Evaluation of Work Zone Strategies and User Delay Costs Associated with Strategies and Treatments

Ken Huen, M.A.Sc.
Research Engineer
Department of Civil Engineering
University of Waterloo
200 University Avenue West
Waterloo, ON, Canada N2L 3G1
Phone: (519) 888-4567 Ext. 3152, Fax: (519) 888-4300
kmyhuen@uwaterloo.ca

Sabrina Ren, M.A.Sc.
Department of Civil Engineering
University of Toronto
35 St. George Street
Toronto, ON, Canada M5S 1A4

Susan Tighe, Ph.D., P.Eng.
Canada Research Chair and Associate Professor of Civil Engineering
University of Waterloo
200 University Avenue West
Waterloo, ON, Canada N2L 3G1
Phone: (519) 888-4567 Ext. 3152, Fax: (519) 888-4300
sltighe@uwaterloo.ca

Brenda McCabe, Ph.D., P.Eng.
Associate Chair of Undergraduate Studies and Associate Professor
Department of Civil Engineering
University of Toronto
35 St. George Street
Toronto, ON, Canada, M5S 1A4
Phone: (416) 946-3505 Fax: (416) 978-5054
mccabeb@civ.utoronto.ca

Paper prepared for presentation at the
Road Monitoring and Traveler Information System Benefits for Maintenance and Construction,
Maintenance and Construction Committee Session

2006 Annual Conference of the
Transportation Association of Canada
Charlottetown, Prince Edward Island

ABSTRACT

The transportation sector is an integral part of the local, provincial and national economies. There are three important issues, including mobility, safety and economics, which must be considered when highway work zones are engineered. These competing issues are important to the key parties involved in highway construction, which include the owner, the transportation agency, hired contractor, consultants and the traveling public. To effectively assess these issues, this research is divided into four Modules. Module One focuses on developing work zone strategies appropriate for the construction being performed. Module Two investigates methods of improving safety within work zones. Module Three develops a prediction model for user delay cost while Module Four is a multi-variant decision model to assist transport agencies in incorporating an appropriate amount of user delay cost for a given facility type.

This paper summarizes a recent research project undertaken in partnership with the Ministry of Transportation of Ontario, the University of Toronto and the University of Waterloo. The paper provides recommended practices and prediction models to improve mobility, safety and balance the economic impacts between key parties. Through interviews with contractors, it was revealed that they did not believe that there was any link between quality problems when specifications were met. Serious concerns were raised concerning productivity, safety and performance of the final product during night construction. It is also difficult to implement the work zone configuration solely designed by the consultants. To resolve these issues, it is recommended that a constructability analysis be carried out prior to construction.

Safety within work zones is considered paramount. The causes of such involving motorists in work zones include unexpected congestion, duration of work zones, speed variation, work zone layout, highway configuration, driver distraction and night work. Each consists of a visibility, a physical limitation and a human factor issue. In terms of the construction worker, the risk is either internal or external to the work zone. Externally, heavy vehicles are the main source of fatalities to workers. Internally, the leading cause of death involves construction equipment and construction vehicles. Therefore, to mitigate the likelihood of incidents occurring, it is important to document the conditions of which it occurred. It would be desirable in police reports to include information and proximity of a work zone if applicable.

INTRODUCTION

There exists tens of thousand lane kilometres of roadway in Ontario. Given this vast network, maintaining the transportation infrastructure must be completed through routine maintenance, rehabilitation and reconstruction. Key players that are involved in road construction include the owner, transportation agency, consultants, contractors and, of course, the traveling public. This paper summarizes the impacts to each stakeholder as well as a proposed prediction model to predict road user delay cost with respect to road construction activities. The research has been divided into four Modules and is summarized by Figure 1.

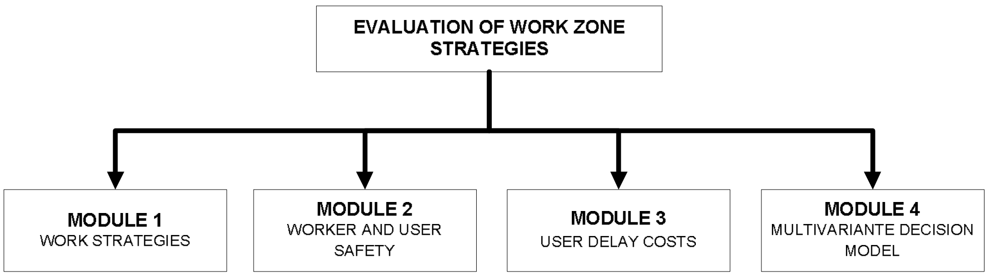

Figure 1. Breakdown of project Modules.

The Ontario Highway Network

According to the Ministry of Transportation of Ontario (MTO), the province is divided into five regions, namely Northwestern (NW), Northeastern (NE), Central (C), Southwestern (SW) and Eastern (E). Within this study, the entire network is divided into two regions by geography: Northern (encompassing NW and NE) and Southern (encompassing C, SW, E). Within each region, rural and urban area designation is given. Finally, within each area, the common highway classification nomenclature is employed, specifically: freeway, arterial, collector and local. A summary is illustrated in Figure 2.

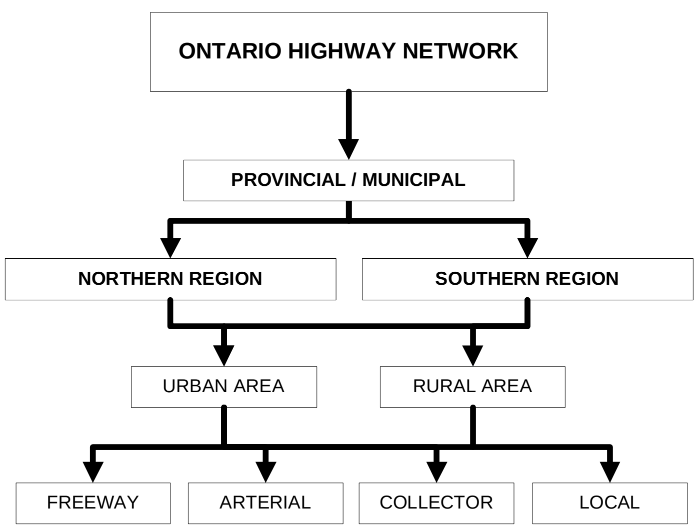

Figure 2. The general breakdown of the Ontario Highway Network to Functional Classifications.

Influences in Work Zones

Various factors will influence highway maintenance and rehabilitation practices. Although many aspects of road construction appear to be unrelated, it can be shown, in Figure 3, that all can be categorized in three primary factors including: situational, technical and economic. Situational factors address conditions that exist and cannot be easily changed or controlled, including highway configuration and seasonal impacts. The selected traffic control plan will influence the technical factors. Examples of technical factors are agency specifications, worker and public safety, and construction methods. In terms of economics in road construction, construction and contracting costs, life cycle costs and incidental costs such as accidents will influence the end product.

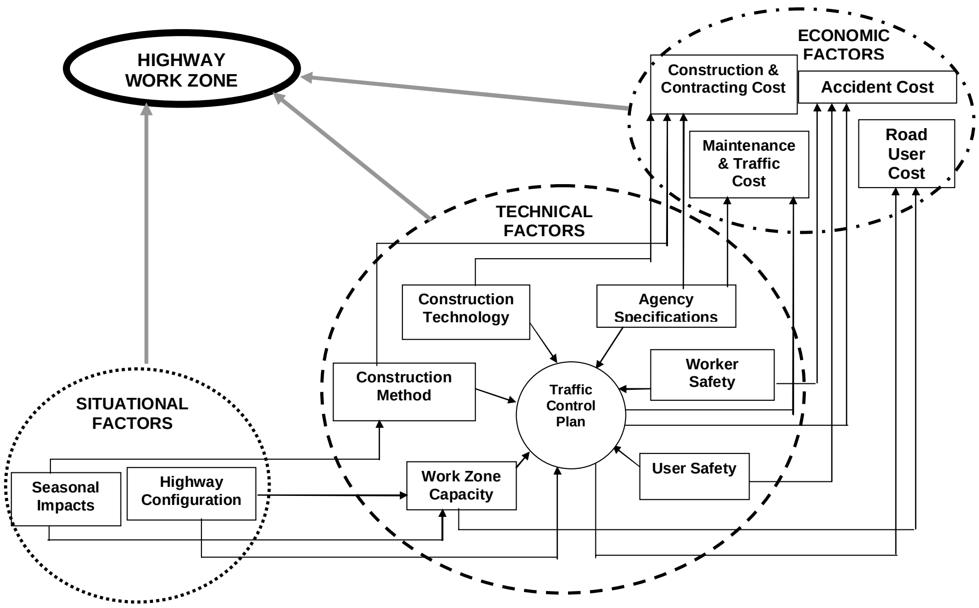

Figure 3. Situational, Technical, and Economic Factors Impacting Work Zones and Their Relationships

Work Zone Safety

It would be ideal, from a safety and pavement quality standpoint, to perform any road construction on a facility that is closed to the traveling public. The proportion of fatalities of workers and traffic vehicles is high in work zones. In fact, 58.5% of worker fatalities are from inside work zones [Pratt 2001]. However, in most cases, it is not feasible both from an economic or practical perspective.

Safety is an important issue for transportation and construction agencies industries [Niekerk 2000]. Although an abundance of research and technologies have been developed to improve highway work zone safety, the number of work zone fatalities has increased over recent years [ATSSA 2001]. The need for further research is required to identify causes and provide recommendations concerning work zone accidents. New technologies offer safer and more efficient traffic control operations in work zones [McCoy and Pesti 2001]. The experience of other agencies, new practices and new technologies need to be studied and implemented to improve traffic through the work zone.

Congestion Release Techniques

Besides intelligent transportation systems (ITS) technologies, public information and outreach designed to improve work zone traffic flow, other strategies are available to reduce work zone congestion. Matching rehabilitation alternatives with work strategies can be very effective. Different construction activities can result in superior pavement quality and efficient construction techniques will lead to a reduction in traffic congestion through the work zone.

Policies often limit lane closures to off-peak hours such as nightly and/or weekend closures. Strategies such as full road closure and diversion to alternate modes/routes have been successfully applied by many transportation agencies [FHWA 2003]. Various incentive policies are in place, such as providing transit and carpool incentives, guaranteed ride home programs and increasing transit service are available to reduce vehicular traffic through the construction zone [FHWA AASHTO 2000].

Economics of Highway Construction

Delays may be caused by internal and external factors. Internal factors may be controlled and mitigated such as equipment breakdown and communication failure. Conversely, external factors may be beyond the control of any party such as weather disruption, financial bankruptcy or unexpected poor ground conditions [Knight and Fayek 2000].

Christian and Hachey [1995] investigated optimizing worker performance through the elimination of redundant or unnecessary work. It was revealed that job satisfaction and worker productivity are directly related. In addition, the typical source of delays and variability were from utilizing rules of thumb, previous job records and employing the expertise of an individual. These shortcuts may result in incorrect construction leading to remedial action to correct these errors. In fact, it was found that the typical concrete worker spends only 63% of the time actually placing the concrete, while the remainder is spent waiting for materials (29%), waiting for supervision (4%) and simply idling (4%). This idle time can accumulate over the span of the project resulting in lost production time to the contractor and ultimately the agency.

Studies suggest implementation of dynamic lane assignments, restrictive lane usage and variable speed limits to reduce the delays associated with the formation of queues. Information can be relayed to drivers through changeable message signs (CMS) upstream of the congestion. Daganzo et al. [2001] recommended dynamic assignment of high occupancy vehicle (HOV) lanes on the approach of a queue through past the congestion. CMS can inform drivers of the state of the traffic upstream and recommend lane assignments appropriate to the conditions.

Risks in Highway Construction

A contractor and the owner enter into a contract based the realization of achieving certain milestones. The responsibility of each party is dictated in the specifics of the contract [Ruster 1996]. In some cases, the contract is deemed fulfilled if the final product is in working order. Other cases, specific specifications must be met prior to contract fulfillment. Therefore, contracts are complex in nature and each party involved should understand their responsibilities, deliverables and limitations.

The study conducted by Fayek et al. [1999] analyzed the nature of the bids and revealed that nearly 75% of contractors assess the value of risk as a percentage of the final bid. The remaining contractors prefer a statistical approach. A lower number of projects available for bidding will result in competition and lower bids being submitted. These lower quotes may be a consequence of undervalue the risk factor included within the bid. The result is a tighter schedule with little financial buffer to accommodate unforeseen circumstances and a higher possibility of project delays. Current trends in reducing agency risk by transferring risks to the contractor are evident in Figure 4.

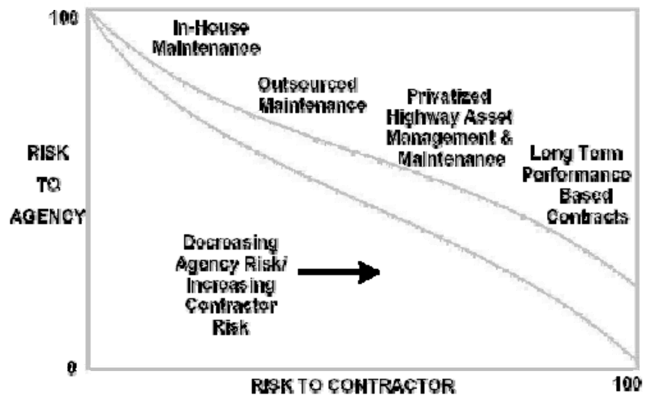

Figure 4. Distribution of Risks with Different Contract Approaches [Queiroz 1999].

Once a contractor is awarded the contract, most agencies impose daily time limit for the work to be done such as construction during peak traffic hours. Contractors working on Ontario busy freeways in the Greater Toronto Area have a mandate to complete overnight repairs by 6 am the following day or have penalties levied at a rate of $10 000 CDN for each minute over time [Discovery 2005].

METHODOLOGY & RESULTS

The objective of Module One is to develop a work zone configuration design matrix as a function of construction category and geometrics of the road and thus work zone. A survey was conducted to examine current practices in Ontario from the contractor and consultant perspective. Module Two examines safety issues associated with work zones. Understanding the possible causes of unsafe environments will also lead to proposing countermeasures to improve safety to all concerned. Module Three investigates economic impacts to the road user. A prediction model to estimate this user delay cost as a result of road construction is developed in this Module. There are two aspects of Module Four. Firstly, development of a multi-variant decision model and incorporating user delay cost into project selection and network level decisions.

Module One: Work Zone Strategies

The objective of this module is to build a decision tool that matches rehabilitation categories with work strategies based on highway configuration, construction performance and construction time restrictions.

Through interviews with contractors, engineers, design consultants, and the MTO, the quality and constructability of several rehabilitation alternatives with various staging plans are investigated and compared. Questionnaires were sent to one design consultant and two contractors that are located in Ontario. In addition, several personal interviews were conducted. The following is a summary of the findings:

- The design consultant has general knowledge about rehabilitation conditions and specifies commonly used alternatives.
- The consultant and contractor did not believe that there was any link between quality issues and work strategies if the final product is within specifications. However, another contractor expressed a strong opinion that some of the work strategies, specifically night closures, significantly affects construction and pavement performance.
- Contractors are not familiar with lane closure policies. They indicate that some policies are better for construction, such as full lane closures, which may double productivity. The productivity, quality of work and safety of night work is an issue for contractors.
- The contractors believe that design consultants are not familiar with construction processes and the majority of work strategies they specify are difficult to implement. One suggested that more constructability analyses should be carried out by the consultants prior to final approval of the design.
- The guidelines and specifications influencing work strategies should incorporate opinions or suggestions from the Ontario Road Builders Association and Safety Association.
- Design consultants usually use software such as Paramics, to predict traffic queuing under certain work strategies. According to the consultant, 70-80% of the predictions are accurate.
- There is no specific attempt to minimize the duration of work zones by the design consultants. Generally MTO Production Rates, which provide average rates only, are used to estimate the duration of a work zone.

<u>Productivity</u>
The total number of working days for a typical highway construction season ranges between 97 and 122 days in Ontario. In the event work cannot be completed before the end of the construction season, the work site is either kept as is or it is paved to allow traffic to temporarily use the facility until the following construction season. Examples of major factors affecting productivity include design alternatives, available resources and material constraints.

<u>Traffic Control</u>
The MTO traffic control manuals provide a basic guide for work zone traffic management and staging plans. However, these strategies do not specifically relate to the rehabilitation treatments and therefore judgement is typically required on selecting a suitable traffic control plan. There are seven general traffic control plans.

Advancing Limited Closure in One Lane is a variable length single lane closure based on traffic or construction needs. Lane Shift onto the Shoulder or Median is commonly employed on resurfacing projects. The principle is to always keep the same number of lanes open during the entire treatment. The traffic is directed onto the shoulder or median. It is suitable for avoiding an unacceptable delay, such as in urban areas. However, this strategy is not preferred in the construction realm. The limited work zone space makes it difficult for contractors to work and move equipment. In addition, the restricted lane widths may result in traffic delays and/or incidents.

Full-Length Single Lane Closure is a single lane over the entire length of the project is closed to facilitate construction. Multiple Work Areas places the work at several isolated areas. Alternating Lane Closures Multiple Work Areas consists of closing one lane from point A to point B, and then closing the other lane from point A to point B. Typically the work proceeds down one lane in the morning, and comes back down the other lane in the afternoon. Single-Lane Closure is employed on two or four lanes highways, divided or undivided. Crossover is available for multi-lane highways where one direction of highway is closed and a single lane of traffic is diverted through the median into the opposing lane.

Construction Working Method

There are two construction working methods, concurrent and sequential. The sequential working method is a construction activity that is completed prior to the subsequent construction activity. For example, the paving activities can start after the demolition activity is finished. Concurrent Working Method is a construction activity that can begin once the prior construction activity is completed in a particular area. For example, the demolition and paving activities can proceed concurrently in parallel.

Matching Rehabilitation Alternatives with Work Strategies

Figure 5 illustrates a procedure for matching rehabilitation or maintenance treatments to appropriate work zone strategies. Common constraints include the highway configuration, available work strategies, construction windows, and traffic demand. Finally, three suitable strategies are provided under three traffic conditions: low (under 750 vehicles per hour per lane), medium traffic (between 750 vehicles per hour per lane and 1200 vehicles per hour per lane), and high traffic (greater than 1200 vehicles per hour per lane).

Quality Requirement for Various Rehabilitation Alternatives

Longitudinal and transverse construction joints are a major source of distress. Avoiding such construction joints, through increasing section lengths, will improve quality and pavement longevity. Longer section lengths will minimize transverse construction joints, especially for long term rehabilitation treatments. This will require a longer construction window to complete. Under low and medium traffic demands, continuous closure should be considered. Under high traffic conditions, if night and weekend schedules are the only alternatives, night work should be avoided.

Reducing longitudinal construction joints, paving two or more lanes simultaneously, is recommended and can be achieved by employing a crossover work strategy. If construction joints cannot be avoided, it is recommended by Kandhal [2002] to investigate utilizing rubberized joint material, making joint with cutting wheel, using rolling from hot side 152 mm away from the joint and using a wedge joint to get better quality.

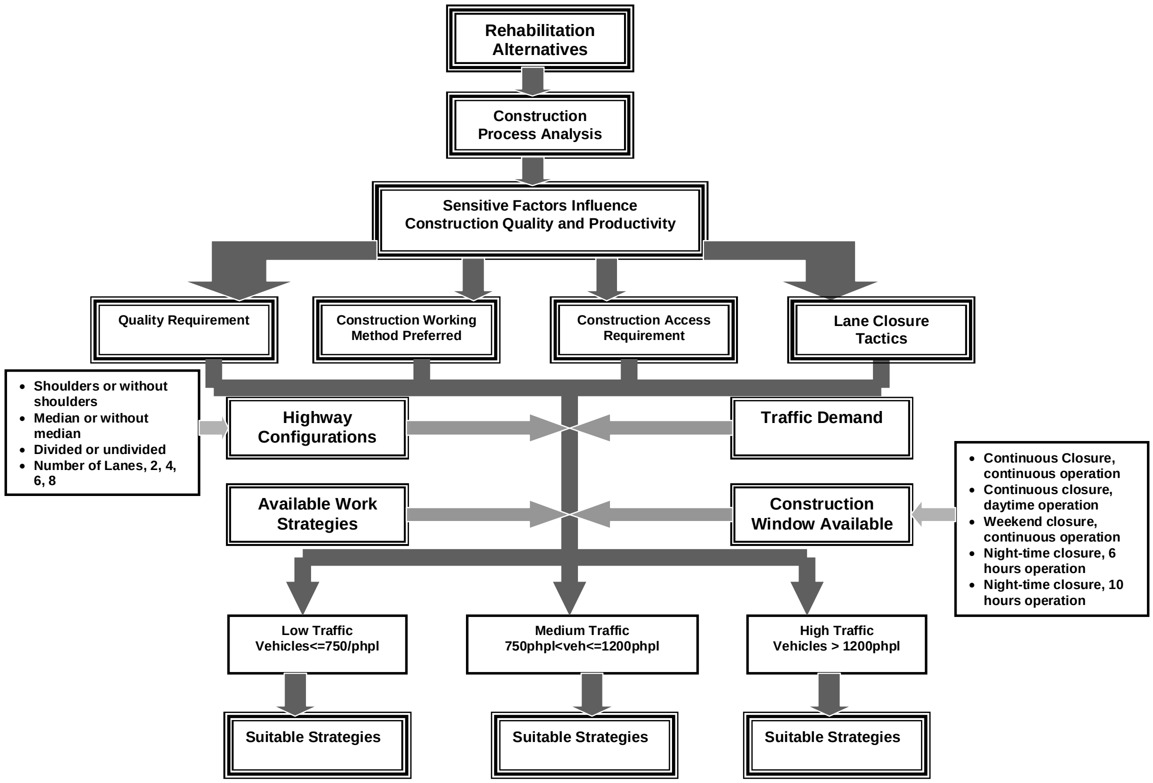

Figure 5. The Procedure for Matching Rehabilitation Alternatives with Work Strategies

<u>Construction Windows</u>

The construction window refers to the period of time that a segment of highway is closed for the construction activity. Three construction windows are commonly used including night-time closures, weekend closure and continuous closure. For the latter, affected lanes are continuously closed during the construction.

The difference in productivity is the result of time wasted in repeated auxiliary activities, such as mobilization & traffic set up, curing or cooling time, cleaning & demobilization. This can be optimized by employing a longer construction window. For example, curing or cooling times could overlap other processes acting at the same time. If this was practiced for longer or larger projects, the time savings would become significant.

In the selection of construction windows, it is suggested that:

- Low traffic conditions: continuous closure for a weekday schedule is recommended, although this strategy has the longest project duration.
- Medium traffic conditions: continuous closure and continuous operation should be considered for its productivity. Longer construction sections with fewer construction joints can increase pavement life. The access lane should be taken into account at the same time; otherwise, the anticipated productivity may not be achieved.
- Congested urban areas: weekend and night schedules are typical options with weekend work being the preferable alternative.
- The public should be informed of closures well in advance.

Lane Closure Tactics

The lane closure tactics should account for construction duration and inconvenience to the road users simultaneously. The pavement research centre at University of California at Berkeley developed a lane-weekend closed measurement to estimate the inconvenience to the motorists. They found that closing two lanes closure versus four lanes, increased productivity 70% with just an 18% increase in inconvenience to the general public. However, there are still some shortcomings with this assessment. For instance, it does not recognize the impact of various traffic volumes in different areas. In a busy urban highway, some closure strategies may not be practical at certain times of the day. More factors should be considered to compare the inconvenience to the motorists and the construction efficiency.

It is suggested that in:

- Low traffic conditions (rural areas): close one direction of the traffic lanes at a time is the first choice. Usually, the detour is seldom used in these areas.
- Medium traffic volume: a two or three lane closure in one direction is desirable to accommodate a construction access lane and enough room for paving the lanes. Closing one section or one direction of the highway is a good alternative if the motorists could be notified in advance and detour roads are available.
- High traffic volume: two or three lane closures at specific times, such as weekends, when traffic volumes are lower are desirable. If more than four lanes are present, such as six or eight lanes in one direction, close half of the lanes.

Highway Configuration Consideration

Highway configurations are often grouped according to the number of lanes, presence of an outside median or shoulders, and whether the facility is divided or undivided. A higher number of lanes offer increased work zone configuration and staging flexibility. A large work area will reduce the number of joints, increase productivity, and improve quality compared to restricted construction areas. Shoulders and medians can improve logistics and movement of vehicles or materials. Driver perception and safety can be significantly influenced when vehicles are temporarily diverted to the opposite set of lanes to facilitate construction. For instance, crossover strategies on four-lane facilities provide an excellent work zone area while motorists must travel with caution through unfamiliar or non-intuitive traffic flow.

Summary of Findings for Work Zone Strategies

The objective of Module One was to build a decision tool that matches rehabilitation categories with work strategies based on highway configuration and construction restrictions. The model was developed first by identifying existing rehabilitation problems and constraints. Second, the commonly used rehabilitation alternatives and work strategies were examined. Finally, work strategies were matched with rehabilitation alternatives in an effort to avoid the identified problems and constraints.

While attempting to match issues found in the literature with those identified in the survey of industry practitioners, it was found that:

- The communication among designers, contractors and other highway agencies is limited.

- There is inadequate research in work strategy planning. Consultants and agencies are more likely to compromise on work strategies rather than disrupt traffic flow.
- The issues with highway rehabilitation include end result pavement quality, construction site accessibility, construction productivity, and project delivery processes.
- Three types of factors are defined to influence the performance of work zones: situational factors, technical factors and economic factors.
- The construction processes of commonly used rehabilitation methods are studied and classified into short, intermediate and long term treatments.
- There are connections between the rehabilitation categories and work zone strategies. Certain strategies could affect pavement quality, construction productivity and traffic control.
- In work strategy design, various aspects should be considered, such as pavement life cycle, construction requirement, highway configuration, and traffic demand.

<u>Recommendations for Work Zone Strategies</u>
An efficient and effective project delivery method should be employed wherever possible. It is necessary to share the information among designers, contractors, and other highway agencies. Project delivery methods with good communication should be considered, such as design-build or construction management. The complete Matrix of Matching Rehabilitation Alternatives with Work Strategies was developed providing a guide to engineers as to recommended lane closure strategies for various maintenance, rehabilitation and construction activities. The basic structure of the decision matrix is illustrated in Figure 6.

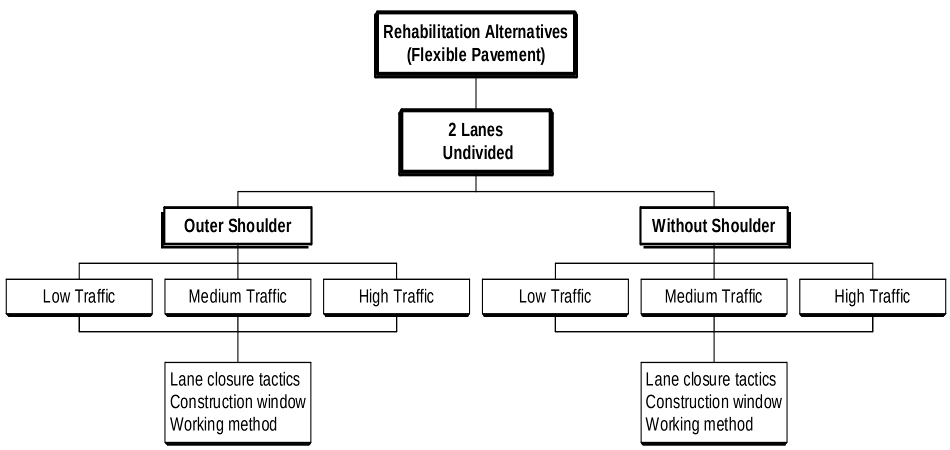

Figure 6. Work Zone Analysis Associated with two-lane Facilities

Module Two: Work Zone Safety

Several studies indicate both construction workers and motorists are at risk of being killed or injured as a result of work zones [Niekerk 2000, FHWA 2001]. Fortunately, new technologies and procedures are being developed to improve the traffic flow around work zones with the anticipated effect of improving worker and user safety. In this Module, the new technologies and research trends are investigated.

A literature review of existing research and interviews with industry experts was conducted. A suite of recommendations are developed to improve the safety for both construction workers and motorists. The examination of work zone safety issues is based on accident reports, surveys conducted by highway agencies, and existing research. A hierarchy of objective technique (HOT) diagrams was developed to examine how improvements can be made to work zone safety, such as new technologies, recommendations and practices.

Recommendations for a New Accident Report

Although safety issues within the work zones have caught the attention of various agencies, it is difficult to collect data about these accidents. For example, Toronto Police Services "Motor Vehicle Accident Report" does not include a detailed section on whether the incident occurred in a work zone. It is important to record the details of an incident within construction work zones to understand potential trends or specific characteristics of a work zone that may be influencing the likelihood of incidents. Items such as incident proximity to the work zone, external factors, signage present and highway configuration, are important to record.

HOT Diagrams to Improve Work Zone Safety Strategies

A HOT diagram is a graphical representation of the logic process divided into categories including concerns, problems, tactics, and solutions. To improve work zone safety, HOT diagrams are focused on improving driver and worker safety. Example of safety issues include congestion, treatment duration, high speed variance of vehicles, work zone layout, driver distraction and the frequency of night work have been identified.

Innovative contracting and financing seek to match anticipated cash flow with project management, while recognizing competing priorities for existing resources. With respect to contracting, it explores various techniques, such as, performance-related specifications, warranties, design-build, cost-plus-time strategies, partnering escalation agreements, lane rental, incentives/disincentives, and value engineering. Finance tools include cost sharing strategies, tolling mechanisms, contractor financing, leveraging techniques, credit assistance, cost management, and containment concepts.

To improve worker safety, solutions typically considered reducing worker exposure to the risks internal and external of a work zone. Providing an effective physical separation of workers and traffic is a challenge for highway agencies. New technologies are available to contractors. For example, movable concrete barriers provide adequate protection to workers while maintaining an adequate physical concrete barrier. It is extremely important to establish standard work regulations in highway work zone areas, such as construction procedures and traffic control within a work zone.

Module Three: User Delay Costs

Module Three is focused on the economic aspect of construction zones, specifically user delays. The goal is to generate a life cycle costing model to predict user delay costs within the jurisdiction of Ontario. This life cycle cost analysis is completed as a function of the functional class of the facility. A marginal user cost model is also developed to predict the extra cost per additional equivalent single axle load (ESAL).

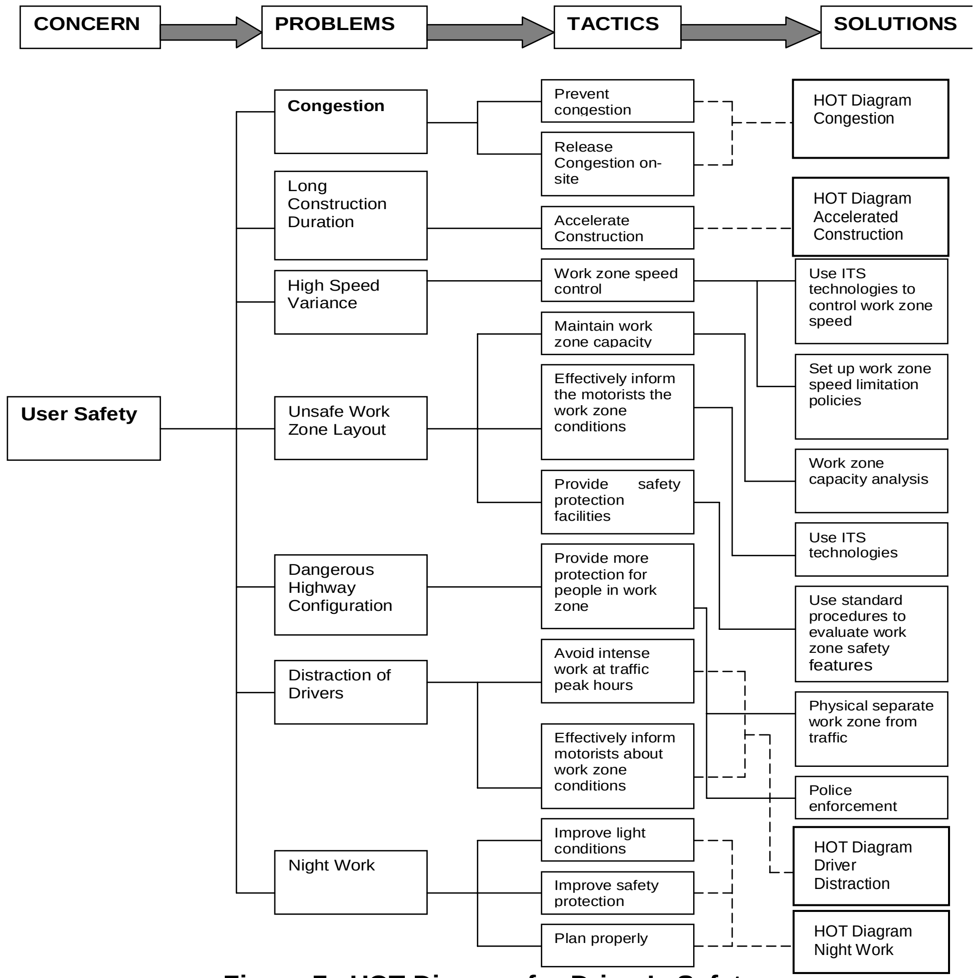

Figure 7. HOT Diagram for Driver's Safety

The pavement structures, traffic attributes and construction costs were based on a 1997 MTO study [MTO 1997, Tighe 1999]. Realistic factors, including discount rates, equivalent hourly wage rate and maintenance values were assumed through engineering judgement. These values were verified through a sensitivity analysis. Although the input variables are based on 1997 values, it can be assumed the magnitude of 2005 values will be greater given the expected traffic growth over eight years. The results obtained in this research can be considered a "best case scenario". A life cycle analysis was performed over a 60-year period with appropriate maintenance and rehabilitation treatments deployed.

Asphalt facilities are investigated exclusively. Concrete and composite pavement structures are areas of future analysis. Bridge construction and vertical or horizontal alignments were considered beyond the scope of the research yet these aspects are important for future research. Detour availability is represented by the percentage of vehicles that will take alternative routes instead of proceeding through the construction work zone. Quantifying congestion of alternative routes is assumed to be beyond the scope of the study. Lane configuration will focus on two- and four-lane facilities with provisions to analyze multi-lane facilities as well. Lane closure strategies employed at each maintenance treatment will vary with traffic volumes delineated through low, medium and high.

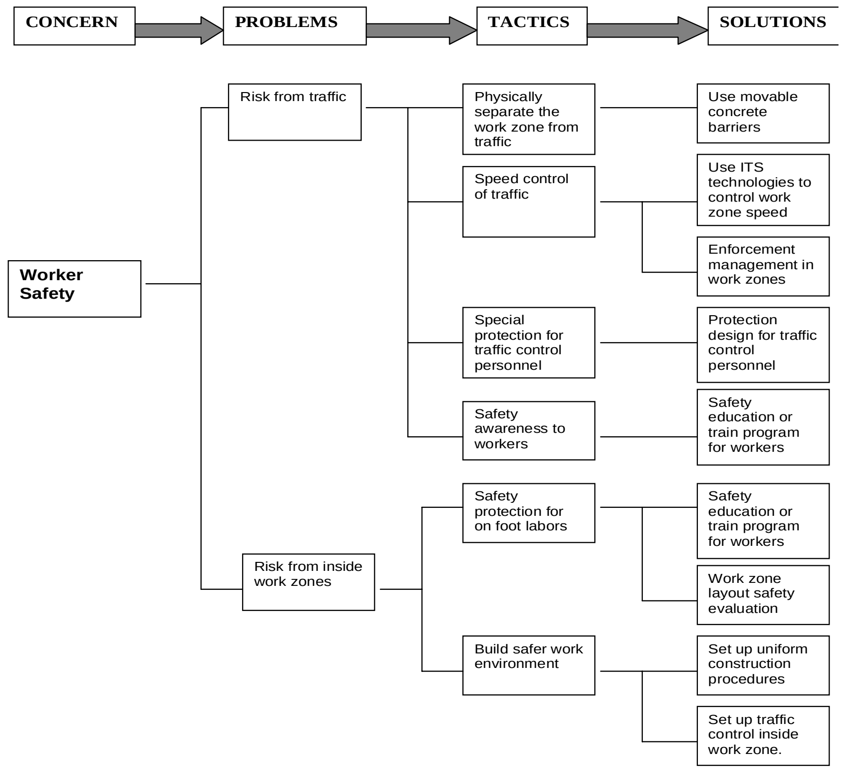

Figure 8. HOT Diagram for Workers' Safety

<u>Factors Employed in Congestion Analysis</u>

There are a vast number of factors that are employed to predict the delay time experienced per vehicle. The peak hour factor (PHF) represents the temporal variation in hourly traffic over a 15-minute period [TRB 1997]. The hourly factor (HF) is the percent of daily traffic in the peak hour. This varies with each facility as a function of the number of lanes available [Tighe et al. 1999]. The number of vehicles passing through a given point over one hour is given by the hourly volume (HV).

Construction work zone layout is important to consider when determining the allowable traffic throughput within this area. The number of lane closures, geometric attributes and signage will affect driver awareness and the ability of the traveling public to navigate through the work zone efficiently and effectively. Metering vehicles through a common lane is required for two-lane facilities. Green cycle time is the time, in seconds, that is allowed for each traffic direction to enter the work zone.

There are several methods of obtaining the delay cost per hour for the user. Tighe et al. [2002] describes a study that utilizes a bi-weekly income range of $1750 to 2500 CDN to estimate the value of time. This value is reduced to an hourly rate and may be used as a unit rate ($CDN/hr) for delay cost calculations. From this study, an estimated hourly delay rate of $25 CDN per hour was used.

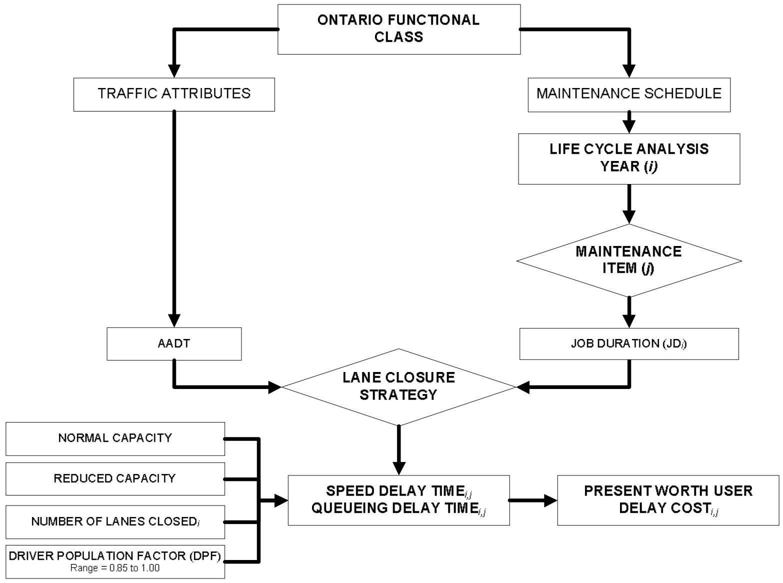

Figure 9. Delay Calculation General Methodology Employed in this Study

Results and Analysis

The shape of the model was determined through an iterative process of curve fitting various single-variable relationship types. This includes logarithmic, exponential and power curves. The two-lane single variable model is based on a power curve while the four-lane single variable model is based on a polynomial of degree four. It is important to note the input is, annual ESALs, and output is the present worth user delay cost over the life cycle of the facility. Equation 1 is applicable for two-lane facilities in Ontario. The four-lane counterparts will yield a separate model as Equation 2 describes (X = LN(ESALs)) [Huen 2005].

$$\mathrm{UDC}_{\text{Two-Lane}} = \mathrm{EXP}\left(1.8476[\mathrm{LN}(\mathrm{ESAL})]^{0.7094}\right) \quad \textbf{(1)}$$

$$\mathrm{UDC}_{\text{Four-Lane}} = \mathrm{EXP}\left(0.0054\mathrm{X}^4 - 0.2122\mathrm{X}^3 + 3.0289\mathrm{X}^2 - 18.062\mathrm{X} + 42.043\right) \quad \textbf{(2)}$$

where UDC = Present Worth User Delay Cost ($CDN)
EXP = Exponential
LN = Natural Logarithm
ESAL = Annual Equivalent Single Axle Loadings
X = LN(ESAL)

Marginal User Delay Cost

The marginal user delay cost determines the additional user delay cost per extra ESAL on a given facility. The marginal user delay cost model is generated by taking the derivative with respect to ESALs of Equations 1 and 2.

$$MARGINAL\ COST_{Two-Lane} = \frac{1.31068744}{ESAL \cdot \ln(ESAL)^{0.2906}} EXP\left(1.8476 \cdot \ln(ESAL)^{0.7094}\right) \quad \textbf{(3)}$$

$$MARGINAL\ COST_{\text{Four-Lane}} = \left(\frac{0.0216 \ln(ESAL)^3}{ESAL} - \frac{0.6366 \ln(ESAL)^2}{ESAL} + \frac{6.0578 \ln(ESAL)}{ESAL} - \frac{18.062}{ESAL} \right) \times EXP\begin{pmatrix} 0.0054 \ln(ESAL)^4 - 0.2122 \ln(ESAL)^3 \\ + 3.0289 \ln(ESAL)^2 - 18.062 \ln(ESAL) + 42.043 \end{pmatrix} \quad \textbf{(4)}$$

where EXP = Exponential
LN = Natural Logarithm
ESAL = Annual Equivalent Single Axle Loadings
X = LN(ESAL)

The absolute costs associated with two-lane facilities provide insight on the impact of lane closures to the public. The maximum marginal cost for these facilities is $1.07 CDN per additional ESAL for a given facility and decreases exponentially given the annual ESALs.

The four-lane counterparts exhibited a substantially lower delay cost, primarily due to the flexibility of the lane closure strategies to provide a less restrictive flow through the construction area. The marginal cost of these facilities reflect this at a maximum of 3.38 cents CDN per additional ESAL per annual ESALs. Given a high volume four-lane facility, the marginal cost increases as illustrated in Figure 10. This is realistic as a high annual ESALs value will represent a high AADT and/or high percentage heavy truck, the capacity would have been reached or even exceeded, leading to congestion.

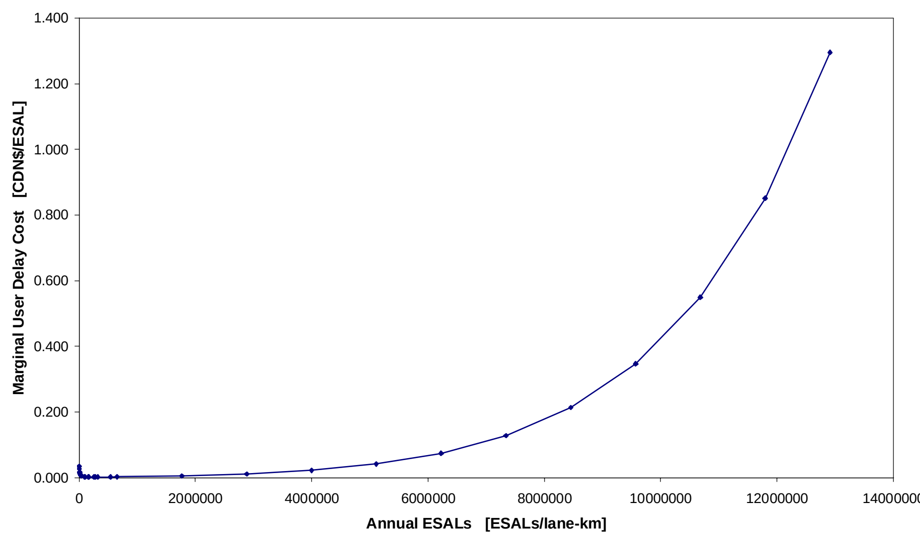

Figure 10. Marginal user delay cost curve for four-lane Ontario facilities at high ESALs.

Table 1. Summary of Marginal Costs.

Facility Type	Marginal User Delay Cost $CDN/ESAL (per lane-km) URBAN	RURAL
NORTHERN		
Local	N/A	N/A
Collector	0.85	0.94
Minor Arterial	0.47	0.57
Principal Arterial	0.56	0.58
SOUTHERN		
Local	N/A	N/A
Collector	0.44	0.55
Minor Arterial	0.38	0.47
Principal Arterial	0.38	0.44
Freeway (4-Lane)	0.01	0.01

It is important to analyze these findings in terms of absolute and relative magnitudes. Two-lane facilities are assumed to carry less vehicles, including passenger cars and heavy trucks, compared to four-lane facilities. Therefore given a typical four-lane corridor, the AADT and resultant ESALs are significantly higher. This is illustrated in the independent variable of ESALs for both facility types, shown above, differ by a magnitude of 1000. The R-Squared values for the two- and four-lane single variable models are 73.7% and 60.1% respectively.

Module Four: Multi-Variant Decision Modeling

The focus of this Module includes the development of a multi-variant model to estimate user delay costs as well as developing a methodology to allocate a portion of this delay cost into the engineering decisions of a given facility. The statistics of the resultant model is determined to understand its reliability and significance. A methodology is proposed to allocate a portion of user delays to the transportation agency. The purpose of this is to suggest an amount of risk an agency should incorporate in their engineering.

Through a linear regression of the entire data set, an initial model was developed. Based on statistical regression diagnostics, this model did not explain an acceptable amount of the variance of the data set. Therefore, blocking the data based on the total number of lanes, namely two- and four-laned facilities, yielded significant improvement. As the magnitude of the delay cost for a two-lane and a four-lane facility differed significantly, this justifies blocking. From this, a significant amount of the variance is explained with the two models for their respective data sets. Delay cost prediction for six or more lane facilities can be considered given a multi-lane data set. Equations 5 and 6 yields predicted user delay cost given attributes for two- and four-lane scenarios over the life cycle of the facility respectively.

$$UDC_{Two-Lane} = EXP\begin{pmatrix} 5.0662 + 0.000255AADT + 0.02328PC + 0.9979LW \\ -0.01522DP - 0.00153DS - 0.09718J \end{pmatrix} \quad \textbf{(5)}$$

$$UDC_{Four-Lane} = EXP\begin{pmatrix} 8.4475 + 0.000154AADT + 0.01828PC - 0.2102LW \\ - 0.01369DP - 0.0261DS - 0.1188J \end{pmatrix} \quad \textbf{(6)}$$

where UDC = Life Cycle User Delay Cost ($CDN/lane-km)
AADT = Annual Average Daily Traffic (Two-Lane Equivalent)
PC = Percent Commercial (%)
LW = Lane Width (m)
DP = Detour Percentage (%)
DS = Design Speed (km/h)
J = Jurisdiction (Northern = +1, Southern = -1)

Apportionment of User Delays

Distribution of costs to key players in the transportation field is an inexact science when dealing with non-realized costs. Allocation of 100% of the road user delay cost to the traveling public is unreasonable. Similarly, for the road agency to take on 100% of this same cost is also controversial as this cost is not actually realized by the transportation agency. Therefore the goal of this section is to devise a methodology to yield a range of percentages to be allocated to the project selection stage for each facility.

It is proposed a high average rate of change of user delay cost shall result in a higher accountability and vice versa to the road agency. To determine the average rate of change, two data points are required. These two points are derived from -10% and +10% the annual ESAL for a given facility. The percent increase in user delay cost is determined from this and is translated to the recommended percentage the transportation agency should be accountable for. In the event the variables AADT and percent commercial were used to determine the two data points, the range between the two points, when transferred to ESALs, may not be consistent, leading to misleading rates of change. Figure 11 summarizes the general methodology proposed. For example, a facility that typically encounters an annual ESAL of 325626 is studied. Firstly, the user delay cost of this facility is determined for ESAL values of 10% below and 10% above 325626. The percent increase of user delays based from the former to the latter ESAL values. In this case, 13.4% and 9.2% of user delays should be accounted in two- and four-lane southern urban provincial principal arterial respectively.

Summary of Findings

Results from the models developed can provide a context of the importance in user delay costs with respect to other costs. For instance, each facility will incur three types of costs, construction, maintenance and road user delay. Comparison among these three aspects can provide an understanding of the magnitude of delays. Table 2 summarizes this cost distribution for urban and rural facility types.

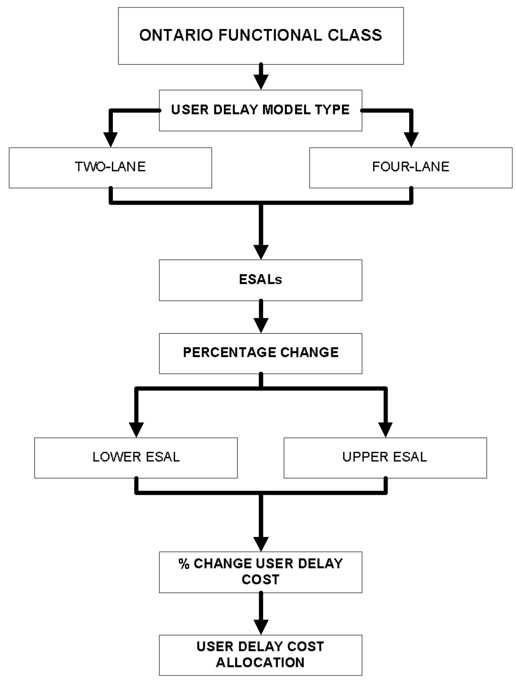

Figure 11. Allocation of user delay cost utilizing percentage change between two ESAL points.

Table 2(a). Summary of Life Cycle Cost Distribution for Urban Areas

	Northern			Southern		
URBAN AREAS	**Constr.**	**Maint.**	**Delay**	**Constr.**	**Maint.**	**Delay**
Two-Lane						
Collector	74.8%	22.2%	3.0%	57.6%	18.8%	23.6%
Minor Arterial	58.0%	23.2%	18.8%	36.5%	15.5%	47.9%
Principal Arterial	66.4%	21.7%	11.9%	35.3%	12.3%	52.5%
Four-Lane						
Collector	77.1%	22.8%	0.1%	75.0%	24.5%	0.5%
Minor Arterial	71.1%	28.5%	0.4%	69.3%	29.5%	1.2%
Principal Arterial	75.2%	24.5%	0.3%	73.2%	25.5%	1.3%
Freeway				73.2%	25.9%	1.0%

Table 2(b). Summary of Life Cycle Cost Distribution for Rural Areas

	Northern			Southern		
RURAL AREAS	**Constr.**	**Maint.**	**Delay**	**Constr.**	**Maint.**	**Delay**
Two-Lane						
Collector	68.7%	27.6%	3.7%	59.2%	26.2%	14.5%
Minor Arterial	57.2%	31.2%	11.5%	47.0%	27.1%	25.9%
Principal Arterial	63.4%	24.6%	12.0%	45.9%	19.1%	35.0%
Four-Lane						
Collector	71.3%	28.6%	0.1%	69.0%	30.6%	0.4%
Minor Arterial	64.5%	35.2%	0.3%	63.0%	36.4%	0.6%
Principal Arterial	71.8%	27.9%	0.3%	69.9%	29.2%	0.9%
Freeway				75.6%	22.9%	1.4%

A Southern Two-Lane Municipal Arterial is predicted to incur user delay costs over its service life of 16% when compared to other costs. The Southern Two-Lane Rural and Urban Principal Arterial is predicted that 35% and 52% of its overall service life costs can be attributed to user delays respectively. For instance, a segment of the Ontario Highway Network is on average ten kilometres. A two-lane principal arterial facility for each Rural and Urban cases will potentially face user delay costs in the magnitude of $2.3 million and $1.5 million Canadian respectively.

The magnitude of user delays can provide management at the network level, an indication of facilities that require significant attention as impeding traffic flow in these areas would potentially result in severe negative effects. Therefore, these sections would require higher budget allocations to provide adequate throughput while maintaining construction productivity. They also may warrant the use of incentive contracts to expedite the construction. The use of innovative materials, such as fast track products, and construction practices such as weekend full facility closure can also reduce user delays.

Accountability Between Key Players

As denoted earlier, the key players concerning delays are the transportation agency, the contractor and the motorist. The division of the life cycle costs between these two key players is performed to provide general context on the impacts to each. A high percentage of life cycle cost appropriated to the motorist is undesired. Within a Southern Arterial facility, the motorist or road user will bear nearly 50% of the overall costs over the service life of the facility. Northern Arterial facilities will have motorists bearing just over 10%. Consequently, the use of incentives, fast track materials and other construction processes to reduce user delays are most applicable to Southern Ontario facilities.

Comparative Analysis with Construction Costs

It is important to understand the magnitude of costs through comparing actual construction values with the theoretical user delay cost. The following is a list, Table 3, of recently completed construction contracts of various highways in the Province of Ontario [MTO 2005].

Table 3. Summary of Attributes and Costs of Contracts in Ontario.

Contract Number	**2003-2012**	**2004-3045**	**2004-5117**
Highway Number	403	26	17
Facility Type	Freeway	Arterial	Arterial
Jurisdiction	Southern	Southern	Northern
Length	15.1 km	15.1 km	39 km
Contract Value	$45.9 Million	$16.7 Million	$8.4 Million
Traffic Impact	Expect 15 minute delays	Traffic control metering	Expect 10 minute delays
Est. User Delay Cost	$114 Million	$1.37 Million	$0.95 Million

The results of the above table is an illustration of the magnitude of projected user delay costs compared to the actual construction cost, through the value of the contract. All contracts analyzed list the type of work being performed as road construction. It is assumed road construction incorporates mill and pave as its primary activity. Facilities within Contract 2003-2012, 2004-3045 and 2004-5117 are assumed to be an Southern Urban Freeway, Southern Principal Rural Arterial and Northern Principal Rural Arterial respectively. The duration of each contract ranges from one year to two years. It was assumed the opportunity cost of this construction timeframe is negligible, therefore, the predicted delay cost was calculated at present worth.

The magnitude of user delays or lost productivity is staggering for the three projects. Nearly an average of $1 Million Canadian is lost in the Ontario economy for each contract except for the projected $114 Million Canadian for Contract 2003-2012. The extrodinary magnitude of user delay cost for Contract 2003-2012 is due to the fact that Highway 403 is a vital facility for commuters and industry. Approximately 200000 AADT exist on this highway, therefore lane closures on this facility will result in substantial impacts to the economies. An analysis on all projects concurrently being performed in the Province of Ontario can realize a significant cumulative annual loss in productivity in Ontario into several billions of Canadian dollars. It is important to note this does not include delays caused by incidents within work zones and the irreparable damage to perishable items.

Statistical Analysis

The two-lane prediction model has an R-squared value of 88.3%. Investigation of the statistical significance of the overall model and parameter coefficient, through t-testing, individual coefficient testing and P-values, was performed. At a 95% confidence interval, the prediction model is significant. In the case of the two-lane multi-variable models, all parameters are significant.

The four-lane prediction model has an R-squared value of 84.1%. Investigation of the statistical significance of the overall model and parameter coefficient, through t-testing, individual coefficient testing and P-values, was performed. At a 95% confidence interval, the prediction model is significant. In the case of the two-lane multi-variable model, all parameters are significant.

CONCLUSIONS AND RECOMMENDATIONS

The research conducted focused on improving construction work zones in the transportation field. This ranged from developing work zone strategies, methods of improving safety, estimating user delay costs and providing a methodology to assist in agency accountability on user delays.

A decision tool that matches rehabilitation categories with work strategies based on highway configuration and construction restrictions was developed. Issues that currently exist in the construction industry include limited communication among key players, inadequate strategic planning when considering work zones layout and functionality, and compromised work zone strategies are preferred rather than disrupting traffic. Finally, a suite of matrices relating rehabilitation alternatives with work strategies was developed.

A comprehensive analysis of existing and new technologies and practices focused on improving work zone safety. Technology can be used to improve safety. Communication with the public is essential as uninformed drivers are likely to become confused and disoriented entering a construction zone. Informed drivers can elect to take alternative routes that will reduce congestion through the affected area. Policies, strategies or best practices can also provide higher protection to personnel and the public.

The primary causes of work zone incidents are congestion, work zone duration, speed control, work zone layout, highway configuration, driver distractions, and night work. Risks for the worker are from external and internal to the work zones. A suite of HOT diagrams were developed to recommend the feasible policies and practices utilized to improve worker and user safety.

Estimation of user delay costs in construction zones was performed. Life cycle construction cost, life cycle user delay cost and the recommended percent allocation to the transportation agency of urban facilities in Ontario. It is difficult to completely eliminate safety issues or economic losses to the motorist. However, a suite of tools presented in this paper provides a means of guidance to the engineer to understand sources of risk and the impacts to all key players involved in road construction.

ACKNOWLEDGEMENTS
The authors would like to express their appreciation to the MTO, specifically Gerry Chaput and Alain Beaulieu, for providing assistance to this research. In addition, financial support through the Highway Infrastructure Innovations Funding Program (HIIFP) was greatly appreciated.

REFERENCES

[ATSSA 2001] ATSSA, "Work Zone Statistics Reveal Record High Number of Fatalities", American Traffic Safety Services Association (ATSSA), 2001.

[Christian and Hachey 1995] Christian, J., D. Hachey, "Effects of Delay Times on Production Rates in Construction", Journal of Construction Engineering and Management, Vol. 121, No. 1, 1995.

[Daganzo et al. 2001] Daganzo, C.F., J. Laval, J.C. Munoz, "Some Ideas for Freeway Congestion Mitigation with Advanced Technologies", Institute of Transportation Studies, University of California, December 2001.

[Discovery 2005] "Frontiers of Construction: Road Warriors", Discovery Canada, 2005.

[Fayek et al. 1999] Fayek, A., I. Ghoshal, S. AbouRizk, "A Survey of the Bidding Practices of Canadian Civil Engineering Construction Contractors", Canadian Journal of Civil Engineering, Vol. 26, pp. 13-25, 1999.

[FHWA, AASHTO 2000] FHWA, AASHTO "Work Zone Operations Best Practices Guidebook" Publication No. FWHA-OP-00-010, 2000.

[FHWA 2001] FHWA, "Work Zone Mobility and Safety, a Roadmap for Work Zones Work Better" Federal Highway Administration, 2001.

[FHWA 2003] FHWA, "Full Road Closure for Work Zone Operations - A Cross-Cutting Study", Report No. FHWA-OP-04-009, EDL# 13795, 2003.

[Kandhal et al. 2002] Kandhal, P.S., T.L. Ramirez, P.M. Ingram, "Evaluation of Eight Longitudinal Joint Construction Techniques for Asphalt Pavements in Pennsylvania", NCAT Report 02-03, 2002.

[Knight and Fayek 2000] Knight, K., A.R. Fayek, "A Preliminary Study of the Factors Affecting the Cost Escalation of Construction Projects", Canadian Journal of Civil Engineering, Vol. 27, pp. 73-83, 2000.

[McCoy and Pesti 2001] McCoy, P.T., G. Pesti, "Dynamic Late Merge Control Concept for Work Zones on Rural Interstate Highway", 2001.

[MTO 1997] Ministry of Transportation of Ontario (MTO). "Impact on Highway Infrastructure of Existing and Alternative Vehicle Configurations and Weight Limits", Ministry of Transportation of Ontario, May 1997.

[MTO 2005] MTO, "Road Construction Reports", Ministry of Transportation of Ontario, July 8, 2005.

[Niekerk 2000] Niekerk, A.V., "Temporary Conditions, Permanent Safety – New Regulations Introduced in Ontario" Asphaltopics, p. 19., 2000.

[Pratt 2001] Pratt, S.G., "Building Safer Highway Work Zones National Institute for Occupational Safety and Health", DHHS (NIOSH) Publication No. 2001-128., 2001.

[Queiroz 1999] Queiroz, C., "Contractual Procedures to Involve the Private Sector in Road Maintenance and Rehabilitation", The World Bank Group, April 1999.

[Raymond et al. 2000] Raymond, C., S. Tighe, R. Haas, "User Cost Analysis of Traffic Staging Options for Resurfacing of Divided Highways in Ontario", Annual Conference of the Transportation Association of Canada, Edmonton, Alberta, October 1 – 4, 2000.

[Ruster 1996] Ruster, J., "Mitigating Commercial Risks in Project Finance", Public Policy for the Private Sector, The World Bank, Note No. 69, February 1996.

[Tighe et al 1999] Tighe, S., T. Lee, R. McKim, R. Haas, "Traffic Delays Cost Savings Associated with Trenchless Technology", ASCE Journal of Infrastructure Systems, 1999.

[Tighe et al 2002] Tighe, S., M. Knight, D. Papoutsis, V. Rodriguez, C. Walker, "User Cost Savings in Eliminating Pavement Excavations Through Employing Trenchless Technologies", National Research Council, Vol. 29, pp. 751-761, 2002.

[TRB 1997] Transportation Research Board (TRB), "Highway Capacity Manual: Special Report 209", Transportation Research Board, 1997.