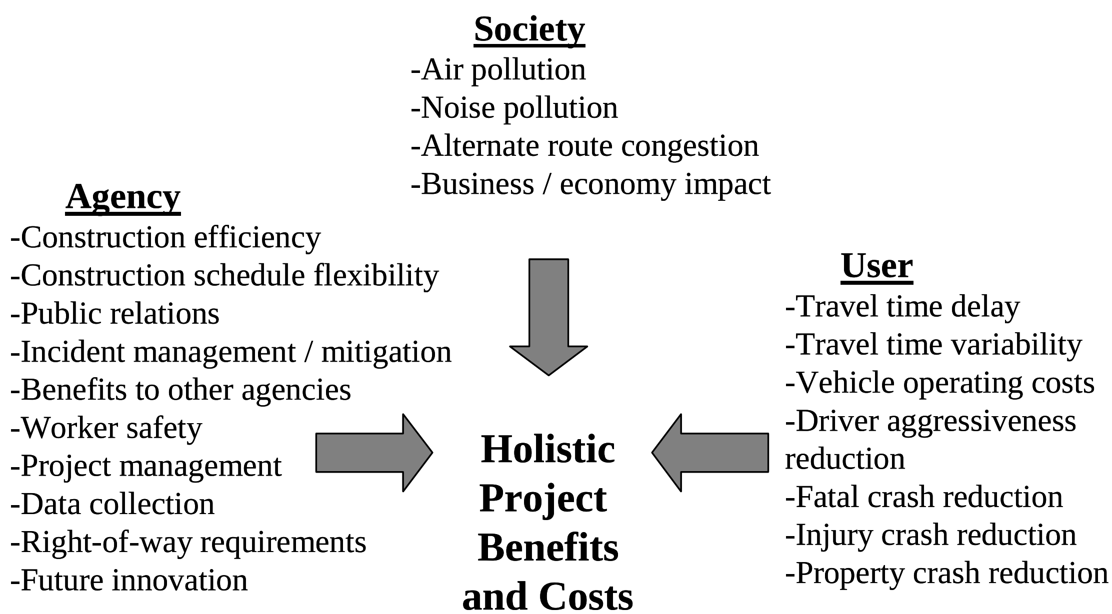
The evaluation of an ITS project requires a combined approach utilizing historical information and modeling and prediction of unknown parameters. Where it is available, historical and research data from previous projects should be drawn upon. Given the incomplete nature of the available data, other methods are also required. The use of models including simulation models is one approach to fill in the required information that is not otherwise available. Modeling has limitations and requires assumptions to be made which may affect the outcome of the analysis. The assumptions and limitations of the analysis should be understood and discussed in the evaluation (Gillen, 1999).

Given that traffic flow is by nature stochastic and that there is a lack of historic information on system performance, there is an element of uncertainty involved in the analysis which should be facilitated to allow comparison over the range of possibilities. Uncertainty can be dealt with by applying risk analysis, using a probabilistic approach, or by performing a sensitivity 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 (Ozbay, 2004).

An example of applying a probabilistic analysis to transportation projects is RealCost, a life cycle cost analysis program developed for assessment of paving projects (FHWA[5], 2004). 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 net present value. Decision making tools such as the DPL program can provide similar analysis to that provided by RealCost, including analysis of sensitivity, risk, uncertainty and expected results. DPL provides improved flexibility to define inputs and to formulate probabilistic calculation of results for a specific application.

There is an increasing emphasis on context sensitive design and holistic transportation analysis. Holistic analysis is a recognition 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 (Poorman, 2005). The initiatives of the FHWA to address traffic impacts in the early stages of planning and the use of a Smart Work Zone could be considered a part of the move to holistic transportation planning. For example, a Smart Work Zone with a website gives people the ability to know current conditions and choose options other than their normal automobile trip that could include alternative transportation, alternative work arrangements or other shifts in their planning. A number of factors that are not typically included in the analysis of transportation projects but are part of a holistic approach are identified in Figure 7. The inclusion of vehicle emissions and user delay costs in the economic analysis is a move towards holistic analysis. The costs and benefits vary depending on the purpose, approach and project.

Some of the items listed may actually cross the category boundaries, and may be either a benefit or a cost depending on the specifics of the application. Some evaluation approaches have attempted to monetize most or all of the benefits and costs of a project, while others treat many of the factors in a subjective and qualitative manner.



(Al-Kaisy, A., 2004, Transport Canada, 1994, Kratofil, 2001, Jiang, 2003)

Figure 7: Holistic Costs and Benefits Associated With a Smart Work Zone Deployment

Transport Canada provides guide lines for the evaluation of the economic merits of expenditures using a benefit-cost analysis (BCA) on all types of transportation projects; air, sea and land (Transport Canada, 1994). In the terminology used by Transport Canada, a BCA does not necessarily mean that the benefit-cost ratio is the measure used to compare options. BCA refers to the process of systematically identifying and quantifying benefits and costs for project options and then determining their relative merits. The results of a BCA may use net present value (NPV), benefit-cost ratio, pay-back period, and internal rate of return (IRR). NPV is suggested as the preferred economic measure by Transport Canada.

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. This approach is similar to the approach used for more common work zone traffic control items such as channelizing devices, arrow panels and PCMS. 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. Since all of the significant benefits and costs are accrued at the time of deployment and use, the pay-back period and internal rate of return are not meaningful for the evaluation of a Smart Work Zone, unless there is capitalization of the system over longer term projects or several projects. The term “net present value” 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 net present value.

Guidelines for evaluation of transportation projects provided through 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. (Forkenbrock, 2001).

Many evaluations of transportation projects, including 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 (Gillen, 1999). 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 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.

In the scope of this study, the analysis was restricted to a comparison with the do-nothing option, but in reality a candidate project, even if beneficial, needs to be compared with other options and projects. In some cases, there may be a bias against ITS applications in favour of hard assets such as asphalt and concrete. This bias will make it all the more important to have a credible analysis of expected results to support the deployment of a Smart Work Zone.

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 into the benefits of work zone ITS, and therefore it is difficult to predict with certainty the benefits that may be realized.

From the perspective of the agency, only the agency costs of deployment and operation can be measured directly in hard dollars. Other effects are either difficult to quantify in terms of monetary value to the agency or are attributed to road users or society in general. User delay and vehicle operating costs are often assigned a monetary value, but the benefits are attributed to road users and not to the agency. The other effects are not directly monetary in nature. Since BCA has been established as a common evaluation method for transportation projects, monetary values and guidelines have been established for some of the key effects. For example, the Federal Highway Administration has established guidelines for the value of a statistical life to be used in assigning a value to safety improvements (FHWA[6], 1994). Likewise, agencies have established guidelines for the value of user delay and crashes of varying severity.

The USDOT uses the Highway Economic Requirements System (HERS) Model for assessment of transportation investments. The HERS model estimates three types of direct highway user benefits which can be quantified in monetary terms: 1) travel time savings, 2) vehicle operating costs and 3) safety effects (Hodge, 2004).

ITS also has potential benefits that are difficult to quantify and where established guidelines do not exist. For example, a successful Smart Work Zone project could have benefits not directly related to the project itself. The responsible transportation agency may gain a benefit in good will and a perception from road users as being progressive and concerned with motorist needs by deploying new technology. On the other hand, an unsuccessful ITS project may be viewed as mismanagement of public funds that could have been spent on roads, health care or education instead. The increased publicity drawn to work zone issues and awareness of motorists may improve the safety of drivers at other sites. As well, there may be more significant benefits that will be realized from ITS in the future as technology develops and the scale of deployment increases, but that future potential can only be realized by deploying systems that are currently available. It should be acknowledged as a limitation of any BCA that not all factors can be accounted for explicitly in the analysis.

2.2.1 Traffic Safety

Improved safety is expected to result from a reduction in the occurrence and magnitude of congestion and improvements in the consistency of traffic flow. The increased awareness by motorists of an approaching work zone provided by the roadside signs is also expected to be a factor in improving safety. Another safety factor may be the reduced aggression of drivers in and around the work zone. Delays of unknown cause and duration may create stress and aggravation for motorists that could affect driver behaviour and performance. Timely and accurate information helps the motorist understand their situation and gives them control to choose an alternate route or continue through the work zone.

As identified earlier, there have been more than 1000 work zone related fatalities annually in North America since 2000 (National Work Zone Information Clearinghouse, 2004). The use of a Smart Work Zone system may therefore be a tool to reduce the fatalities that occur. Reducing the number of fatalities, if it is achieved, will be the result of two primary effects. The first desirable effect is a reduction in the total number of crashes that occur. This may be a result of reduced queue lengths, better driver awareness, and improved driver attitude. The second desirable effect is a reduction in the severity of the crashes that still do occur. This could be a result of reduced speed and speed differential on the mainline, a shift in crash types, and a shift in crash location from high speed freeway locations to lower speed alternate routes.

Before estimating the change in crash rates due to a Smart Work Zone, it is necessary to determine the base crash rate expected without a Smart Work Zone. One approach is to estimate the work zone crash rate in relation to the crash rate for the same highway segment prior to the presence of a work zone. Crash rates are routinely calculated for highway segments as the number of crashes per distance traveled by motorists. These crash rates can provide a base value for determining the relative safety of different segments. Research has indicated that the presence of a work zone can increase the crash rate for a highway segment, with most studies indicating an increase ranging from 7 percent to 30 percent. The influence of a work zone on crash rates can be difficult to quantify precisely and may be affected by many factors including traffic volume, duration of work zone, and length of work zone (Ullman, 1991, Khattak, 2002). Research by Tarko in Ohio examined the relation of crash rates to a number of variables, including type of work, duration of work, traffic volume, and work intensity, and established a model for prediction of crashes on a project that may also be used to determine the expected crashes (Tarko, 1999).

Finding an appropriate method to determine the impact of a specific treatment, such as a Smart Work Zone, on highway safety can be challenging. As cited earlier, there is limited research on the safety effects of a Smart Work Zone. The most direct measure of effectiveness is the change in crashes after the treatment is deployed. A choice can be made as to which crashes to consider: property damage only, injury, or fatal crashes. Of the greatest interest is usually the reduction of fatal crashes as they carry the greatest social cost.

The most direct method is to count the number of fatalities that occur under the treatment conditions and compare them to a non-treatment condition. Several issues arise with this approach, especially as related to Smart Work Zones. When safety upgrades are made to a highway system it is sometimes possible to use historical data from several years previous as a baseline. A construction project drastically changes the operating environment and therefore any historical data from that location can not be used for direct comparison. The infrequent occurrence of fatalities means that it is difficult to compile significant results from relatively short term construction projects. To directly evaluate the effect of a Smart Work Zone on traffic fatalities may require calculations based on the long term use of Smart Work Zones on multiple projects within a jurisdiction.

A second method to estimate the impact of a safety treatment on fatalities is to use a more commonly occurring event as an indirect or surrogate measure of safety. One indicator of a reduction in the fatality potential at a location may be a reduction in property damage or injury crashes. Everything else being equal, it is logical to consider that over time, a measure that reduces crashes should also reduce fatalities. As mentioned earlier, the safety treatment may also cause a shift in the severity of crashes which would affect the relationship between total crashes and fatal crashes. Although crashes are more frequent than fatalities, over a short period crash data may still be insufficient to draw conclusions regarding safety effects of a treatment.

Another surrogate measure method is a conflicts analysis. Driver behaviours that are thought to be an indicator of a potential crash are observed and counted with and without the treatment in place. For example, hard braking, lane wandering, or aggressive lane changes could all be indicators of the level of safety at a particular location (Van Aerde, 1995).

The final step in determining the economic benefit of safety from the deployment of a Smart Work Zone is to assign a monetary value to the reduction of injury and fatal crashes. Numerous studies have been undertaken to assign a value to the lives saved and injuries prevented by safety improvements. The value is made up of monetary costs such as medical and emergency costs, work loss, traffic delay, employer costs, and property damage. There is also a quality of life cost that values the pain, suffering and degraded quality of life resulting from the injury or death. The total monetary and quality of life costs are known as the comprehensive cost.

The value of life used by various agencies with regards to traffic fatalities is typically in the range of two to seven million dollars per life saved (NHTSA, 2002). The United States Department of Transportation has set as a guideline for economic evaluations a value of $3.0 million dollars for a statistical life (USDOT[2], 2004). Where individual agencies have a recommended value to be used in the economic evaluation of potential projects, this can be used in the analysis of a Smart Work Zone and entered into the decision making model created during this project. For example, North Carolina DOT provides guidance for the analysis of safety impacts of transportation projects and recommends a value of $3.7 million dollars for a fatal crash (Troy, 2005).

There are numerous sources that have defined the economic value associated with an injury crash. A 1994 FHWA technical advisory recommended that for economic evaluations a crash cost of $40,000 be used for moderate severity crashes (FHWA[6], 1994). The ITS Deployment Analysis System (IDAS) suggests that a default value of $59,719 be used for injury crashes (Cambridge Systematics, 2000). Based on data on frequency of crashes and associated cost of crashes of varying severity levels as determined by the National Highway Traffic Safety Administration, the average cost per injury crash is estimated at $58,128 in year 2000 dollars (NHTSA, 2002). North Carolina DOT recommends a value of $46,000 for non-fatal injury crashes (Troy, 2005).

2.2.2 Travel Time Delay

Travel time delay is defined as the difference between travel time on a roadway segment under free flow conditions and the actual longer travel time due to some cause. The cause of delay may be a traffic incident, demand that exceeds capacity, a work zone, weather or road conditions, or a variety of other factors. In the focus of this study, the cause of delay is the presence of a work zone with a lane closure. A work zone often results in reduced capacity by eliminating one or more of the travel lanes, narrowing lanes, or shifting alignment. The disruption of traffic flow due to merging and speed reduction can also result in traffic delay. Travel time delay is considered an important performance measure for a freeway system and is commonly used for ranking of different projects under consideration or for economic evaluation such as a benefit-cost analysis (Wang, 2004). In addition to the value of the time lost due to delay, there is also a cost in additional vehicle operating costs when delay occurs in a work zone. For clarity in this research, the additional vehicle operating cost due to delay is explicitly identified, and then added to the time value portion in determination of the value of travel time delay.

Four components of delay in work zones have been identified as follows:

- Deceleration on the approach to the work zone;
- Queuing delay;
- Reduced speed through the work zone, and;
- Acceleration back to normal highway speed (Jiang, 2001).

When long delays are experienced at a work zone, the deceleration and acceleration times become relatively small compared to the delay from reduced speed and queuing.

For an economic evaluation such as a benefit-cost analysis, it is common to look at the total delay hours or the average delay per vehicle as the measure of performance. As an overall project evaluation, this approach yields convenient and usable results.

The total delay hours or the average delay per vehicle may not fully capture the value of travel time delay for an individual. Travel time reliability has been suggested as an important measure of service, and for time critical travel, may be an even more significant factor than the average delay time. If travel time is inconsistent, drivers must allow extra time in their travel plans for the possibility that travel may be slow, or risk missing time critical events such as deliveries, travel connections, or meetings if they have not allowed extra time (Chen, 2003).

The type of delay may also be a factor in determining the value of delay to road users. Individual drivers have differing reactions and perceptions of the type of delay experienced, with some preferring the delay in the form of stopped traffic followed by a period of faster moving traffic while others prefer continuous slow moving traffic with no stopped time. Research is inconclusive as to which is the preferred alternative for the majority of drivers (Levinson, 2004).

Capacity is an important factor in determining the delay that will occur in a work zone. The Highway Capacity Manual suggests a base value of 1600 vehicles per hour per lane be used and adjustments applied for the intensity of work, heavy vehicles, and ramps in the vicinity of the work zone (Transportation Research Board, 2000). With adjustments for common factors, the range of capacity may vary between 1050 and 1750 vehicles per hour per lane for a freeway section reduced from two lanes to one lane.

The economic value of reducing user delay is dependent on the value assigned to each unit of user delay. Each traveler on a transportation system has a unique set of circumstances related to the valuation of time. The value of travel time variability is also unique for each individual. It is impossible to assess each individual circumstance and therefore it is necessary to use aggregate values to represent traffic in broad categories.

Another issue in valuation of time is the consideration of whether a small increment of time saving for a high number of users has the same value as large increments of savings for a few users. The rationale is that a few seconds can not be put to any useful alternate activity, but several minutes can be used for another purpose and therefore carry greater value. Researchers vary on how to address this issue (Forkenbrock, 2001). In this study, an equal value is used for all time savings, but distinguished between trucks and cars. It should also be noted that the operation of the Smart Work Zone does not begin to alleviate delay until the mainline delay has exceeded five minutes, so drivers are already experiencing a noticeable delay. Using the modeling techniques of this research, it is possible to create a profile of the time savings per vehicle which could be helpful in assigning the value of delay.

Much work has been performed which assigns a value to user delay, as cited below, but there is not consensus on what appropriate values should be for this type of evaluation. It is important to recognize that the value of user delay varies across geographical regions, vehicle occupancy, trip purpose, vehicle type, type of commodity being transported, and size of payload. Therefore, suitable user delay values must be determined for each project.

A survey of typical user delay costs used by transportation agencies in 1998 found values ranged between $8.70 and $12.60/vehicle-hour for cars, and between $21.14 and $50.00/vehicle-hour for combination trucks (Daniels, 1999). The United States Department of Transportation recommends for "local" travel a value of $8.90 per person hour be used and for inter-city travel a value of $12.20 per person hour, in 1995 dollars (USDOT[3], 1997). On a vehicle basis, this rate should be increased by the occupancy rate which varies between 1.14 for work trips and 2.17 for social and recreational purposes (USDOT[4], 1997). In an FHWA study on freight mobility, it is stated that "shippers and carriers assign a value to increases in travel time, ranging from $25 to almost $200 per hour, depending on the product carried. The value of reliability (i.e., the cost of unexpected delay) for trucks is another 50 percent to 250 percent higher" (FHWA[7], 2001).

The value of user delay is an important input into the evaluation model, but the determination of values is beyond the scope of this research. As each agency may have its own policy on assigning value to travel time delay, it is not necessary to reach a fixed value for completion of the evaluation model. Rather, the value of user delay for both cars and trucks is a user input that can include a range of expected values so that appropriate values for the specific project circumstances can be used.

2.2.3 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 (Choocharukul, 2002). Travel time and the general wear and tear on vehicles from substandard pavement conditions can both have an affect on vehicle operating costs (Hodge, 2004). 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 based on a first-principles approach to overcome the drawbacks of an econometric approach (Berthelot, 1992).

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 an improvement 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. If there is a significant difference in travel distance then 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 (Altamira, 2004). To facilitate the inclusion of vehicle operating costs in the evaluation of a Smart Work Zone without becoming an onerous task, a simplified approach is required. As traffic demand volume on a freeway increases and travel delay increases, fuel consumption will increase with the delay. It has been estimated, based on the Highway Economic Requirements System (HERS) model equations, that excess fuel consumed per hour of delay ranges from 2.2 gallons for a small car to 4.4 gallons for a sport utility vehicle (DeCorla-Souza, 2002). A more conservative approach, based on the assumption that delay time is idling time, estimates fuel consumption at 0.435 imperial gallons (0.522 US gallons) per idling hour (Natural Resources Canada, 2004). A heavy truck consumes an average of 0.8 gallons of fuel per hour of idling (EPA 2004). As of May 19, 2006 average gasoline prices in the central Atlantic region of United States were $3.001 per gallon and average diesel fuel prices were $3.014 per gallon. These prices for diesel and gasoline are twice the market value that existed in 2003 when the case study site in I-95 was deployed (Energy Information Administration, 2006). Using the conservative consumption value of 0.522 US gallons / hour and a fuel price of $3.001 per gallon the cost of fuel consumed due to delay by a car is estimated as $1.57 / hour of idling. Based on estimated consumption of 0.8

gallons per hour and a diesel fuel price of $3.014 per gallon, the value of fuel consumed by an idling truck is $2.41 per hour of idling.

2.2.4 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 reducing 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 the concern with 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 many countries the Kyoto Protocol is being supported as a guideline to control and reduce emissions while in United States, the Clear Skies program works towards the reduction of pollution (Emissions Marketing Association, 2002).

2.2.4.1 Emission Rates

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 emissions for various vehicle types (Environmental Protection Agency[1], 1998). 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.

Vehicle type and idling emissions only account for one of the factors in determining emission rates. A relationship exists between vehicle speed and the rate of emissions. For VOC and CO emissions, the lowest emissions occur over a range of approximately 50 to 90 km/hr. As speeds increase beyond this range there is a sharp rise in emission rates. NOx emission rates follow a different pattern. NOx emissions are high at speeds below 20 km/h and then remain relatively constant as speed is increased up to 90 km/h. As speeds continue to increase beyond 90 km/h NOx emissions decrease slightly. Vehicle acceleration also results in an increase in the rate of emissions (El-Shawarby, 2004).

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 will typically be longer in distance than the mainline and may include stops and starts.

2.2.4.2 Emission Costs

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. This is the case in the industrial sector where emissions trading takes place and allowances for Sulphur Dioxide and Nitrous Oxide are bought and sold and an emissions marketing association exists to promote this activity (Kinsman, 2002). 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. 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. Reference values based on previous research are listed in Table 1 and may be used as a starting point in determining an appropriate value for emissions.

Table 1: Valuation of Emissions Cited From Selected Sources

Source	VOC	CO	NOx
Petrov, Maryland Department of Transportation (Petrov, 2002) $US / ton	$6,700	$6,360	$12,875
Intelligent Transportation System Deployment Analysis System (Cambridge Systematics, 2000) 1995 $US / ton	$1,774	$3,731	$3,889
Small and Kazimi (as adjusted for inflation and cited by Kratofil, 2001) ($US / metric ton)	$6,190	$1,150	$6,650
FHWA Economic Requirements System Technical Report (FHWA[6] ,2000) ($US/ ton)	$1,802	$23	$2,608
Bell (Bell, 1994) (1990 $US / ton)	$3,300	$907	$4,209

Values quoted are directly from the referenced document in the units, currency and year noted and are not adjusted for inflation or other time-value effects.

In the 1994 study by Bell, pollutant values proposed by governmental agencies in 37 different research studies were compiled and the median value identified (Bell, 1994). The median value is proposed as most appropriate by some authors for this type of analysis, as extreme values do not affect the median to the same extent that the mean value is affected by extreme values.

2.2.5 Smart Work Zone System Deployment and Operation Costs

There are a number of factors that affect the cost of a Smart Work Zone such as the procurement method, the complexity of the project, the amount and type of equipment specified, the duration of the project, support requirements, and the competitive market conditions. The procurement of Smart Work Zone systems has been undertaken through a variety of methods. Methods have included sole source awards, low bid tenders, inclusion as a line item in construction tenders, or as a request for proposals. Projects range in complexity from several sensor locations and a few signs to multiple approaches, extensive signing, portable video monitoring stations and website reporting. There are both mobilization and operating costs associated with smart work zone deployment. For longer duration projects, the mobilization cost becomes a smaller portion of the overall project cost when considered on a monthly basis.

When Smart Work Zones are procured using a low bid process exclusively for the Smart Work Zone, it is relatively easy to obtain accurate system costing information. When the Smart Work Zone is procured as part of a larger contract or through other procurement methods, it can be difficult to obtain accurate information.

A system in Wisconsin providing travel and route advisories was estimated to cost between $200,000 and $400,000, on a furnish and operation basis, for a full construction season (Horowitz, 2003). A similar system installed in Lonoke County in Arkansas cost $262,500 for 350 days of operation (Tudor, 2003). These results are in the same range as results from competitive bids for the supply of Smart Work Zone systems in North Carolina.

2.3 Traffic Modeling

Traffic flow and queuing theory are well established for the determination of delay under normal traffic operating conditions such as signalized intersections. Traffic flow and queuing theory have also been applied to work zone settings (Jiang, 2001). Traffic flow and queuing theory can also be applied to Smart Work Zones but may require some additional considerations since Smart Work Zones create a dynamic situation wherein demand, queue development, and alternate route usage are interdependent and can change in reaction to current conditions.

Analysis and modeling of traffic flow characteristics can be performed at either a microscopic level or at a macroscopic level (May, 1990). At a macroscopic level, the analysis considers the behaviour of groups or units of traffic. At a microscopic level, the analysis considers each vehicle as an individual unit with unique characteristics and properties. Macroscopic and microscopic approaches may each have advantages in the analysis of Smart Work Zones, so both were considered in this study.

Parameters considered at the macroscopic level may include flow rates, hourly capacity and demand, average speeds, and density rates. Larger scale systems with higher density can be studied efficiently at a macroscopic level when a study of the behaviour of groups of units is sufficient.

Parameters considered at the microscopic level include individual vehicle acceleration, speed, time headway, distance headway, and driver behaviour. At a microscopic level it is possible to study the behaviour of individual units in the system and how changes in that behaviour affect the overall traffic flow. The ability to model individual behaviour in a Smart Work Zone, such as lane changes, merging, and route selection, is potentially of great interest.

Two commercially available traffic modeling packages, QuickZone and VISSIM, were selected for consideration in the study as representatives of the macroscopic and microscopic traffic modeling approaches respectively.

2.3.1 Macroscopic Traffic Flow Analysis

2.3.1.1 Queuing and Traffic Flow Theory

A summary of traffic-stream characteristics as defined by McShane is provided here (McShane, 1990). Volume (or rate of flow), speed, and density may be used to macroscopically describe a traffic stream. Each parameter is described individually and then in relation to the other parameters.

The number of vehicles passing a point on a highway, a specific lane, or in one direction of a highway during a time interval is defined as the traffic volume. The time interval is typically daily, hourly, or sub-hourly. The average annual daily traffic (AADT) is the average number of vehicles passing the site in one day, over a one year time period. On any given day, the actual traffic will vary from the AADT due to effects of seasons, day of week, and the various purposes of road users. Hourly and subhourly volumes may also be of use in characterizing a traffic stream as volumes may vary greatly throughout a given day. Peak hourly volume refers to the highest hourly volume occurring during a day and is often used for determining the design capacity that a roadway must provide.

Flow is a measure of traffic movement and is typically measured as vehicles per hour or vehicles per hour per lane.

Density is a measure of the amount of vehicles on a limited segment of highway and is defined as the number of vehicles per specified length of highway or lane. Density provides a measure of the quality of traffic flow as it indicates the space, or lack of space, for vehicles to move in the traffic stream.

For an individual vehicle speed is the distance traveled by a vehicle in a specified unit of time. In a traffic stream there is not a single speed, but a distribution of discrete individual vehicle speeds. Average or mean speeds can be computed as time mean speed or as space mean speed. The distribution of the speed is often important as well, and a percentile speed such as the 85^{th} percentile may be used to describe the speed characteristics of a traffic stream.

The interrelationship between the three macroscopic measures of traffic, volume, speed and density, is expressed by the simple equation below:

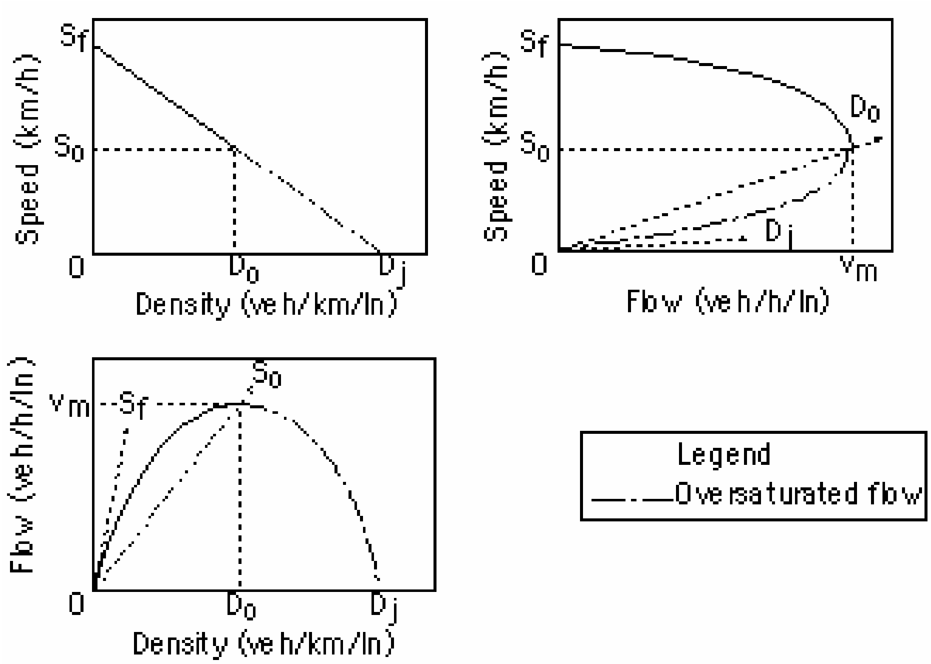
$$F = S \times D$$

where: F = rate of flow

S = space mean speed

D = density

In graphical form, the simple relationship between the three variables is illustrated in Figure 8, assuming a linear relationship between speed and density as proposed by Greenshields in 1934. Field observations have shown that traffic does not strictly follow this linear form, particularly when flow is near the maximum rate, and a variety of regression models have been proposed as alternatives to the linear speed-density form.



(Transportation Research Board, 2000, adapted from May, 1990)

Figure 8: Generalized Relationships Among Speed, Density, and Flow Rate On Uninterrupted-Flow Facilities

Several points are important to note as they relate to work zone traffic management. A given flow rate may occur under higher speed low density conditions or under lower speed high density conditions. As density increases, the flow rate increases towards its maximum value, also known as capacity. A traffic stream operating near capacity is unstable and provides little margin for absorbing disruptions in the traffic flow. At the point of near capacity, the traffic stream can revert from high speed stable flow to low speed unstable flow. Once flow becomes unstable it may take some time and a significant reduction in demand before stable traffic flow can be re-established.

Work zones often require a large number of lane changes, lane shifts and other activities that may trigger chain reactions leading to unstable flow. Construction activities such as trucks moving in and out of the traffic stream may also cause disruptions. To maintain good traffic flow, it is important to keep density levels below the critical value and to limit the disruptions to the smooth flow of traffic. A Smart Work Zone can assist by diverting some of the traffic to an alternate route and by encouraging smoother traffic flow through better awareness and guidance.

Queuing delay can occur under two traffic flow states. The first is when average demand exceeds average capacity for a given time period and vehicles must wait for their opportunity to pass through the work zone. The second condition under which queuing delay can occur is when average demand does not exceed average capacity, but due to the stochastic nature or randomness of traffic flow queuing develops for short periods of time. If the traffic parameters are known, queuing theory can be used to determine the number of vehicles in a queue. Traffic queue theory calculations detailed by Jiang et al are summarized here (Jiang 2003).

The number of vehicles in the queue at the end of a specified time period is equal to the number of vehicles in the queue at the start of the period plus the difference in the number of new arrivals and the number of departures during the time period, and can be calculated as follows:

$$Q_i = Q_{i-1} + F_{ai} - F_d$$

where:

Q_i = Total vehicle queue at the end of hour i

Q_{i-1} = Total vehicle queue at the end of hour i-1

F_{ai} = Hourly volume of arrival vehicles at hour i

F_d = Vehicle queue discharge rate

The total delay in vehicle-hours that occurs in a one hour time period can be calculated from:

$$D_i = Q_{i-1} + \frac{1}{2}(F_{ai} - F_d)$$

where:

D_i = Total delay in vehicle hours in hour i

Q_{i-1} = Total vehicle queue at the end of hour i-1

F_{ai} = Hourly volume of arrival vehicles at hour i

F_d = Vehicle discharge rate

Variables that affect the calculation of total user delay can be understood in the context of these simple equations. Traffic counts that provide data in hourly intervals or shorter periods from the highway segment under consideration can be used to determine the expected volume for a specific time period under consideration. When detailed traffic counts are not available the AADT is commonly used as the basis to estimate traffic volume. For the particular hour under consideration, several adjustments may be applied to the AADT to compensate for variations in traffic by time of day, day of week, and season of the year. When detailed count information is not available, the Highway Capacity Manual provides guidance for making these types of adjustments (Transportation Research Board, 2000).

It is also important to consider that the presence of the work zone may alter the expected hourly arrival rate of vehicles from what would occur under normal driving conditions. Drivers that are aware of the presence of the work zone and are familiar with the adjacent road network may use alternate routes. Locations with a higher percentage of commuter traffic should be expected to have more drivers using alternate routes. An awareness program to encourage changes in driver behaviour may be an integral part of an agencies traffic management strategy, and if successful will result in a shift in traffic patterns. Drivers aware of the congestion occurring around a work zone may also choose to change the timing of their trip by going earlier or later, or not going at all. All of these effects result in a decrease in the arrival rate of vehicles.

Knowing the number of vehicles in the queue, an estimate can be made of the length of the queue assuming vehicle spacing and lengths. The jam density is expressed as the number of vehicles per mile or kilometre when speed is equal to zero. Queue length can be calculated as the number of vehicles in the queue divided by the density. In reality, there is a background density already present on the roadway and as a queue builds some of the space is already occupied by existing vehicles and should be taken into consideration (McShane, 1990). In addition, full utilization of the available space is not realized, especially in a work zone setting, due to inconsistencies in traffic movement and the fact that some vehicles merge early leaving unused capacity in one or more lanes.

Another consideration in determining the length of a queue is the shock-wave effect that has been identified to occur in traffic flow. A bottleneck or disruption causes a build-up of congested traffic if arrivals exceed departures, and a congested condition will form. As more vehicles arrive at the back of the queue, the end of the queue will move upstream, sometimes at very high speeds. When departures start to exceed arrivals, the number of vehicles in the queue may start to decrease, but the physical location of the upstream end of the queue may continue to move upstream as more vehicles come upon the slow or stopped traffic. A simple example of the shock-wave effect is a traffic signal where a queue builds during the red phase. When the light turns green, the vehicles at the front begin to move reducing the number of vehicles in the queue, but the physical end of the queue continues to move backwards as more vehicles arrive at the end of the line of stopped vehicles (May, 1990). Temporary disruptions in traffic flow at a work zone such as forced merges can have an effect far upstream from where the disruption occurred and result in variations in traffic flow and density.

2.3.1.2 Macroscopic Traffic Flow Analysis Using Quick Zone 2.0

QuickZone 2.0 analysis software, developed under the direction of the FHWA, is a work zone delay estimation tool to assess various approaches to construction phasing and traffic control so that traveler delay can be better assessed and addressed in construction planning. Hour by hour assessment is conducted using a simple deterministic queuing model for each segment of the network being examined. QuickZone is Microsoft Excel based and provides a user interface and worksheets for entering required information for the analysis. Information required for analysis includes site geometry and capacity of mainline and detour routes, project timing and phasing, mitigation strategies, and traffic flow characteristics. Travel demand is adjusted according to daily, weekly, and seasonal variations (MitreTek Systems, 2002).

On an hour by hour basis, QuickZone compares the expected travel demand, including defined variations by time of day, day of week and month of year, against the capacity for each link. On an hourly basis, traffic is transferred to downstream links at a rate consistent with the available capacity of the downstream link. Bottlenecks in the network meter the traffic flow to downstream links. The delay of vehicles queued at a bottleneck is summed to determine user delay.

QuickZone includes capabilities to model the use of variable message signs and highway advisory radio to advise travelers of traffic conditions. QuickZone assumes equilibrium between the detour route and the mainline route and unlimited diversion when travel advisories are deployed, meaning that driver choices will result in the minimum delay. Real conditions never match this ideal, and this has been identified as a short coming of the approach of many assessment models (Horowitz, 2003). To address this short coming during the study, a method using a control link was created in the model network so that the percentage of vehicles diverting from the mainline could be controlled to more closely reflect actual operating conditions. Outputs from QuickZone provide several measures that can be used to compare work zone traffic management strategies. For each strategy QuickZone computes maximum queue length, maximum user delay, and total user delay.

2.3.2 Microsimulation and Analysis Programs

Microsimulation analyzes traffic flow at the individual vehicle level. A number of microsimulation programs are available including PARAMICS, CORSIM, FREESIM, and VISSIM. For this application important characteristics include being able to define the physical geometry and characteristics of the roadway, control of driver behaviour including lane selection and lane change behaviour, and characterization of the vehicle volume and distribution over time.

In the probabilistic economic analysis model, any appropriate determination method can be used to determine traffic delay. For this study, VISSIM was chosen as a representative of the microscopic approach to determine the effects of a Smart Work Zone on traffic characteristics. VISSIM has been used by other researchers for work zone applications and provides the desired ability to define traffic input, control traffic behaviour, and measure queue length, delay time and other parameters (Fontaine, 2005).

VISSIM simulates the movement of individual driver/vehicle units through the roadway network based on defined characteristics of the vehicle and the driver. The vehicle interacts with the road network elements such as number of lanes, traffic control devices, and speed control areas. Each vehicle also interacts with the other vehicles that are part of the road network to determine travel behaviours such as lane changes, speed adjustments and positioning relative to the other vehicles.

VISSIM is based on a psycho-physical driver behaviour model developed by Weidemann. The model is based on an iterative process of acceleration and deceleration that takes place as one vehicle overtakes another. As a driver approaches a lead vehicle from behind, the driver will at some point perceive that they are getting too close and begin to decelerate until they are no longer getting closer. Driver perception is imperfect and therefore the deceleration will continue past the point of equal speeds to a point where the driver perceives that they are actually increasing in distance from the lead vehicle. At this point the driver then accelerates to again close the distance between the two vehicles. This cycle of deceleration and acceleration continues until the driver reaches the desired following distance. The individuality of each driver is modeled by a stochastic distribution of speed and spacing thresholds across each vehicle type. (PTV Planung Transport Verkehr AG, 2001).

2.4 Summary of Literature Review

This literature review provided insight into the history, operation, and evaluation of Smart Work Zone systems. The review provided background information on the effectiveness of Smart Work Zone systems on previous deployments to be used as inputs in evaluation of future projects.

The literature review identified costs and benefits for consideration in the holistic analysis of transportation projects and methods of analysis. More detailed information on the measurement and valuation of traffic safety, user delay, vehicle operating costs, and emissions was presented. Traffic modeling was examined in the literature review to outline the function and characteristics of commercially available macroscopic and microscopic traffic software models.

3 Formulation of Smart Work Zone Analysis Framework

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. The evaluation of benefits is necessary to support decision making regarding whether to deploy a Smart Work Zone. Since the decision typically involves an expenditure of additional funds, some form of economic analysis is anticipated. The major elements of the economic analysis model that was developed in this research are illustrated in Figure 9. The development and definition of each element within the model is described in this chapter, in the sections as indicated in the diagram.

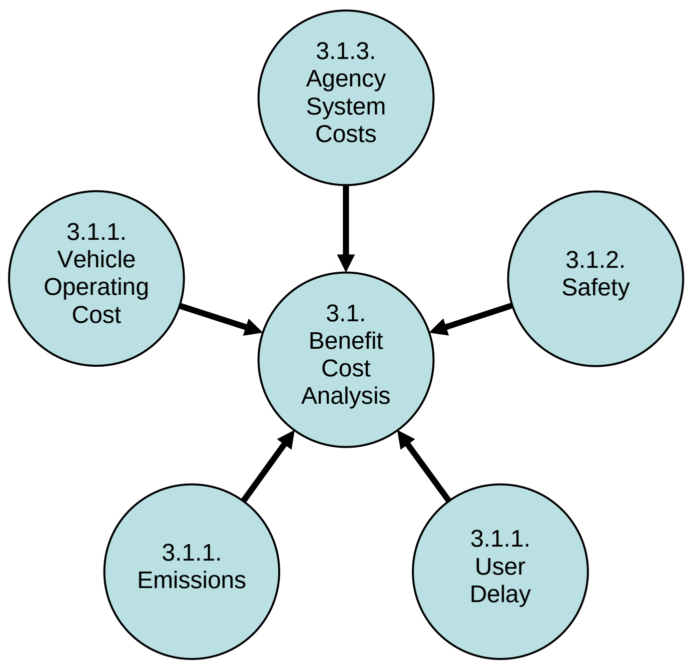


Figure 9: Main Components of Performance Analysis Model

Safety and mobility are two important concerns of most highway construction projects, and are therefore the focus of the quantitative analysis of work zone safety projects. This approach concurs with the USDOT Highway Economic Requirements System model which considers three direct highway user benefits: 1) travel time savings, 2) vehicle operating costs reduction and 3) improved safety. Another important effect of improved transport efficiency is vehicle emissions. Although the quantification of emissions in relation to a Smart Work Zone is relatively undeveloped, provision is made to include emissions in the model developed within this research.

Approximately 20 effects associated with the deployment of a Smart Work Zone were identified in Figure 7. The quantification of each of these costs and benefits is possible, but it is not practical or necessary for every project under consideration. In cases where these ancillary effects are potentially significant for a specific project, they should be considered. Recognizing that for a specific project there may be other factors of concern provision is made for the inclusion of additional inputs into the analysis.

An appropriate work zone modeling framework must deal with the reality that there is a limit to the available historical data on which to base the decision. This is particularly true for Smart Work Zones where the depth of research is limited and a specific project may have unique characteristics not encountered on previous projects. Therefore it may be necessary to rely on the application of engineering first principles and modeling techniques such as traffic simulation to determine complex input parameters. It is also prudent to acknowledge the uncertainty of predicting results with less than perfect information and to incorporate and quantify the uncertainty in the analysis.

3.1 Formulation of Quantitative Analysis Model

The chosen method to quantify the value of a Smart Work Zone project was a discretized probabilistic decision model using a benefit / cost analysis approach supported by inputs from modeling of specific aspects of Smart Work Zone operation. The modeling approach employed in this research is first-principles based as defined by the site geometrics, traffic characteristics, and Smart Work Zone technologies for the specific site. 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 and reduced fatal crashes. This approach facilitates the consideration of the agencies multiple objectives based on monetary values established from analysis of other transportation projects.

Costs were considered as the monetary cost of deploying and operating the Smart Work Zone system. The method of procurement commonly being used by agencies is to pay for the system to be furnished and operated by a contractor or vendor rather than a system acquisition by the agency. Therefore, no capital costs are typically incurred by the agency for use of a Smart Work Zone, and there are no life cycle or residual costs or benefits associated with the Smart Work Zone system beyond the completion of the project.

Since Smart Work Zones are a relatively new concept, historical information and research to date is insufficient to quantify with certainty the impacts that the system will have on traffic flow, traffic safety and driver behaviour. The lack of historical information and research is not unique to Smart Work Zones, and applies to the analysis of all ITS projects. In the absence of complete historical information the analysis approach depends on modeling to provide the measures of expected results.

The decision model structure for the calculation of the expected benefit cost ratio and net value is shown in Figure 10. The decision model can be implemented in a spreadsheet format such as Excel or using an advanced decision analysis model such as DPL.

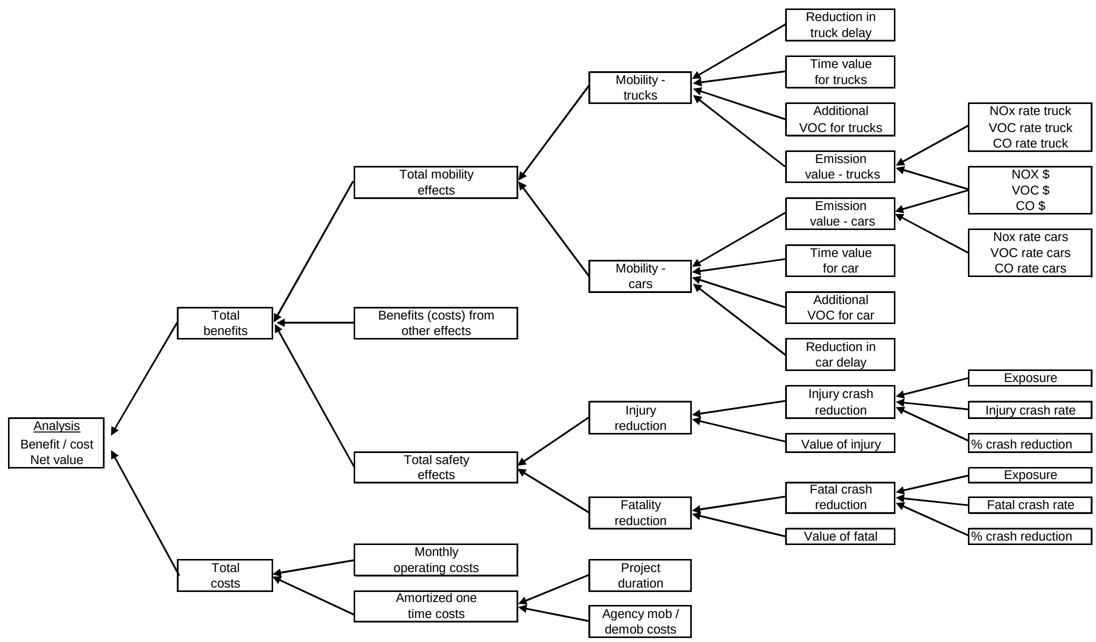


Figure 10: Quantitative Benefit Cost Analysis Structure

As illustrated in Figure 10, the following listing identifies the independent and dependent variables that are part of the quantitative benefit cost analysis.

Dependent variables:

- Benefit / Cost Ratio (Value of benefits / value of costs), and;
- Net Value ((benefits – costs) / month of operation).

Independent model variables:

Mobility Effects Sub-Model

- Reduction in truck delay (hours / month);
- Reduction in car delay (hours / month);
- Value of user delay time – cars ($ / hour delay);
- Incremental vehicle operating cost – cars ($ / hour delay);
- Value of user delay time – trucks ($ / hour delay);
- Incremental vehicle operating cost – trucks ($ / hour delay);
- Value of volatile organic compounds, carbon monoxide, and nitrous oxides ($ / metric ton);

- Truck emission rate of volatile organic compounds, carbon monoxide, and nitrous oxides (metric tons / month);
- Car emission rate of volatile organic compounds, carbon monoxide, and nitrous oxides (metric tons / month);

Safety Effects Sub-Model

- Statistical value of fatal crash ($ / fatal crash);
- Statistical value of injury crash ($ / injury crash);
- Fatal crash rate without Smart Work Zone (crashes / 100 million vehicle miles traveled);
- Injury crash rate without Smart Work Zone (crashes / 100 million vehicle miles traveled);
- Work zone traffic exposure (Vehicle miles traveled), and;
- Reduction in crashes with Smart Work Zone implementation (percent of crashes without Smart Work Zone prevented by implementation).

Agency Costs Sub-Model

- Mobilization cost ($ / mobilization);
- Monthly operation cost ($ / Month), and;
- Months of operation (Months).

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. The three sub-models of the decision structure are discussed in the following sections.

3.1.1 Formulation of Mobility Effects Sub-Model

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. The value of delay time includes both the user's value of time and the vehicle operating cost. Increased delay time also results in an increase in idling emissions from vehicles.

The amount of user delay reduction to be expected from deploying a Smart Work Zone is not readily apparent. In addition, research into the impacts of a Smart Work Zone on user delay is limited. As well, each application of a Smart Work Zone is unique to each 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 benefit cost analysis 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. Expected travel time and delay were estimated for the do-nothing case. For comparison, travel time and delay were also estimated for the case with a Smart Work Zone. 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.

3.1.2 Formulation of Safety Effects Sub-Model

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 crash rate may typically be from 7 percent to 30 percent (Ullman, 1991, Khattak, 2002).
- Research has resulted in models developed to predict crashes on a work zone project, such as a model developed by Tarko in Ohio that considers a number of variables, including type of work, duration of work, traffic volume, and work intensity (Tarko, 1999).

The potential for improvement in work zone safety is related to the traffic exposure at the site. If a work zone is present and operational on a continuous basis then the presence of a Smart Work Zone can influence the entire traffic volume. In many cases a work zone is only present periodically 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.

3.1.3 Formulation of Agency Costs Sub-Model

The costs to an agency to deploy and operate a Smart Work Zone generally represent the main costs considered in the benefit / cost 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 performance analysis model includes two agency costs, one for mobilization and the other for ongoing operation. Since the evaluation is performed on a monthly basis, the mobilization cost is distributed evenly over the expected term of the project. 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.

3.2 Probabilistic Formulation of Model

Excel has the capabilities necessary to handle the analysis in a deterministic manner, as the only decision is whether to proceed with the project and therefore the results are not dependent on other decisions that might be made. Simple decision tree formulations can be created based on a discretized distribution. Excel is advantageous since it is universally available and most practitioners have experience with its use.

A limitation of Excel is that it does not deal directly with uncertainty of input values and sensitivity of the results. This can be addressed by considering the results of performing several "what-if" calculations for sensitive variables. This approach is feasible for simple cases and limited sets of values, but can become cumbersome and time consuming. If the probabilities of several outcomes are to be incorporated in a single analysis, the calculation becomes even more difficult. Therefore, Excel was used as a check for model calculations but a model that could better incorporate sensitivity and uncertainty was desired.

The format of the decision model can be adapted from a simple deterministic model in Excel to an advanced decision analysis tool such as DPL that explicitly deals with uncertainty in the determination of results. 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. A sensitivity analysis and tornado diagram can be created by varying each variable through its expected range of values. After the sensitivity analysis some of the variables can be assigned fixed values if they are insignificant or are known with confidence. As an output from the model developed in this research, a risk analysis can be performed to quantify the uncertainty that remains for sensitive variables. The probability distribution for each sensitive variable is defined and then possible outcomes are determined across the range of values for the combination of variables. The result is a profile of the full range of possible outcomes and the probability of the outcome value occurring, effectively quantifying the uncertainty of the value of input variables.

3.3 Definition of Input Values for Sensitivity Analysis

Prior to applying the economic analysis model to a specific case study site, it was necessary to validate the model. Inputs were drawn from previous research, guidelines for economic analysis, and established sources for data such as published crash rates. Since the case study site to which the analysis was ultimately applied was located in the United States, the validation of the economic analysis was performed in US dollars. For the sensitivity analysis expected, minimum and maximum values were defined based on values subjectively representing a similar amount of uncertainty. The minimum and maximum values were selected as possible, but not very likely to occur. The values defined for each of the input parameters are shown in Table 2. The source of the values and the process of defining the inputs are defined in subsequent sections of this chapter.

3.3.1 Traffic Mobility

To check the sensitivity and validation of the model, realistic estimates of expected mobility improvements were required. A study of the application of a Smart Work Zone to a project on I-94 in Wisconsin included an estimate of the savings in travel time. The Wisconsin study assumed a diversion rate of seven percent on weekends and five percent on weekdays, and estimated time savings were 91,216 hours per month of operation (Horowitz, 2003). The percentage of trucks was arbitrarily estimated at 10 percent for the purpose of model evaluation. This estimate provided the initial input required for traffic mobility parameters. To provide an estimate of the sensitivity of the model to variations in the travel time estimates, a range of +/- 10 percent was used for minimum and maximum values of delay reduction.

Various sources for the valuation of delay time were cited in the literature review. For the model evaluation, values of travel time were chosen based on the typical values in common use for transportation project analysis.

Table 2: Input Parameters for Validation and Sensitivity Analysis of Performance Model

Variable	Description	Minimum	Most Likely	Maximum
Mobility				
Delay Reduction	Reduction in user delay (hours/month)	82,094	91,216	100,338
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)	$2.00	$2.50	$3.00
Truck emissions rate	Idling emissions of CO, NOx, and VOC (g / truck idling hour)	VOC = 12.1 CO = 109.6 NOx = 43.1	VOC = 12.5 CO = 133.6 NOx = 36.0	VOC = 14.0 CO = 189.7 NOx = 26.7
Car operating cost	Cost of fuel ($/hour)	$1.00	$1.50	$2.00
Car emissions rate	Idling emissions of CO, NOx, and VOC (g / car idling hour)	VOC = 16.7 CO = 234.5 NOx = 4.9	VOC = 18.5 CO = 262.0 NOx = 5.0	VOC = 19.3 CO = 273 NOx = 5.1
Emissions value	Value of emissions of CO, NOx, VOC (US$ / 1000 kg)	VOC = $1802 CO = $23 NOx = $2,608	VOC = $3,300 CO = $1,150 NOx = $4,209	VOC = $6700 CO = $6,360 NOx = $12,875
Safety				
Exposure	Vehicle Miles Traveled / Month	1,101,600	1,224,000	1,346,400
Work Zone Fatal Crash Rate	Fatal Crashes / 100MVMT	1.38	1.52	1.66
Work Zone Injury Crash Rate	Injury Crashes / 100MVMT	74.84	82.33	89.81
Safety Improvement Factor	% Reduction in Crashes	0%	5%	10%
Non-fatal Injury crash cost	Average value of injury crash ($ / injury crash)	$19,000	$32,500	$46,000
Fatal crash cost	Average value of fatal crash ($ / fatal crash)	$1,300,000	$2,500,000	$3,700,000
Agency				
Months	Duration of operating period (months)	8	9	10
Mobilization	Cost of system mobilization ($)	$75,000	$87,500	$100,000
Operating Cost	Monthly system cost ($/month)	$12,000	$16,000	$20,000

Operating costs of vehicles, as considered in the analysis, include the cost of fuel, but not the wear and maintenance costs. As described earlier, the travel distance related wear and maintenance portion of operating costs is insignificant if the percentage of vehicles using the alternate route is small and the travel distance is similar. This was assumed to be the case during the validation portion of the project.

Emission rates were estimated based on the idling emission levels from vehicles in the traffic stream. The engine type affects the quantity of each type of emission. To determine the sensitivity to variations in the makeup of the vehicle population, the percentage of gas and diesel vehicles was varied to determine the range of emission rates for use in the sensitivity analysis.

The literature review identified a number of sources for the valuation of emissions, as presented earlier. The range of possible values for the sensitivity analysis is drawn from the cited values to provide minimum, maximum and expected values.

3.3.2 Traffic Safety

The required input parameters for the economic analysis are the expected number of fatal and injury crashes in the work zone without a Smart Work Zone, the percent reduction in crashes with the implementation of a Smart Work Zone, and the statistical value of fatal and injury crashes.

Most jurisdictions measure and publish injury and fatal crash rates as a measure of safety on their highway system. Since the estimate of delay savings was taken from a project in Wisconsin for the validation portion of the research, Wisconsin crash data was also used for the traffic safety portion of the research. The crash rates on highways in Wisconsin for the year 2004 were 1.38 fatal crashes / 100 million vehicle miles traveled and 74.84 injury crashes / 100 million vehicle miles traveled (Wisconsin DOT, 2004). These crash rates are for all conditions and not specifically for work zones. As cited in the literature review, the presence of a work zone may result in an increase in the crash rate, with values ranging from 7 to 30 percent. For evaluation, the minimum crash rate input value was set equal to the base rate, and then increased by 10 and 20 percent for the expected and maximum rates respectively.

A key factor in the safety analysis is the change in safety that may result from the deployment of a Smart Work Zone. Unfortunately there is limited research available on the safety impacts of a Smart Work Zone, although some studies have indicated an improvement in safety. Other studies have indicated improvements in surrogate measures such as speed, speed variability, and conflicts. In the absence of strong data, estimates of potential improvement between zero and 10 percent were used in the analysis.

The traffic volume must also be estimated in determining safety, as this determines the exposure of traffic to the work zone, with or without the Smart Work Zone. The traffic volume for the validation was taken from the project referenced as the source of user delay.

3.3.3 Agency Cost Input Parameters

The costs of several Smart Work Zone projects were cited in the literature review. For the sensitivity analysis and validation of the economic model, some typical values were chosen covering a range of total project cost from $171,000 to $300,000.

3.4 Sensitivity Analysis and Validation of Economic Evaluation Model

The input values as described in Table 2 were used in conducting a sensitivity analysis. Each of the inputs was varied through minimum, most likely and maximum values, while all other inputs were kept at their expected value. The results of the sensitivity analysis are illustrated in Figure 11.

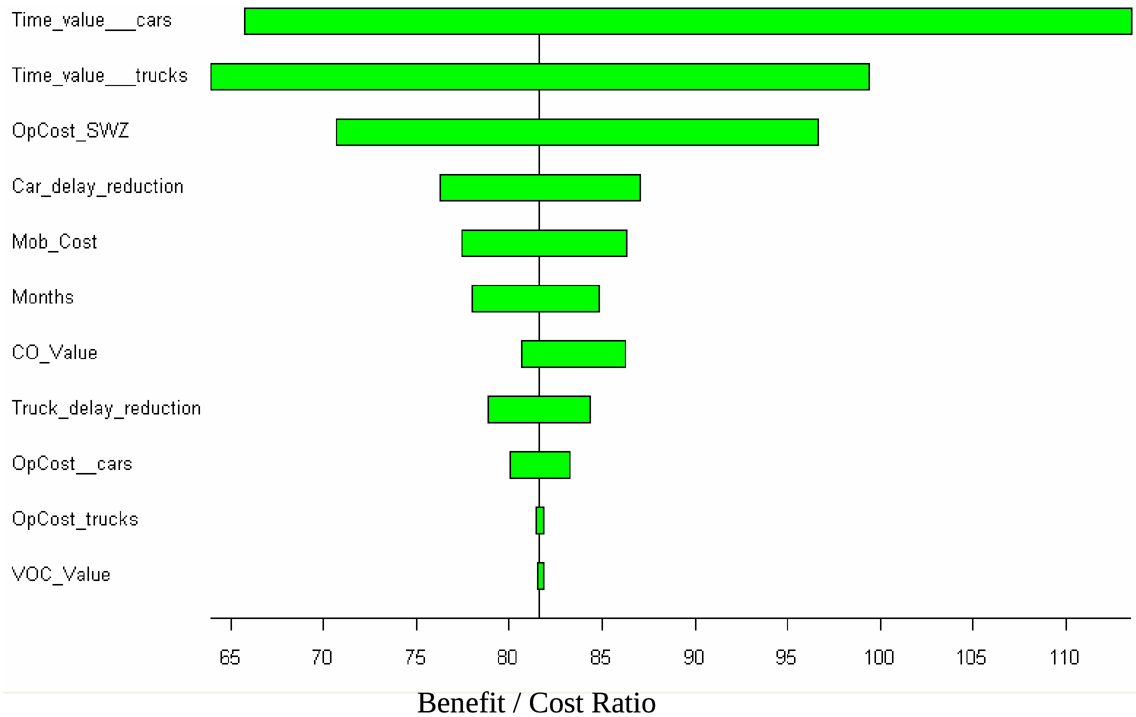


Figure 11: Sensitivity Analysis of Economic Model

The sensitivity analysis indicates that the variables with the greatest sensitivity to uncertainty of their values, ranked by magnitude of their influence on the calculated benefit, were those assigning value to the user delay of trucks and cars. The values used in the analysis represent the range of values from various sources. It is anticipated that a particular agency may have a narrower range of values to be used based on internal policy. It is also noted that in the outcome, there is a linkage between the value assigned to user delay and the amount of user delay that is predicted.

The uncertainty of the variables related to the agency cost of mobilization and operation of the system were also ranked highly in the sensitivity analysis. The operation cost assumes a fee for service and usage that includes supply of equipment, software license, and all operation and maintenance of the system. This is a common procurement method that results in no capital and life cycle costs to the agency.

Based on the analysis the expected benefit / cost ratio for this project is estimated at 81.6 and the net value is estimated at $2,074,381 per month of operation. Total costs were estimated at $25,722 per month while benefits of the Smart Work Zone deployment were estimated at $2,100,104 million dollars per month.

A breakdown of the relative contribution of each of the benefits is shown in Figure 12. The benefits derived from reducing user delay for cars and trucks comprise more than 90 percent of the estimated benefits. Another seven percent of the benefits are attributed to reductions in vehicle operating costs. For this application the improved mobility that is anticipated from the deployment of a Smart Work Zone overshadows the other derived benefits.

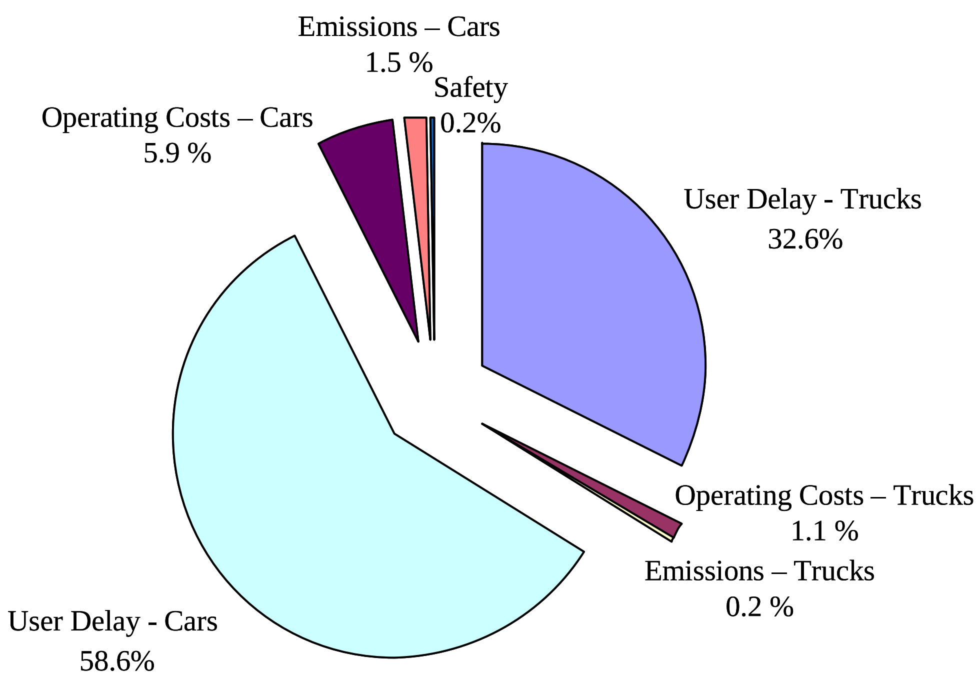


Figure 12: Relative Contribution of Benefit Types to Total Benefit Estimate

A comprehensive evaluation including all the elements of this model has not been conducted on a similar project, but there are some evaluations that can be used for comparison. An evaluation of a 150 day deployment of a Smart Work Zone in Michigan estimated costs of $500,000 per month and benefits of $980,000 per month (Kratofil, 2001). An evaluation of the I-94 project in Wisconsin, that provided some of the input values for the sensitivity analysis, estimated benefits of $324,000 / week and a system cost of $200,000 to $400,000 for an entire construction season. (Horowitz, 2003).

By observing the results of the sensitivity analysis and the reaction of the outcome to the change in input values, it is observed that all the results are as predicted. As each variable was adjusted through its range of expected values, the outcome increased or decreased as anticipated. The actual calculations made by DPL were confirmed by using an Excel spreadsheet. Estimated benefits were of an appropriate order of magnitude when compared to other project evaluations of this type. Based on the evaluation of the model framework, it was determined that the model was ready for application to the case study site.

4 Case Study Application of Analysis Model

The purpose of the case study application was to apply the probabilistic Smart Work Zone analysis model developed in this research to an actual site where a Smart Work Zone has been used. The expected scenario for the application of the model is to support the decision making process to determine if a Smart Work Zone is applicable for a future construction project. There is a growing emphasis, including the FHWA *Rule on Work Zone Safety and Mobility*, to move the consideration of traffic effects to a point earlier in the planning and design process of road construction projects (FHWA[4], 2004). One of the challenges of addressing traffic management earlier in the process is the lack of information that may exist for analysis and decision making. The process that was followed in the application of the performance model to the case study site and the sections of the report where each task is described is illustrated in Figure 13.

4.1 Description of Case Study Application

North Carolina has implemented Smart Work Zone technology on at least nine different projects over a period of several years. One of the typical applications has been on rural interstate rehabilitation projects.

The case study site chosen for the application of the Smart Work Zone analysis model was a highway repaving project located on Interstate 95 in North Carolina just north of the community of Rocky Mount between mileposts 145 and 154. A Smart Work Zone was deployed on the project from March to November 2003 to manage expected traffic queues and promote safety and mobility.

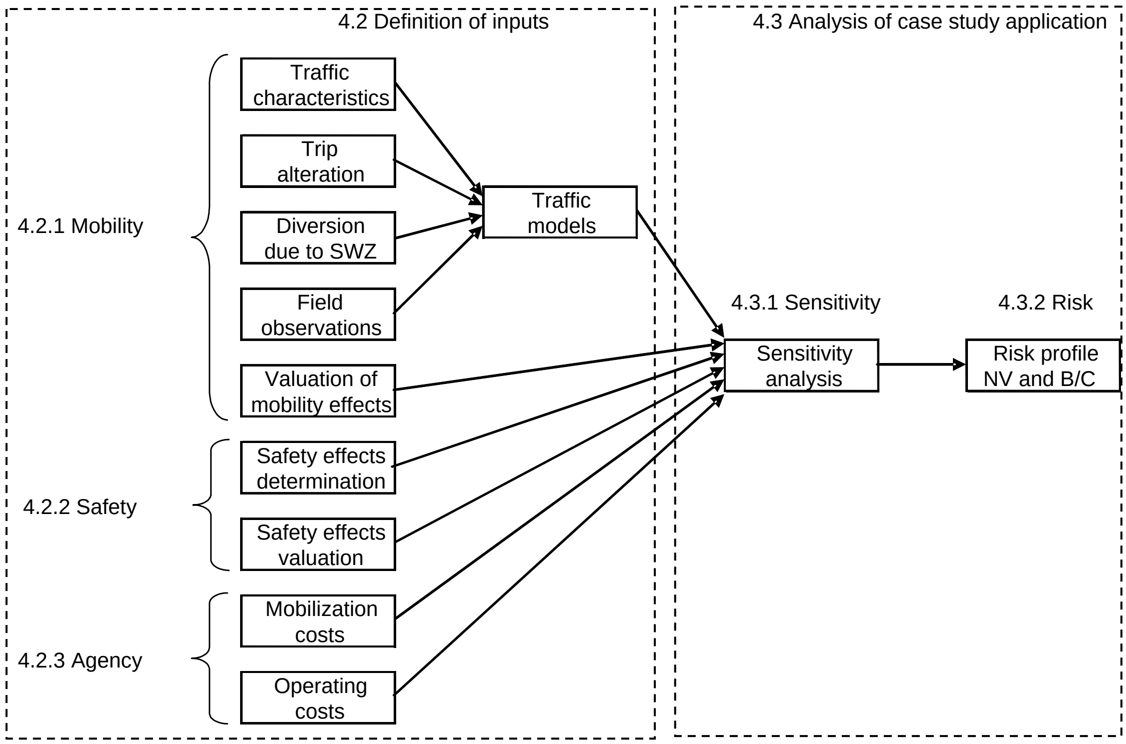


Figure 13: Analysis Process for Application of Performance Model to Case Study Site

The system in use within the case study site was the Travel Messenger™ TM100 system provided by International Road Dynamics (Bushman[2], 2004). 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. Three additional message signs were positioned to provide route guidance to motorists on the recommended alternate route.

Three levels of messages were provided to motorists, depending on the traffic conditions. Messages were displayed on three lines and up to three frames in sequence. Generic messages informing motorists of a work zone ahead, such as "Traffic Slowing Ahead / Prepare To Merge" and "Current Traffic Info / No Delay Exits 150-141", were displayed when no delays were detected. When short delays were detected, but not long enough to warrant the use of the alternate route, the current delay estimate was displayed with a message such as "Traffic Stopped Ahead / 10 Minute Delay". When delay time reached the point where the alternate route would offer a shorter travel time, the amount of delay and the suggested alternate route were displayed using a message such as “Traffic Stopped Ahead / 20 Minute Delay / Use Exit 141 As Alt”.

The Travel Messenger™ system also provided information remotely via a website to traffic managers and the general public. A public website made information available to travelers prior to departure so they could plan to avoid the area during periods of heavy congestion. By encouraging drivers to use alternate routes or change the timing of their travel plans, demand and congestion can be decreased. Information provided to traffic managers allows them to monitor the traffic flow and respond to incidents or periods of excessive congestion in a timely and appropriate manner.

Table 3 provides the key site and project characteristics for the case study application and the source of the information used.

Table 3: North Carolina Case Study Site and Project Characteristics

Input parameter	Value	Source
Average Annual Daily Traffic	37300	NCDOT count data
Daily demand pattern	Mid-morning to late afternoon plateau (5% to 7% of daily traffic)	NCDOT count data
Weekly demand pattern	Weekday low (84%), weekend peak (124%)	NCDOT count data
Annual demand pattern	Mid summer peak (46,500) and January / February decline (32,700)	NCDOT count data
Percent trucks	17%	NCDOT count
Length of work area	1.5 miles	Typical value
Length of work zone	3.5 miles	Typical value
Alternate route length	6 miles	Site map
Alternate route travel time	8 minutes	Site investigation
Mainline route length	5 miles	Site maps
Mainline speed	70 mph	Posted speed
Work zone speed	45 mph	Posted speed
Closure type	2 lanes to 1 lane	Traffic management plan
Closure timing	6 am to 6 pm, Monday to Thursday	Traffic management plan
Fatal crash rate (without work zone) (crashes / 100 million vehicle miles traveled)	1.55	NCDOT data
Injury crash rate (without work zone) (crashes / 100 million vehicle miles traveled)	27.34	NCDOT data

4.2 Definition of Model Input Parameters

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. The input parameters were first defined for the sensitivity analysis and then the most sensitive were used for the risk analysis. Since the case study site was located in United States and applicable input values are defined in US dollars, the economic analysis is performed in US dollars. For the sensitivity analysis expected, minimum and maximum values were defined. The values defined for each of the input parameters are shown in Table 4. The source of the values and the process of defining the inputs are defined in the subsequent sections of this chapter.

4.2.1 Mobility Evaluation

One of the requirements to meet the objectives of this research was to develop the capability to quantify traffic flow conditions resulting from the deployment of a Smart Work Zone using traffic modeling techniques. Since many traffic modeling tools are already available and widely used, the approach taken was to apply available tools to the specialized application of a Smart Work Zone. For the case study site it was possible to obtain field measurements that could be used to verify the modeling of the Smart Work Zone application. After verifying that the model gave reasonable results for the condition with a Smart Work Zone, it could then be used to estimate the conditions that would have existed without the Smart Work Zone.

There are two basic approaches to the analysis and modeling of traffic: macroscopic and microscopic. At a macroscopic level, arrival and service patterns are considered to be continuous and traffic is analysed as a group of vehicles considering parameters such as flow rates and average speeds. At a microscopic level, arrival and service patterns may vary and vehicles are considered on an individual basis as they interact with the traffic stream. To compare the capabilities of the microscopic and macroscopic approaches, one commercially available model using each approach was selected.

Table 4: 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	$1.50
Truck emissions rate	Idling emissions of CO, NOx, and VOC (g / truck idling hour)	VOC = 12.1 CO = 109.6 NOx = 43.1	VOC = 12.5 CO = 133.6 NOx = 36.0	VOC = 14.0 CO = 189.7 NOx = 26.7
Car operating cost	Cost of fuel ($/hour)	$0.50	$0.75	$1.00
Car emissions rate	Idling emissions of CO, NOx, and VOC (g / car idling hour)	VOC = 16.7 CO = 234.5 NOx = 4.9	VOC = 18.5 CO = 262.0 NOx = 5.0	VOC = 19.3 CO = 273 NOx = 5.1
Emissions value	Value of emissions of CO, NOx, VOC (US$ / 1000 kg)	VOC = $1802 CO = $23 NOx = $2,608	VOC = $3,300 CO = $1,150 NOx = $4,209	VOC = $6700 CO = $6,360 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

QuickZone 2.0 is a macroscopic assessment tool developed with the support of FHWA specifically for the task of analysing delays and queues in work zones. One of the advances in Version 2.0 is the consideration of the amount of delay that will be encountered on an alternate route when assigning vehicles to an alternate route, an important consideration when evaluating an ITS application that results in diverted traffic.

VISSIM is a microscopic tool commercially available and widely used by transportation professionals for assessment of traffic flow, including ITS applications. VISSIM has desirable functionality for this type of analysis including definition of vehicle and traffic stream characteristics. VISSIM has been used by other researchers to study work zone traffic behaviour including the application of Smart Work Zones (Fontaine, 2005).

For purposes of evaluation of the model capabilities, data was collected from the site while the Smart Work Zone system was in operation on October 30, 2003. The information collected from the case study site included site geometry, work zone capacity, traffic demand, traffic composition (percent trucks), motorist behaviour, and travel time shifting. Since the comparison period is short, and many varying system configurations and site conditions were experienced throughout the entire project, this analysis should not be considered as representative of the entire project deployment. The data collection period occurred after eight months of system deployment and driver exposure to the system that may have influenced driver attitudes, either positively or negatively, towards the system.

4.2.1.1 Case Study Site Layout

The site geometry and physical equipment layout during the time of the study are illustrated in Figure 14. The roadway at this location is an Interstate four lane divided rural freeway with a posted speed limit of 70 miles per hour. The work area consisted of a right lane closure from approximately milepost 148.3 to milepost 145.4, leaving the left lane open for traffic. Access to the designated alternate was at Exit 150, approximately 3.6 km upstream from the start of the lane closure. The alternate route followed Highway 33 west for a short distance, then continued south on Highway 4 for approximately 8 km crossing to the east side of I-95. From this point, traffic could follow a connector approximately 1.6 km west to return to I-95 at Exit 145 or continue south on Highway 4 to Highway 43 and then return to I-95 at Exit 141. For traffic modeling purposes, it was assumed that all diverted traffic used the shorter alternate route. The locations of the system components, in terms of distance upstream from the point of full lane closure, are as follows:

- Sensor trailer 3: 0.01 km
- Sensor trailer 2: 1.95 km
- Sign 3 and camera: 2.35 km
- Sensor trailer 3: 4.61 km
- Sign 2: 4.93 km
- Sign 1: 8 km

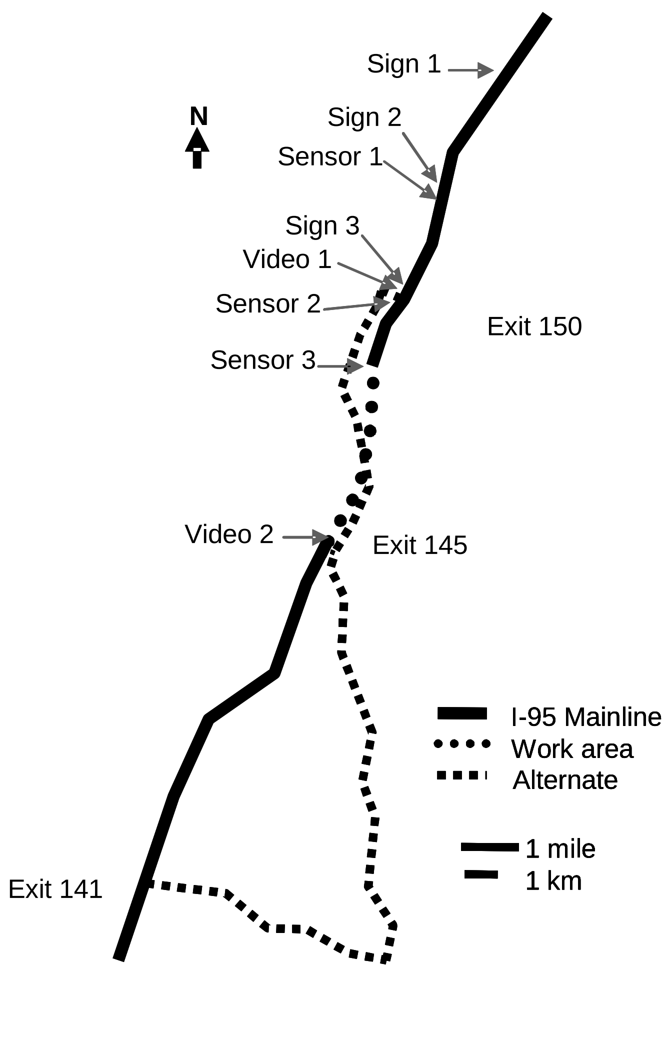


Figure 14: Case Study Site Geometry and Equipment Layout

4.2.1.2 Traffic Demand and Capacity

Work zone capacity is an essential parameter in determining traffic flow characteristics and queue development patterns. Guidelines such as those provided by the Highway Capacity Manual and research from other sites can be helpful for determining capacity, but because of the many variables that can affect work zone capacity, specific data from the case study site was necessary. Sensor trailer 3 was located at the taper area where two lanes reduced to one, and under congested conditions the traffic volume at this location is equivalent to the capacity, assuming there are no bottlenecks further downstream. To ensure accuracy, the traffic sensor count data was adjusted for the entire day using actual counts, determined during periods under congested conditions, from video recorded at a location just downstream of the work zone. Total traffic counts, including cars and trucks, over 10 minute intervals for the case study scenario are indicated in Figure 15.

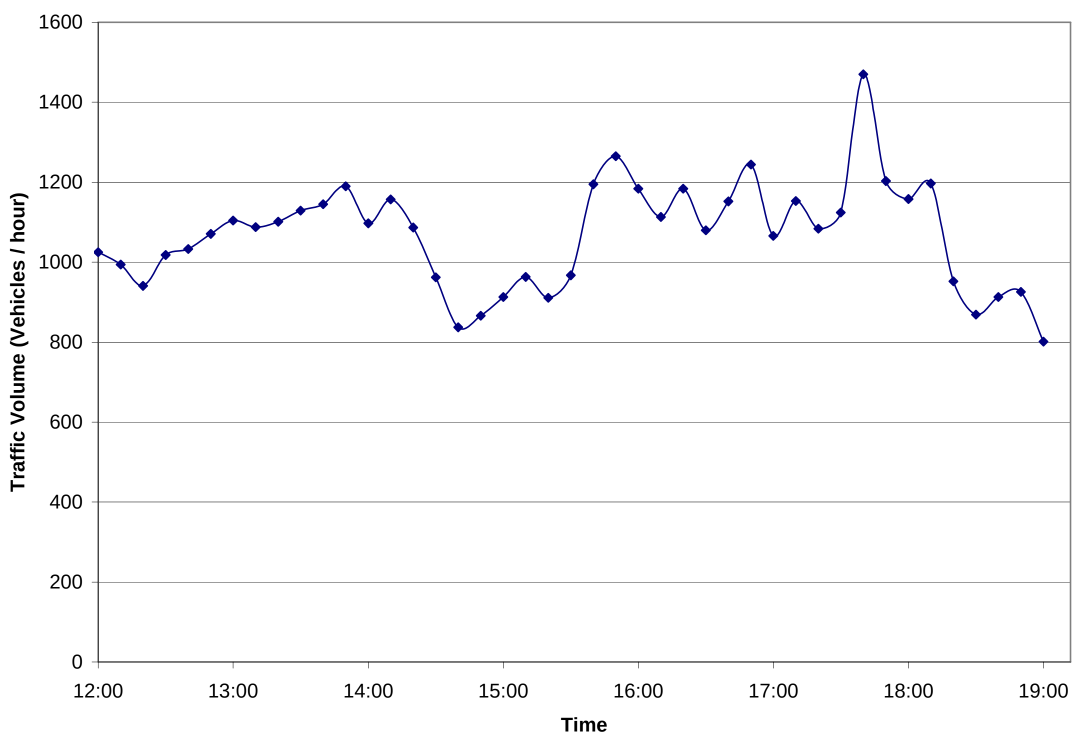


Figure 15: Observed Total Traffic Volume at Case Study Site: October 30, 2003

Traffic demand was determined using the sensor data from trailer 1, furthest upstream from the work zone. Recordings from a portable video camera located at Exit 150, the last exit point prior to the work zone, were used to verify and calibrate traffic counts from trailer 1 based on actual observed counts.

4.2.1.3 Effect of Smart Work Zone on Alternate Route Usage and Trip Planning

The volume of traffic using the exit to the alternate route was monitored under various sign message states to determine the percentage of traffic that was influenced by the Smart Work Zone messages. When the predicted travel time exceeded a minimum threshold of five minutes, the signs would advise drivers of the expected delay and suggest the alternate route that could be used. The percentage of traffic using exit 150 was determined for the range of sign and traffic conditions that occurred. Alternate route usage was found to increase by five to fifteen percent when detour route advisories were provided as compared to the condition with no advisory message (Bushman[2], 2004). This diversion value is similar to the findings on other projects of this type as cited in the literature review (Horowitz, 2003).

Local commuter traffic that is aware of the presence of a work zone may alter travel plans, either changing the time of travel or the travel route, to avoid congestion. If there is a large shift in travel patterns, the volume of traffic at the site may be affected, and should be considered in the analysis. Part of the Smart Work Zone system deployed was a website providing information of current conditions to the public.

To determine the extent to which local traffic was altering their travel plans in response to the Smart Work Zone, a mail out survey to local residents was used. Surveys were mailed to 1468 residents in the vicinity of the construction projects and 22.7 percent were completed and returned. Survey results were broken down based on the frequency with which motorists traveled through the work zone area. Results indicated that approximately 80 percent of local motorists were aware that the system was providing more up to date information than at other work zones. They perceived the information as “always accurate” or “sometimes accurate” in over 95 percent of cases. Over 95 percent of motorists supported the future use of these types of systems in North Carolina.

Although awareness of the roadside components of the system was high, almost 85 percent of motorists were unaware that a website existed to obtain current travel conditions. Respondents that were aware of the website and had internet access, comprised only 12.4 percent of total respondents. Approximately 20 percent of those that were aware of the website and had internet access checked the website "sometimes" or "often". The low awareness and usage of the website by local residents and the high percentage of out of state traffic indicates that travel shifting for this project was approximately one percent and therefore adjustments to the input volumes were not required (Bushman[3], 2004).

For comparison to the prediction from the two models, a simple queue arrival / departure calculation was performed based on the input data, and the queue length estimated from these calculations. The results of this calculation are shown in Figure 16.

The length of queue is determined based on the number of vehicles in the queue and the estimated density of traffic. The line labelled "full utilization" assumes that there is no density prior to queue formation, and all the queuing vehicles fully utilize the available space in both lanes. In reality, there is a background density already present on the roadway and as a queue builds some of the space is already occupied by existing vehicles (McShane, 1990). In addition, full utilization of the available space is not realized, especially in a work zone setting, due to inconsistencies in traffic movement and the fact that some vehicles merge early leaving unused capacity in one or more lanes. The line labelled "reduced utilization" estimates the queue length taking into account the less than optimal use of available space.

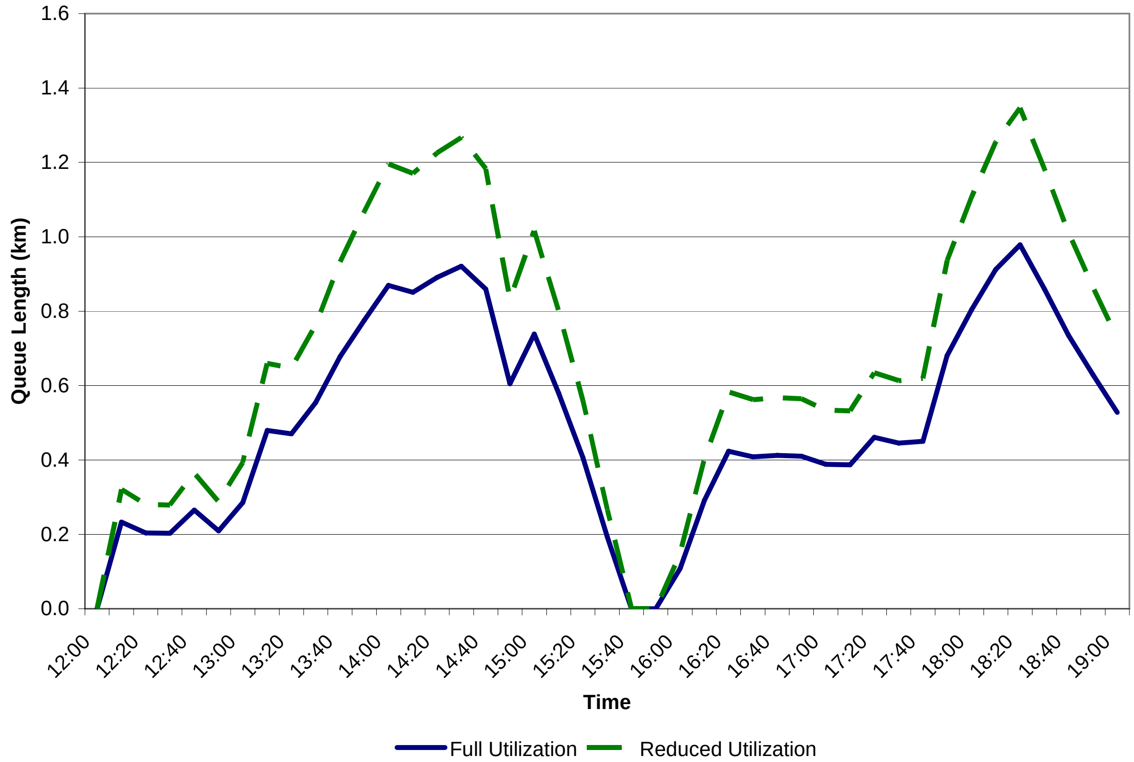


Figure 16: Calculated Queue Length Based On Observed Volumes and Simple Arrival / Departure Calculation

4.2.1.4 VISSIM Model Formulation

A roadway network is constructed in VISSIM by defining highway links and connectors. The road parameter definitions include the physical geometry of the site including the number of lanes, the roadway type, and interconnections between road segments. Lane closures can also be specified to restrict specific vehicle types from using a portion of the road segment. The roadway network created for the study site, based on actual site geometry, is shown in Figure 17.

In creating a VISSIM model, vehicle parameters for the traffic stream are also defined. A traffic composition was defined for the study based on the approximately 17 percent trucks observed in the data collected from the site. Traffic volumes were defined for 10 minute intervals based on the actual site data from October 30, 2003.

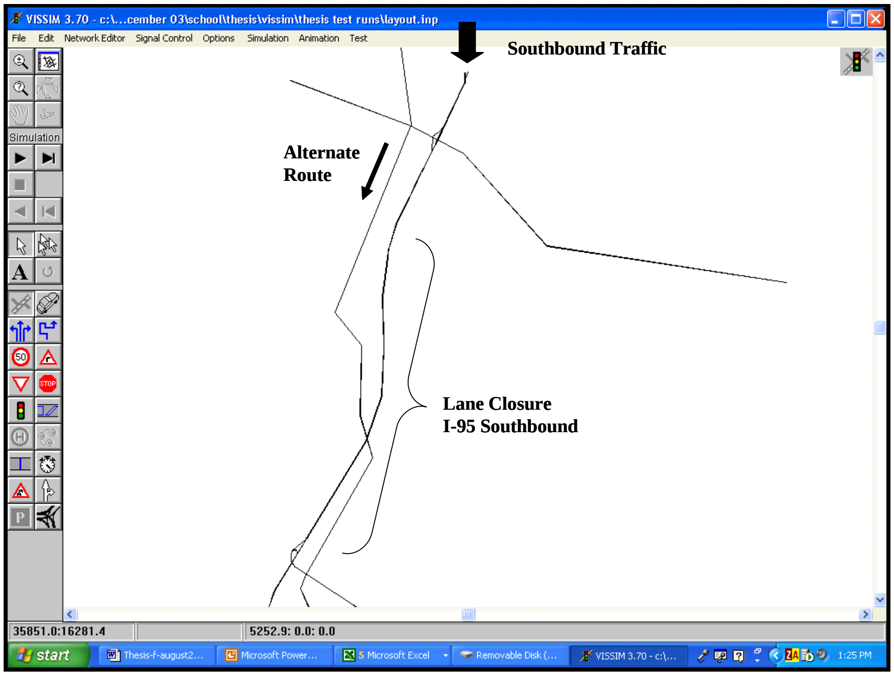


Figure 17: North Carolina Case Study Road Network Layout Created In VISSIM

Driver behaviour is also defined by parameters of the VISSIM software. Lane changing behaviour was set as "freeway" which allows free lane selection and use of all lanes, subject to lane closures that may be in effect. Speed reductions and route selection can also be defined, which is useful in simulating the diversion of traffic to the alternate route. Other driving parameters related to acceleration, deceleration, headway and gap are also definable (PTV Planung Transport Verkehr AG, 2001).

The final element of the simulation model was to set up data collection parameters so that the results of simulation runs could be evaluated. VISSIM provides more than 10 different operational evaluation parameters that can be collected during a test run. During the formulation stage the two parameters used were traffic volume and length of queue development. Traffic volume measurements were used to measure volumes at key points within the system and to verify that the desired input flows and traffic patterns were being achieved and to monitor the effect of the lane closure on traffic flow. Queue length development was used to perform a sensitivity analysis as input parameters were varied and was also used in the verification stage.

Demand and capacity are two basic traffic parameters that are known to be important in defining traffic flow in a work zone. Therefore, these parameters were monitored in setting up the initial operation of the system. Vehicle input volumes were entered into the system based on the collected data to duplicate the observed field demand. VISSIM allows exact numbers of vehicles to be specified for each time interval; therefore it was possible to match the simulated traffic demand to the observed field conditions. Multiple vehicle classes can be created in VISSIM, each with unique behaviour, operating characteristics, and response to the roadway and traffic conditions.

Capacity of a road segment is not directly controlled within a VISSIM model. Rather, capacity is a result of the interaction between the road network, traffic composition, and vehicle operation characteristics. Therefore, it is not possible to simulate with exactness the capacity through the work zone. Figure 18 illustrates the capacity as measured in the field as compared to the simulated capacity recorded just downstream of the lane closure.

The field measurements illustrated a high degree of variability in the capacity at the work zone which is not indicated by the unmodified VISSIM simulation. The total simulated volume through the work zone over the entire test period was within one percent of the actual, but the average standard deviation of the percent difference for each time interval over the entire period was 17 percent. To more closely reflect the measured capacity, the characteristics of some vehicles were modified in the vicinity of the merge area to create variation in capacity more closely reflecting the observed conditions. The results of the modified simulation are also shown in Figure 18. After modification, the total simulated volume through the work zone over the test period was within 0.5 percent of the actual and the average standard deviation of the percent difference was reduced to less than 10 percent. The modified operating characteristics were used for all further testing.

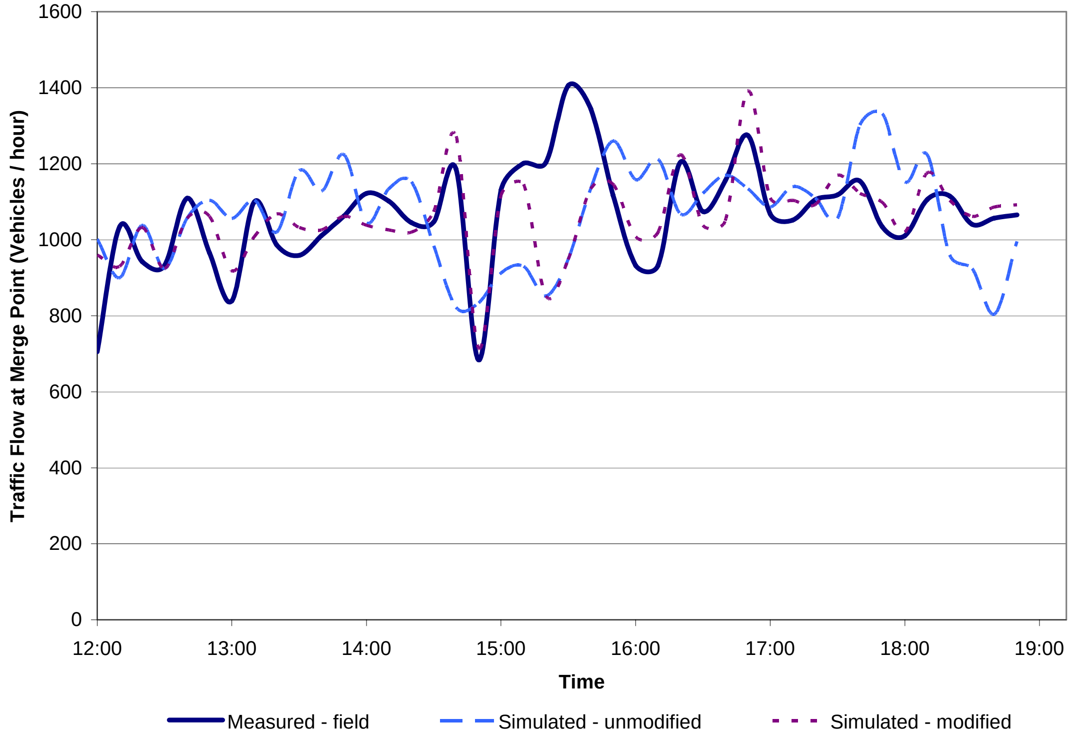


Figure 18: Comparison of Field Observed and Simulated Flow Using VISSIM

4.2.1.4.1 VISSIM Model Variability Analysis

A variability analysis was conducted to determine the change in simulated output parameters as input variables were modified. The variability analysis considered changes in two input characteristics – the lane merge behaviour of motorists and the demand volume of traffic entering the work zone area. Maximum queue length during each simulated time interval was used as the measure of comparison between various scenarios.

Lane merge behaviour can affect the queue length due to several factors. First, the smoothness of merging and traffic flow at the taper area can affect capacity through the work zone. A reduction in conflicts at the merge area by reducing late merges has been shown to result in smoother traffic flow, as indicated by reduced stops and shorter duration of stops in the queue traffic (Datta, 2001). Second, a change in merge behaviour may affect the length of queue. For an equal number of vehicles in a queue, the queue length will be longer if all vehicles are queued in a single lane instead of using both lanes.

To simulate the effects of lane merge behaviour, three scenarios were tested:

- Free lane change behaviour for all vehicles up to taper;
- 25 percent of traffic restricted to using through lane only on approach, and;
- 75 percent of traffic restricted to using through lane only on approach.

The results of the variability analysis for changing driver behaviour are illustrated in Figure 19.

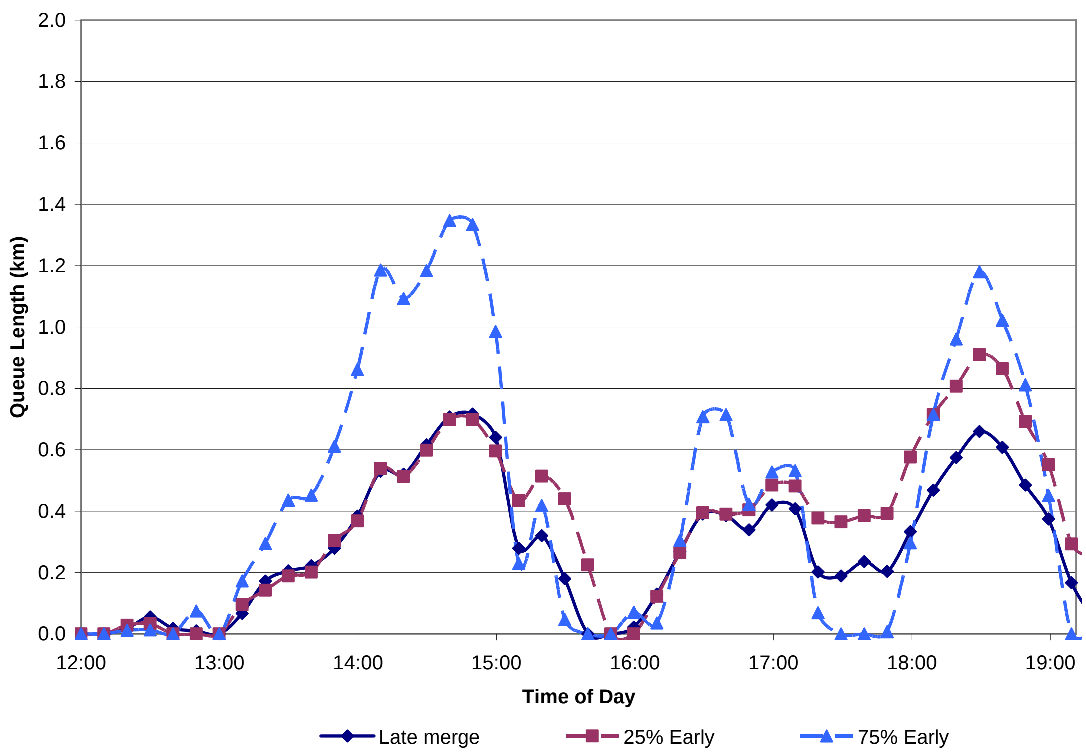


Figure 19: Effect of Merge Behaviour on Queue Build-Up Simulated Using VISSIM at Case Study Site

Changing lane usage behaviour affects the characteristics of queue build-up and queue dissipation. At time 13:00 a queue begins to build and continues to build for approximately two hours. During this phase the free merge and 25 percent early merge simulation results are almost identical, while the 75 percent early merge simulations results in a queue build-up approximately twice as long. At approximately 15:00 hours, the queue begins to dissipate.

The simulation indicates that the 75 percent early merge condition is able to dissipate a queue much more quickly than either of the other two conditions. Under the 75 percent early merge condition, despite having a queue length twice as long at the start of the dissipation period the queue is very quickly reduced and is shorter than the other two scenarios by 15:20. One possible reason for the more rapid queue reduction is the reduction in conflicts due to early merging leading to smoother and more efficient flow at the merge point. Another possible reason is that the physical length of the queue is longer, but more of the vehicles are in a single lane under an early merge condition. For the same amount of vehicles moving through the work zone, the reduction in physical queue length will be greater for a single lane of traffic than for two lanes of traffic.

Figure 20 illustrates the variability of the simulated queue to changes in the input traffic demand. The five input traffic demand conditions tested were the base volume based on field measurements, increases in volume of 5 percent and 10 percent, and decreases in volume of 5 percent and 10 percent. As seen in Figure 20, input demand volume has a significant impact on the expected queue length predicted by the VISSIM simulation. The maximum queue length predicted to occur between time 14:30 and 15:00 ranges in length from 36 m when volume is decreased by 10 percent to 1550 m when volume is increased by 10 percent. The variation is even more pronounced for the later peak in queue length predicted at approximately time 18:30. The maximum queue length was predicted to occur around 18:30 and ranges in length from 216 m, when volume is decreased by 10 percent, to 2522 m when volume is increased by 10 percent.

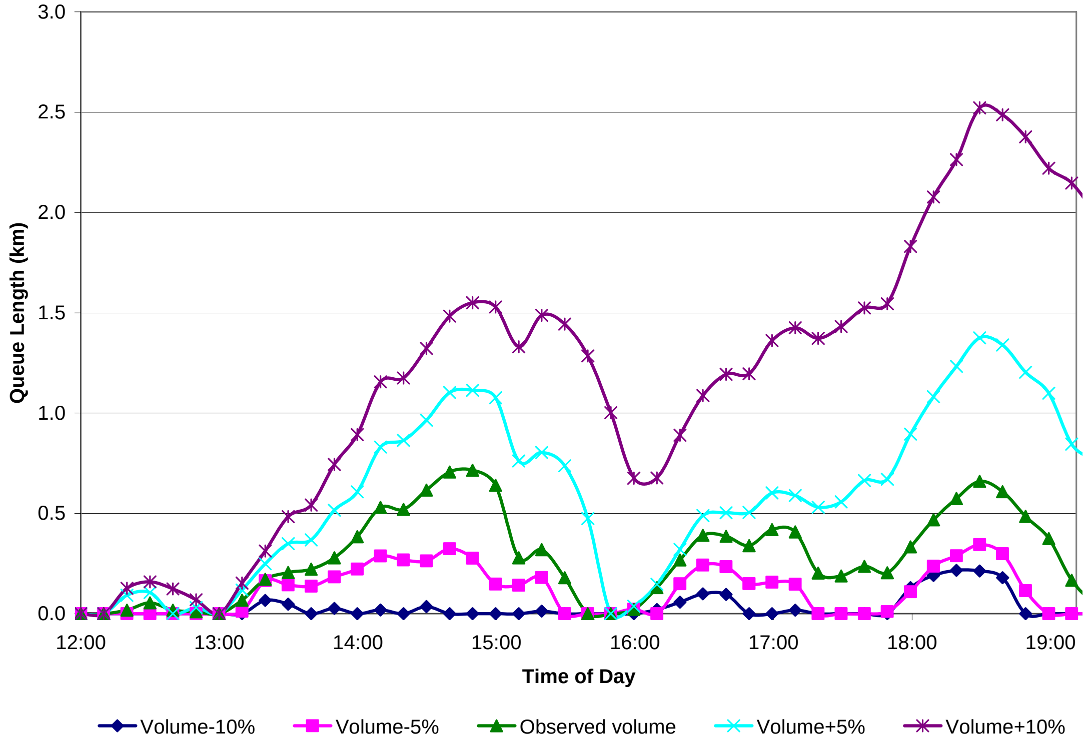


Figure 20: Effect of Input Traffic Volume on Simulated Queue Build-Up in VISSIM Simulation for Case Study Site

4.2.1.4.2 VISSIM Model Evaluation

The observed queuing that occurred in the field was determined based on field measurements and observations on October 30, 2003, as illustrated in Figure 21 below. Figure 21 also shows the simulated results from VISSIM for variations of the input parameters that were illustrated in Figure 19 and Figure 20, including the base volume and merge behaviour, a 10 percent increase in demand volume, early merging by 75 percent of vehicles, and a combination of increased demand and early merging. Early merging means that 75 percent of vehicles were forced to change lanes into the continuous lane at a point upstream from the taper area, rather than waiting to merge until the final opportunity.

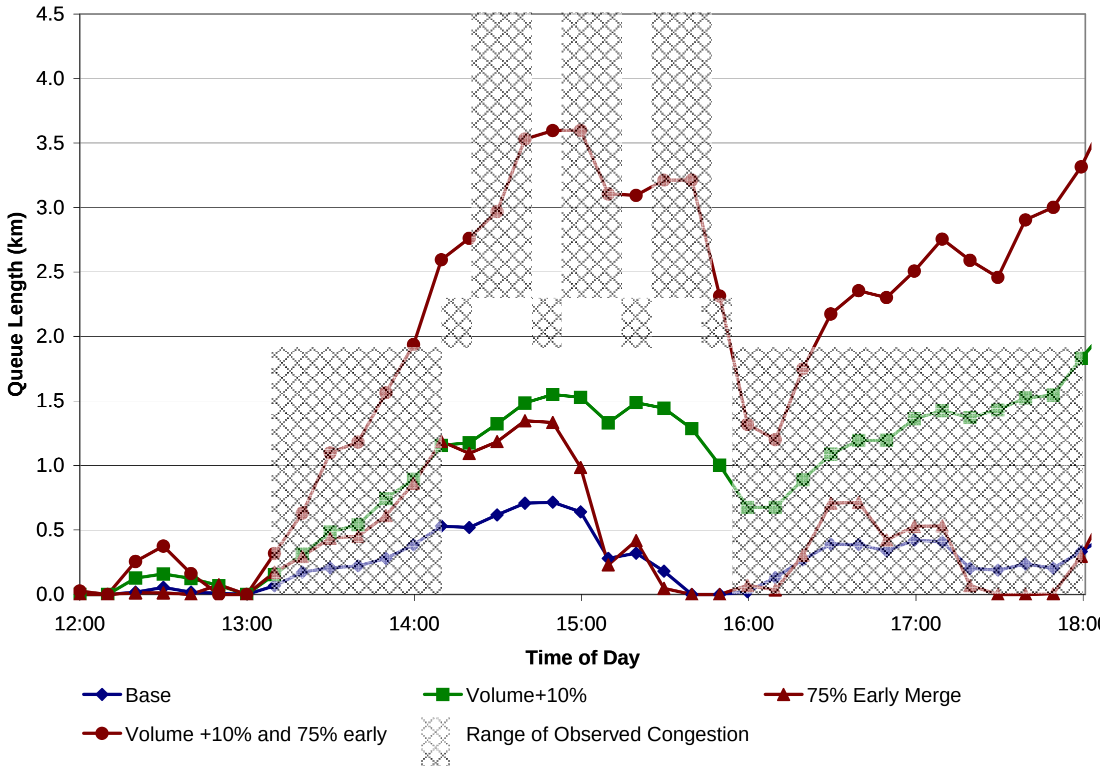


Figure 21: Comparison of VISSIM Simulated Queue Length to Field Observations

The data analyzed to determine queue length consisted of speed, volume, and occupancy data collected by each of the three sensor trailers that were part of the system as well as recorded video taken at Exit 154 southbound. The detection points are labelled in Figure 14 as sensor 1, sensor 2, sensor 3, and video 1. Since discrete detection points were used, it was possible to estimate the range of the queue length, but not the actual length. These ranges are illustrated in Figure 21 by the shaded areas indicating the observed length for each period of time. Based on the location of each of the detection locations, the queue length was classified in one of the following ranges:

- No queue
- Queue less than 1.95 km
- Queue between 1.95 km and 2.35 km
- Queue between 2.35 km and 4.61 km
- Queue greater than 4.61 km

On October 30th, queuing was measured to occur between 13:23 and 18:00. For short periods of time the queue was longer than 2.35 km, but never exceeded 4.61 km. The actual queue in the field, based on the detection locations, fell somewhere between the lower and upper limit. There are three main phases to the queue development.

Phase One: 13:20 to 14:20: Queue less than 1.95 km

Phase Two: 14:20 to 16:00: Queue exceeds 1.95 km, periods exceeding 2.35 km

Phase Three: 16:00 to 18:00: Queue less than 1.95 km

In Phase One, all the modeling scenarios produced estimated queue length results that fell within the bounds of the observed field conditions.

In Phase Two the length of queue is underestimated by the base volume and merger behaviour. The estimated queue lengths are longer with the 10 percent demand increase and the 75 percent early merge scenarios, but are still under-estimated compared to the observed field conditions. The scenario of 10 percent volume increase and 75 percent early merge together produced an estimated queue length that fell within the range observed in the field.

In Phase Three the observed length of queue was less than 1.95 km. During the majority of this phase the length of queue is estimated within the proper range when the base, 10 percent demand increase and the 75 percent early merge scenarios are considered. The scenario of 10 percent volume increase and 75 percent early merge together produced an estimated queue length that exceeded the range of queue length observed in the field.

In summary, all of the VISSIM modeling scenarios were able to match some of the observed conditions in the field. Each of the VISSIM modeling scenarios also over-predicted or under predicted some of the expected queue lengths for periods of time. VISSIM was able to replicate some of the field conditions, but was not a perfect model of the observed field conditions.

4.2.1.5 QuickZone Model Formulation

The QuickZone 2.0 macroscopic analysis program was used to analyze the development of queues at the I-95 case study work zone. A roadway network is constructed in QuickZone by defining nodes and links. Each link consists of a start and end node connected by a roadway segment. The characteristics of each link are defined including number of lanes, capacity, and speed. Links are also defined as a work zone, mainline, or detour route segment. AADT and truck percentage are entered, with adjustment factors based on time of day, day of week and month of year. Using data collected from a nearby count station and manual counts during the study, the traffic profile for the case study site was defined. The layout of a work zone as represented by QuickZone is illustrated in Figure 22.

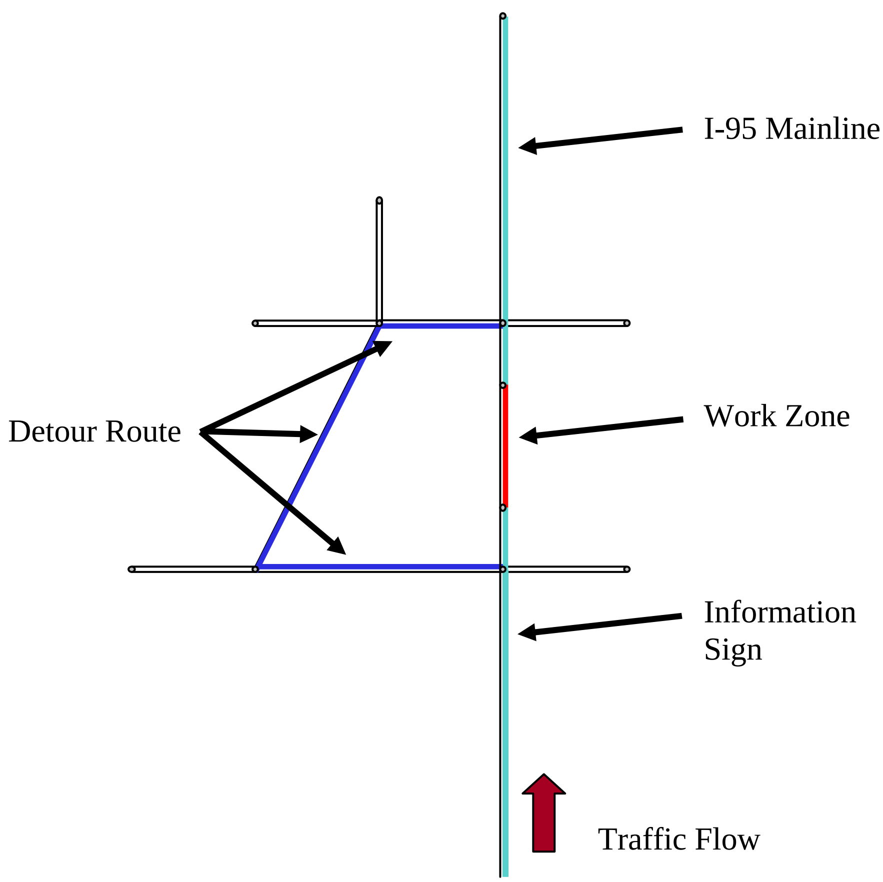


Figure 22: QuickZone Representation of Work Zone with Detour Route

4.2.1.5.1 QuickZone Model Variability Analysis

A variability analysis was conducted to determine the change in simulated output parameters by QuickZone as input variables were modified. The variability analysis considered changes in two input characteristics: 1) the work zone capacity, and 2) the traffic demand. Maximum queue length during each simulated time interval was used as the measure of comparison between various scenarios.

The demand observed in the field on October 30th, 2003 was used as the base case for comparison. The traffic volume was defined on an hourly basis, assuming uniform flow for each hourly period. The variability of the results was determined for increases and decreases of five percent and ten percent for capacity as illustrated in Figure 23.

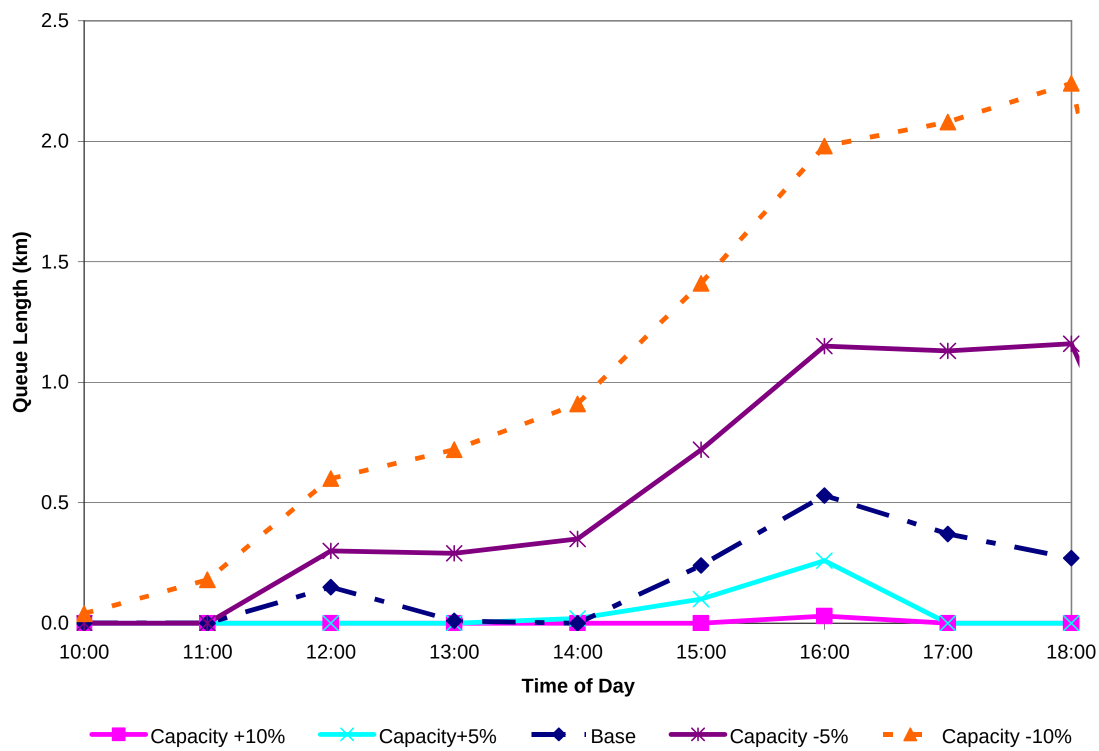


Figure 23: Effect of Changes in Input Capacity on Estimated Queue Length in QuickZone Model

4.2.1.5.2 QuickZone Model Evaluation

The predicted queuing determined by QuickZone was compared against the observed conditions in the field. The field observations are the same results from October 30, 2003 as those used in the comparison with VISSIM presented in Figure 21. The queuing predicted by QuickZone and the actual field observations for the same conditions are presented in Figure 24.

The results shown in Figure 24 include the prediction from QuickZone with the actual traffic volume and the volume increased by ten percent. QuickZone does not provide the capability to change merging behaviour as was done with the VISSIM model. In Phase One, from 13:20 to 14:20, the QuickZone estimate for queue length falls within the observed conditions for both traffic volumes.

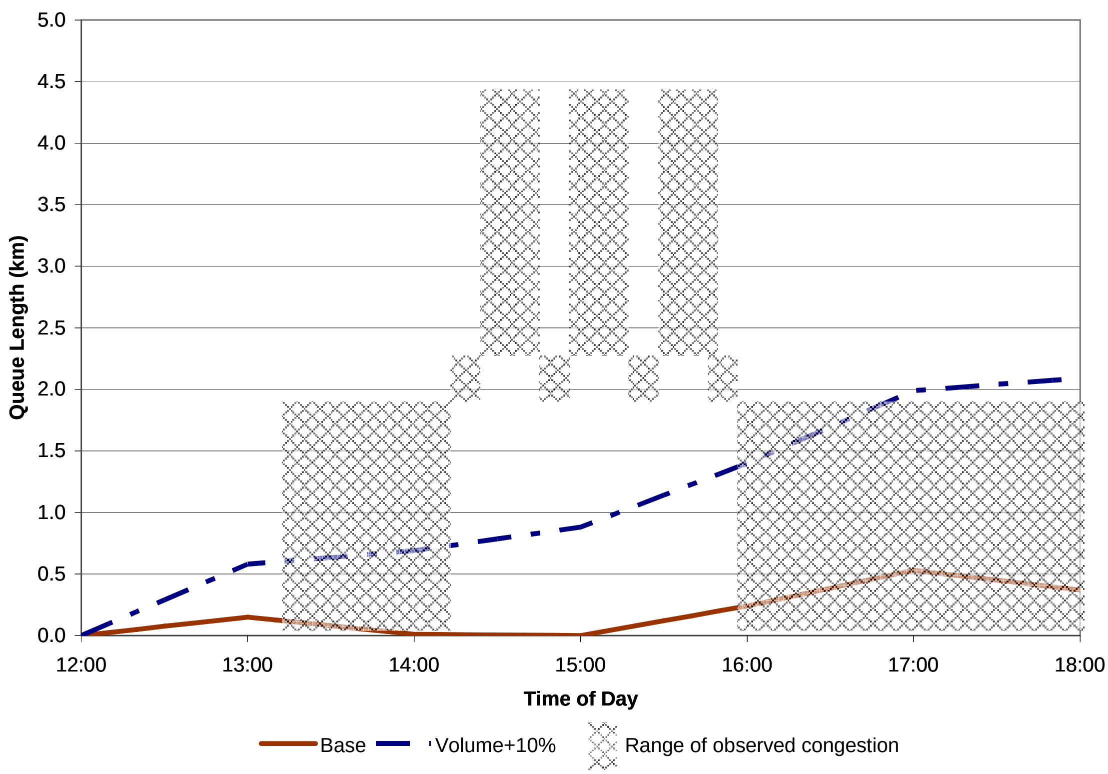


Figure 24: Comparison of QuickZone Simulated Queue Length to Field Observations

During Phase Two, from 14:20 to 16:00, queuing was observed to be in excess of 1.95 km. QuickZone predicted almost no queue at the base volume and a queue between 0.7 km and 1.4 km when volume plus 10 percent was used as the input. The QuickZone estimate was less than the observed conditions. In Phase Three the QuickZone prediction generally fell within the bounds of the observed conditions, but did overestimate the queue length towards the end of the period for the volume plus ten percent condition.

In summary, QuickZone provided an estimate of queue length that fell within the observed conditions in some cases, but significantly underestimated the queue during the period of greatest queue length. The queue build-up predicted by QuickZone also appears to have a time lag when compared to the field observations, possibly due to the hourly calculation time interval. A comparison between Figure 21 and Figure 24 indicates that the VISSIM simulation was better able to represent the observed field conditions. This is attributed to the capability in VISSIM to modify merging behaviour and to analyze shorter time intervals to provide a greater level of detail and analysis as site traffic flow conditions change.

4.2.1.6 Comparison of Traffic Analysis Models

Two models were examined for application in the modeling of Smart Work Zones. Both models were able to match some of the observed conditions, but either over-estimated or under-estimated during some periods.

QuickZone provides the necessary input parameters and controls to model a Smart Work Zone application. The inputs are based on data that should be available for most sites, such as traffic volumes, traffic composition (percent trucks) work zone capacity, and traffic patterns. The model could be configured reasonably well to reflect the expected conditions, to the level of detail allowed by the model. The model is based on hourly inputs and therefore can only produce results to that level of detail. Some control of driver behaviour is facilitated at a network level, with vehicles allowed to take an alternate route, cancel a trip, or change the timing of a trip.

VISSIM includes more input parameters than QuickZone and greater capability to customize the model for specific applications. Individual vehicle characteristics and complex roadway geometry and characteristics can be modeled. In addition, conditions can be modified over time, including traffic stream volume and composition, speeds, lane changes, and route choice.

VISSIM is a more complex model and therefore more data needs to be entered and the configuration is more time consuming. The QuickZone model is designed for the assessment of a work zone without requiring more than a few hours of time. Therefore QuickZone data entry and configuration is simpler and less time consuming.

QuickZone provides the key results for the assessment of a work zone including the length of queue, number of vehicles in the queue, and the delay to motorists. There is also a summary of vehicle behaviour such as alternate route usage, trip cancellation, and change of trip timing. At a macroscopic level, QuickZone provides analysis on an hourly basis.

VISSIM can provide the same types of results as QuickZone to measure parameters such as the length of queue, number of vehicles in the queue, and the delay to motorists. VISSIM also provides much greater flexibility than QuickZone in how the measurements are taken. For example, travel time can be measured for any chosen time interval and is not restricted to an hourly estimate like QuickZone. The travel time can be calculated for all vehicles, or can be determined for a specific group of vehicles such as heavy trucks. Also, the travel time can be measured from various start and end points and over multiple travel routes.

QuickZone is designed to evaluate approaches on a project level and facilitates the accumulation of information over extended periods of weeks, months and years if necessary. Traffic and system parameters can be adjusted as they vary over time. VISSIM can accommodate varying conditions, but each must be treated as a separate case. To model conditions over an entire construction period, several different scenarios would need to be created in VISSIM and analyzed independently.

The evaluation of the two model approaches showed that both have the ability to provide some useful information for use in work zone benefit cost analysis, but that there are some differences between the observed and modeled conditions. Both models have been thoroughly tested and validated in other applications. The results presented here are based on a limited amount of data and do not necessarily invalidate the model approach, but more work may be necessary to increase the accuracy of the models for this application to obtain a higher level of confidence in the results.

In this case, the models can provide an indication of expected conditions, but can not precisely predict the expected queue length over all traffic conditions. Uncertainty will always be a factor in traffic modeling and should not be ignored. This uncertainty should be addressed as much as possible by increasing the accuracy and confidence level in the model approach, but some uncertainty will always remain. Therefore it is recommended that any analysis that is done should include a consideration of the variability of traffic predictions and sensitivity of the benefit cost analysis results to changes in the traffic predictions.

4.2.1.7 Determination of Mobility Input Values

As input into the economic analysis for the North Carolina I-95 case study, the hours of delay were determined by using VISSIM to model the scenario of the work zone with and without a Smart Work Zone. Three levels of traffic volume inputs were considered, chosen to reflect the uncertainty in estimating volumes from AADT data, to establish a range of expected values for the amount of travel time that may be saved. The work zone was simulated without a Smart Work Zone and with the presence of a Smart Work Zone to determine the individual and total expected delay time. Traffic demand and capacity remained the same for both simulations. When the measured delay exceeded 5 minutes on the mainline, then traffic was diverted to the alternate route at a level to maintain delays not exceeding five minutes, with a maximum of up to ten percent of the traffic diverted to the alternate route.

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, it is not realistic to use as a base case a condition that would cause 60 minutes of delay to traffic. 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.

Various sources for the valuation of delay time were cited in the literature review (Daniels, 1999; USDOT[3], 1997; FHWA[7], 2001). For the application of the analysis process to the case study, values were chosen that are representative of the spectrum of values assigned to travel time. It has been identified by some that short delay periods are not valued by drivers at the same rate as delays that are longer. The Smart Work Zone in this application does not begin reducing delay until there is at least 5 minutes of delay for mainline traffic. Therefore, the delay value to vehicles is beyond the initial insignificant amount. In addition, travel time reliability has been cited as an important factor in the valuation of delay, and has not been added explicitly into the values used in the analysis.

Operating costs as considered in the analysis include the cost of fuel at the time the project took place, but not the vehicle wear and maintenance costs. As described earlier, the wear and maintenance portion of operating costs related to travel distance is insignificant if the percentage of vehicles using the alternate route is small and the travel distance is similar on the mainline and alternate routes. For the case study application, the percentage of vehicles using the alternate route had a maximum value of 10 percent and the increased travel distance on the detour route was only 1.6 km longer than the mainline route. Therefore the assumption is valid for this case.

Emissions were defined based on the idling emissions levels from vehicles in proportion to the known traffic composition. Traffic data provided the classification of vehicles, but not the type of engine. The engine type affects the quantity of emissions of various types. To represent the range of potential vehicle makeup, the percentage of gas and diesel vehicles was varied.

The literature review identified a number of sources for the valuation of emissions, as presented earlier. The range of possible values for the sensitivity analysis is drawn from the cited values to provide minimum, maximum and expected values.

4.2.2 Safety

The required input parameters for the economic analysis are the expected number of fatal and injury crashes in the work zone without a Smart Work Zone, the percent reduction in crashes with the implementation of a Smart Work Zone, and the statistical value of fatal and injury crashes.

Actual crash rates during the operation of the Smart Work Zone were investigated. However, given the high importance placed on having the system in operation, it was not feasible to do a study with and without the Smart Work Zone in place on this project. There were short periods of time when the work zone was present, but the Smart Work Zone was not in operation. A comparison was made between crashes with and without the Smart Work Zone, but the time periods were insufficient to draw any conclusions. In evaluating a new highway safety improvement it is typical to look at before and after periods of at least three years. Since the entire project only lasted eight months there was insufficient data for a comparison of crash rates. The investigation did provide information on crash frequency that may be useful in future research

(Bushman[4], 2004). Therefore, a more generalized approach to estimating crash rates and crash improvements was used for the economic analysis.

The base crash rate for the case study site, before construction, was obtained from North Carolina Department of Transportation (NCDOT) statistics. Part of the site was in Halifax County and part of it was in Nash County. Therefore, crash rates from both counties were averaged, resulting in 1.55 fatal crashes / 100 million vehicle miles traveled and 27.34 non-fatal injury crashes / 100 million vehicle miles traveled. During the sensitivity analysis, the crash rate was increased by a factor of 0 percent, 10 percent, and 20 percent to account for the presence of a work zone, based on typical findings from several researchers, as cited earlier.

A key factor in the safety analysis is the change in safety that may result from the deployment of a Smart Work Zone. Unfortunately there is limited research available on the safety impacts of a Smart Work Zone, although some studies have indicated an improvement in safety. In the absence of strong data, estimates of potential improvement ranging from no improvement up to a 10 percent reduction were used in the analysis.

Based on the AADT of 37,000 vehicles per day and a defined work zone length of 3.5 miles, the traffic exposure at the site is 1.97 million vehicle miles traveled / month. This work zone was not present and active at all times, and therefore the exposure had to be adjusted for the actual hours of operation. The project operating procedures only allowed closures to take place from 6 am to 6 pm from Monday to Thursday and from 6 am to 12 pm on Friday. This is a common strategy used for this type of project by NCDOT. Based on these hours of operation and the traffic volume patterns at the site, the actual work zone exposure for a one month period is 35 percent of the total exposure. Therefore, 0.69 million vehicle miles traveled had the potential of being affected by the presence of a Smart Work Zone.

4.2.3 Agency Cost Input Parameters

There are a number of factors that affect the cost of a Smart Work Zone such as the procurement method, the complexity of the project, the amount of equipment, the duration of the project, and the competitive market conditions. The procurement of Smart Work Zone systems has been done through a variety of methods. Methods have included sole source awards, low bid tenders, inclusion as a line item in construction tenders, or as a request for proposals. Projects range in complexity from several sensor locations and a few signs to multiple approaches, extensive signing, portable video monitoring stations and website reporting. There are both mobilization and operating costs associated with smart work zone deployment. On longer duration projects the mobilization cost becomes a smaller portion of the overall project cost when considered on a monthly basis.

When Smart Work Zones are procured using a low bid process exclusively for the Smart Work Zone, it is relatively easy to obtain good cost information. When the Smart Work Zone is procured as part of a larger contract or through other procurement methods, it can be difficult to obtain accurate information. For purposes of this analysis, bid results from several similar projects in the 2003 construction season were used as the basis of estimates. As an emerging technology, the market is competitive for the supply of Smart Work Zones and new advances are being used to reduce costs, so there has not been an increase in typical system costs since 2003. The duration of the project used for analysis was 8 months, with a variation of 1 month. This would represent a construction period of March 1 to October 31 which is a typical construction period in many locations and is representative of the specific project being considered.

4.3 Probabilistic Economic Analysis of I-95 Case Study Application

The economic analysis model 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.

4.3.1 Sensitivity

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 25.

The results of the sensitivity analysis indicate that the expected result for the North Carolina I-95 case study project is a benefit cost ratio of 6.4. The tornado diagram shows the ranking of the uncertainty of input variables that are most sensitive, and the magnitude of the variability of the results. 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.

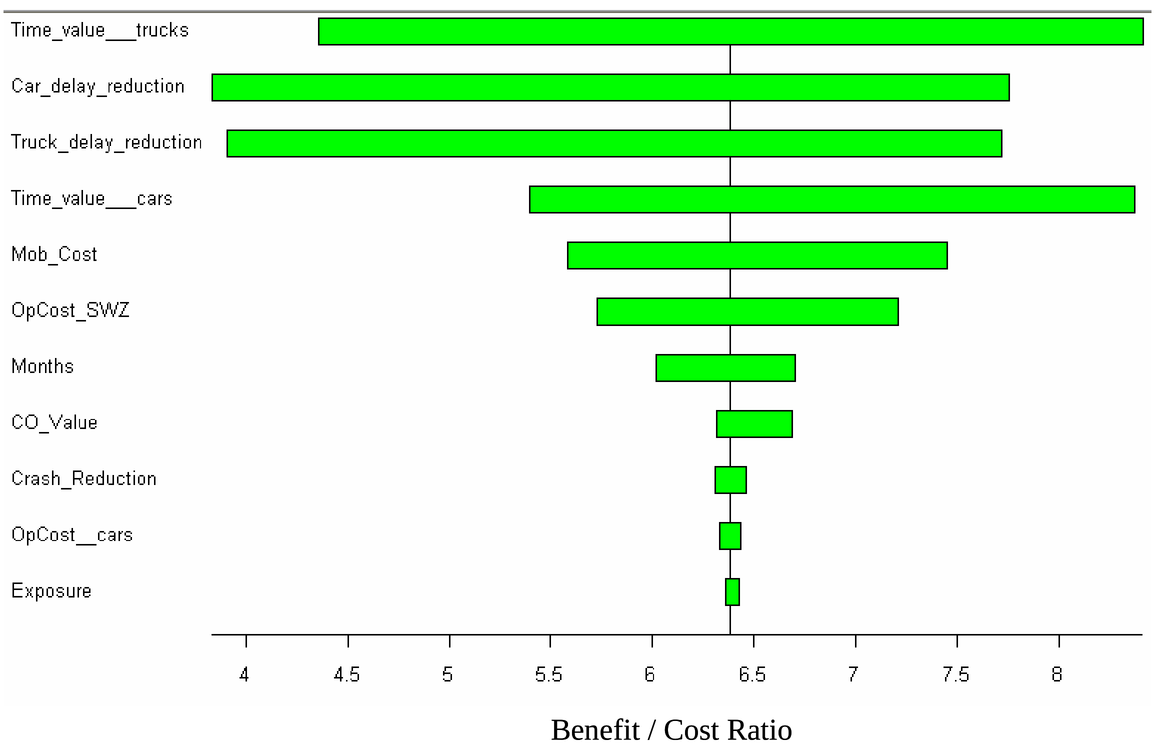


Figure 25: Sensitivity Analysis of Economic Model Independent Variables As Applied To Case Study Site

When the results of the sensitivity analysis for the case study project are compared to the results for the validation analysis in Figure 11, the top eight variables are all the same but there are some variations in the ranking. In the validation analysis the system operating cost was more significant than in the case study analysis, while the reduction in delay to cars and trucks was less significant in the validation analysis.

As noted earlier, there is a linkage between the value assigned to delay and the estimated hours of delay reduction. To determine the effect of this linkage on the ranking of the variables, the cost of user delay for cars and trucks were fixed at their minimum values. With these values fixed, another sensitivity analysis was performed on the eight most sensitive variables remaining.

The results of the sensitivity analysis with user delay fixed at minimum values are shown in Figure 26. Although there are some shifts in relative magnitude, the uncertainty related to the delay reduction variables is still the most sensitive of the input variables. 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. A breakdown of the relative contribution of each of the benefits is shown in Figure 27. More than 94 percent of the expected benefits are derived from a reduction in user delay, attributed approximately equally between savings to cars and trucks.

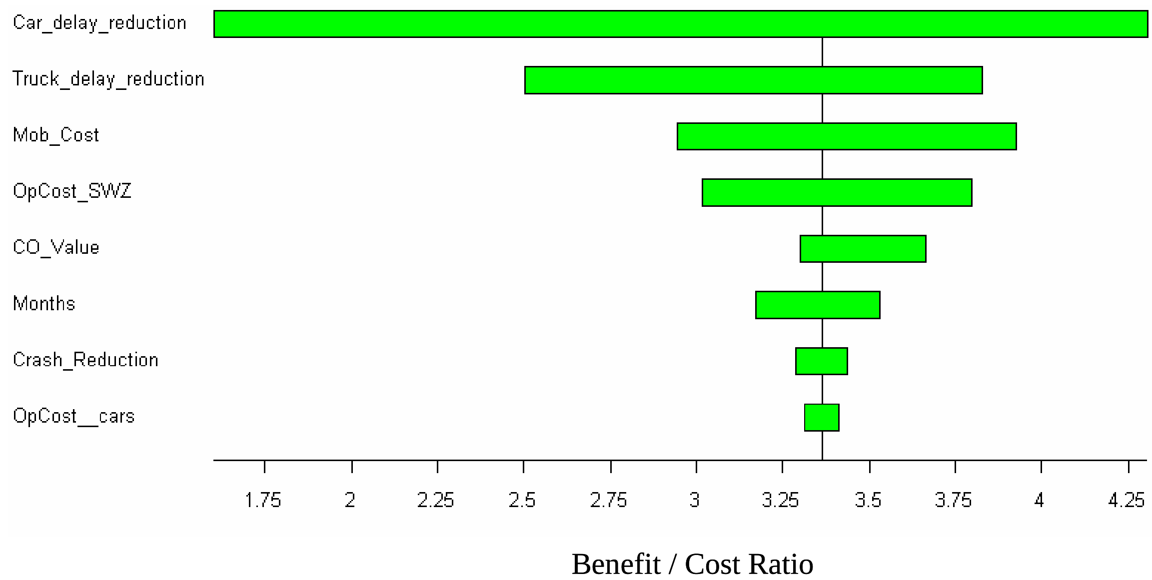


Figure 26: Sensitivity Analysis of Case Study Site with User Delay Fixed At Minimum Value

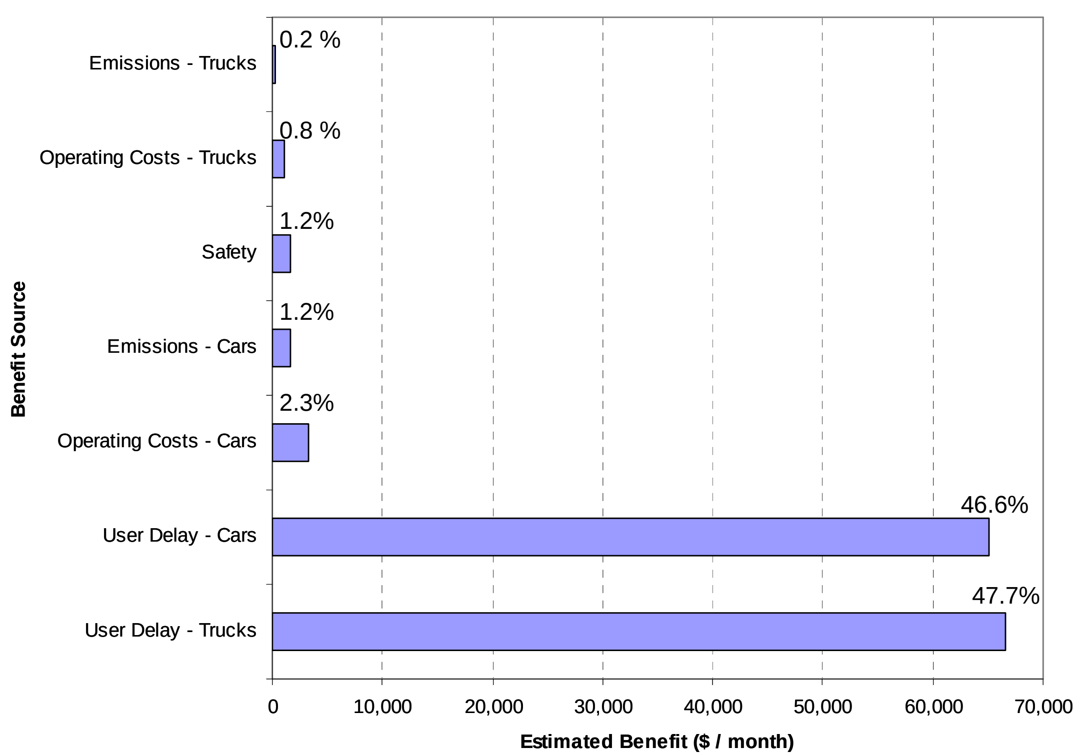


Figure 27: Contribution of Benefit Types for Case Study site

4.3.2 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 large effect on the outcome if their value changes through its expected range. There is some uncertainty with the actual value of these variables, and the 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 4. 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 28.

The x-axis is the estimated benefit cost ratio for the project under consideration. The y-axis is the cumulative probability of the benefit cost 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 benefit / cost ratio is between 3.3 and 9.1 and at a 95 percent confidence interval, the predicted benefit / cost ratio is between 1.2 and 11.9.

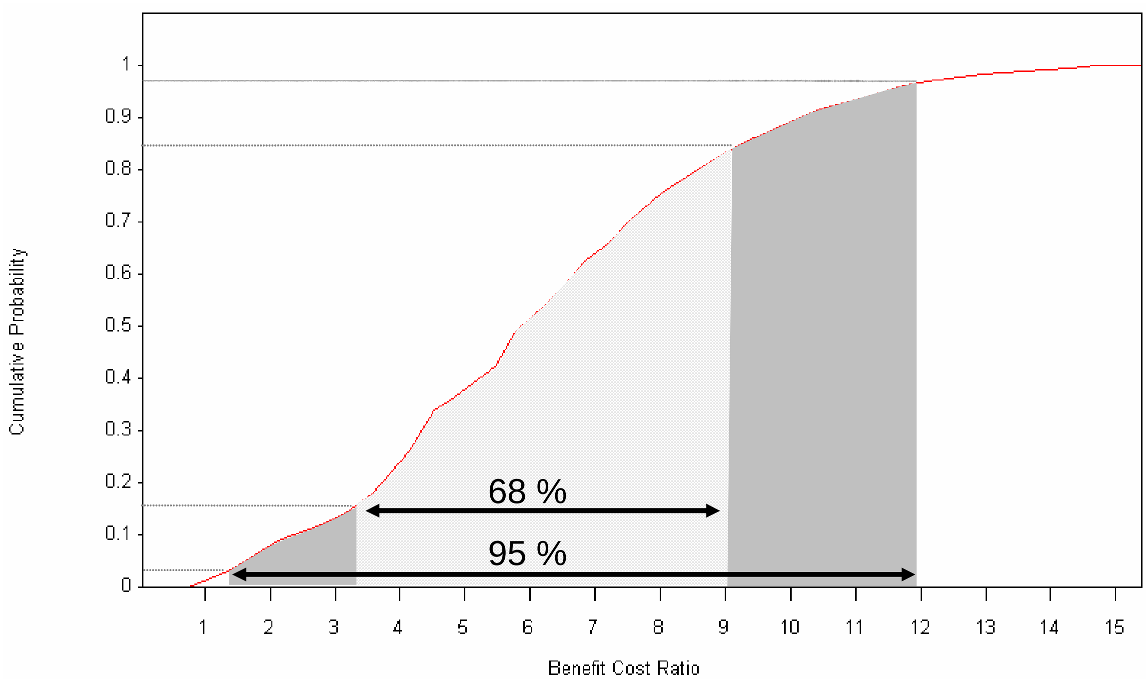


Figure 28: Risk Analysis of Deployment at I-95 Case Study Site, Computed As B/C Ratio

The risk profile can also be computed in terms of net value. Although benefit cost ratio is a very common evaluation measure for transportation projects, some analysts may prefer the net value instead. In some cases, NV may also provide additional insight and better decision making information. For example, an agency may decide that they will only fund one ITS project in a year. A small scale project may have a projected cost of $100,000 and projected benefits of $300,000, yielding a B/C ratio of 3.0. Another project may have a cost of $400,000 and a projected benefit of $800,000, yielding a B/C ratio of only 2.0. The NV of the larger project is $400,000 compared to only $200,000 for the smaller project. Therefore, even though the B/C is smaller, it still may be a more desirable project.

The risk profile and predicted confidence intervals, as computed based on NV, is illustrated in Figure 29.

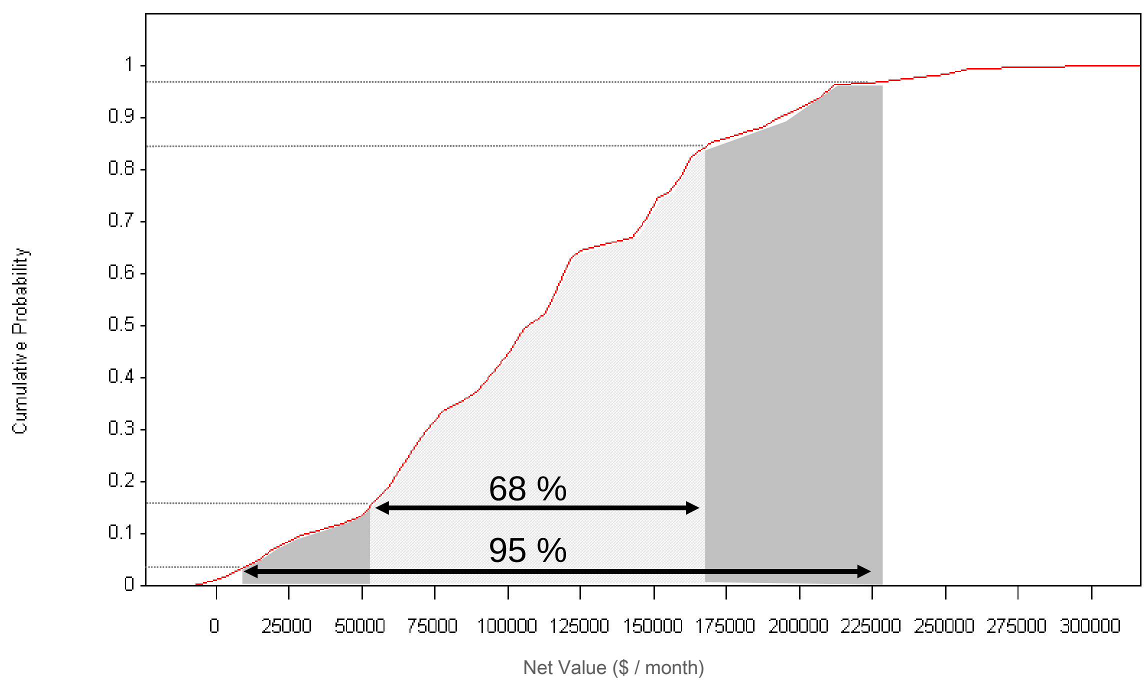


Figure 29: Risk Analysis of Deployment at I-95 Case Study Site, Computed As Net Value

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

5 Summary, Conclusions and Future Research

5.1 Summary

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.

The performance analysis model was successfully developed by drawing upon the current research in relevant areas and supplementing it with traffic modeling using VISSIM, a commercially available microsimulation model. The model was successfully implemented in DPL, a commercially available decision analysis program that facilitated the analysis of benefits and costs and also provided a quantification of the uncertainty of the results in the form of sensitivity analysis and risk profile.

The first step in the research was a literature review on current research into the performance evaluation of work zone projects and the costs and benefits of deploying a Smart Work Zone. Based on the research the structure and content of the performance analysis framework was established and the dependent and independent variables defined. The framework was implemented in DPL to facilitate the desired probabilistic decision analysis including quantification of uncertainty and risk. The performance analysis model was also implemented in Excel to provide a check on the calculations of the probabilistic model. The performance analysis model was verified using inputs from previous research projects and checked for accuracy, response to changes in input variables, and predicted outcomes.

The performance analysis model was then applied to a specific case study application project that took place on I-95 in North Carolina in 2003. When applied to the case study project, the economic analysis model provided an estimate of the expected benefit cost ratio, net value, and a risk profile quantifying the uncertainty of the results. For the case study application, the predicted benefit / cost ratio, at a 68 percent confidence interval, is between 3.3 and 9.1. At a 95 percent confidence interval, the predicted benefit / cost ratio is between 1.2 and 11.9.

The primary limitation of the developed model is the availability of accurate input values. This was addressed by drawing upon the best available research and by including an assessment of the uncertainty in the analysis. The limitations of modeling methods for work zones and lack of in-depth research into the effects of a Smart Work Zone affect the level of confidence that can be achieved.

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 repeat the analysis several times to cover the expected operating scenarios and develop an assessment that covers all aspects of the entire project. As further research is done in this area, a more comprehensive archive of analyzed conditions may be developed that can be drawn upon, without the need for detailed investigation of every scenario. The scope of the analysis was restricted to the mainline and alternate route and did not take into account network impacts due to diverting traffic. This was a valid approach on the case study project which was a rural work zone with available capacity on the alternate route, but may be a limitation if applied in an urban setting.

5.2 Conclusions

The objective of this research to develop a probabilistic Smart Work Zone analysis model with the ability to value the expected benefits and quantify the uncertainty in terms of reduced user delay, reduced vehicle operating costs, reduced emissions, and improved safety from the deployment of a Smart Work Zone was successfully achieved.

The objective of the research was achieved by the development, validation, and demonstration of the performance analysis model. The model includes the following characteristics:

- Probabilistic analysis
- Sensitivity analysis and risk profile to quantify uncertainty
- Inclusion of user delay, vehicle operating costs, emissions, and safety in the analysis
- User definable inputs for application to various project conditions
- Flexibility to accept inputs from several traffic flow models

Two traffic models, QuickZone and VISSIM, using macroscopic and microscopic analysis approaches respectively, were examined in the research. When compared to observed field conditions, both models were able to accurately simulate some but not all of the observed conditions. VISSIM provided the ability to use shorter time intervals and to modify individual vehicle behaviour and was therefore more adaptable to the specific conditions of the case study site on I-95 in North Carolina.

The performance analysis model provides a tool to be used by decision makers to make more informed decisions regarding the deployment of a Smart Work Zone. Projects of interest can be analyzed to determine the expected benefits and costs, and associated uncertainty, to be used in determining whether to proceed with a Smart Work Zone project.

When applied to the specific case study scenario taken from one set of conditions on an actual deployment of a Smart Work Zone in 2003 on I-95 in North Carolina, the model predicted, at a 95 percent confidence level, the expected benefit / cost ratio was between 1.2 and 11.9. Under suitable conditions of traffic volumes, available alternate routes, and site geometry, a Smart Work Zone can produce favourable results in terms of improved safety and mobility. Under heavily congested conditions, the diversion of even a small amount of traffic to a more efficient route can provide sizable travel time improvements for all traffic.

5.3 Future Research

The current research has created a framework for analysis of Smart Work Zone projects that accounts for the main economic factors and provides a quantification of the uncertainty associated with the input values. The accuracy and confidence level of the analysis can be improved by improving the confidence level of each of the inputs. The framework helps to identify the most significant variables and provides direction for future research.

Additional research in the following areas will increase the confidence in input variables and will therefore improve the probabilistic analysis:

- Measurement and analysis of the effect of a Smart Work Zone on traffic flow, across a range of site conditions and application scenarios.
- Realistic modeling of the effect of a Smart Work Zone on traffic flow including the dynamic interaction between traffic and the system, across a range of site conditions and application scenarios.
- Measurement and quantification of other effects of a Smart Work Zone deployment such as safety improvement and emissions reduction.
- Reduction of detailed analysis to a simplified user tool to be applied to common situations.

As additional research is conducted to measure the effect of a Smart Work Zone on traffic flow, across a range of site conditions and application scenarios, there should also be related research into optimizing the matching of the technology and implementation to the specific site needs. Each application will be unique and understanding the best technology for the application will increase the benefits realized from deployment of a Smart Work Zone.

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