Freeway Workzone Capacity and Associated Economic Concepts

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Like many other transportation agencies, the Ministry of Transportation Ontario (MTO) is also using the same work zone closure strategies and standards that it has used for decades. However, the lane closure strategies should incorporate the impacts of construction duration and inconvenience to the road users and find the balance where users face minimal inconvenience while contractors have the appropriate amount of time to finish the work and produce a high quality product. In-order to evaluate and assess the appropriate time for lane closures, it is important to estimate the capacity of the lanes. The capacity estimates can help in determining the optimized time for lane closures to minimize the user delays while providing sufficient time for contractors to achieve the desired productivity and quality of work. There are different models, computer Software and wide variety of studies to evaluate and estimate the Workzone Capacity and associated User Delay Costs at workzones. These costs are primarily affected by traffic flows, vehicle speeds, and work zone capacities.

In-view of the above, this study is designed to estimate freeway capacity of construction workzones and discuss the associated user delay costs and economic issues. For this study, the capacity at the work zones was measured as the mean queue discharge flow rate during forced-flow conditions. Forced-flow conditions were defined as congested conditions during which a sustained queue formed. There are several studies and approaches for collecting traffic volume data for estimating workzone capacity. For this study, it was decided to utilize a manual counting method for volume data. This would help provide the visual confirmation of queuing and intensity of work activity at workzones. Six sites located in Southern Ontario, were selected for this study. The data from these sites is used to develop a mathematical model for estimating workzone capacity for Ontario.

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Dedication

This thesis is dedicated in the loving memory of my father Niaz Muhammad Shaikh.

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Chapter 1
Introduction

1.1 Introduction

Traffic volumes on our roads are increasing but the growth in road infrastructure are minimal. The road network is also reaching a middle age and requires more maintenance and reconstruction work hence there are more work zones. These work zones disrupt traffic flow as they reduce number of lanes for traffic and create localized bottlenecks. This reduction in the traffic capacity leads to traffic congestion that has serious social, economical and environmental implications. The congestion is not only frustrating for traveling public but it is also affecting the economy. In today's competitive business environment, growing number of companies are adopting supply chain management techniques and Just-in-time manufacturing strategies. These businesses can not afford delays in delivery of their products and materials caused by unexpected road reconstruction works. The general publics traveling through the workzones is also affected by the congestion. The vehicles traveling through the workzones require additional travel time and effort to traverse through the workzones. Changing driving maneuvers result in excess costs to motorists in terms of time, fuel consumption, and wear and tear of vehicle parts. Thousands of productive workers are also forced to spent valuable time in congestions caused by these work zones. Therefore, the workzones have become a big contributing factor in creating congestion, driver frustration and accidents.

According to the United States Federal Highway Administration, (FHWA) safety statistics issued in 2004, motor vehicle crashes are the leading cause of death among Americans 1-34 years old. The total societal cost of crashes exceeds $230 billion annually. During the calendar year 2002, a total of 42,815 deaths occurred on highways in the United States and about 2.5 of all highway accidents occur around the workzones. Transport Canada indicated a total of 190 recorded fatalities and 10,677 non-fatal injuries over the five year [Bushman 2004]. The study provided a breakdown of fatalities distributed across each province. More than half of all fatalities, 55 percent, occurred in Ontario, followed by 14 percent in British Columbia and 9 percent in Quebec. Considering that these are the three most populated provinces in Canada it is reasonable to expect that they would also have a higher percentage of fatalities than provinces with lower population. Over the same five year period, there were a total of 14,702 highway fatalities recorded in the database [Transport Canada, 2003]. In Canada 1.3 percent of all fatalities were work zone related over this period, compared to 2.5 percent in United States.

Transportation agencies are therefore under enormous pressure to deal with growing congestion problem while facing the increasing need to perform rehabilitation and reconstruction work on existing roads. The multifaceted challenges for the agencies are forcing them to compress schedules, finish projects early, while performing the work at night and maintain the safety and mobility of traffic at all times. This can be achieved by developing optimized workzone strategies to reduce total cost, construction time and impact of work zone on throughput. Agencies now have to properly quantify and systematically assess soft costs related to projects. This would help them quantify the work zone safety and mobility implications of alternative project options and design strategies. This assessment will help agencies identify the projects with greater work zone impacts so the necessary resources can be allocated more effectively to those projects.

Like many other agencies, Ministry of Transportation Ontario (MTO) is also using some old lane closure strategies and standards. The lane closure strategies should weigh the impacts of construction duration and inconvenience to the road users and find out the balance where users face minimal inconvenience while contractors have the appropriate amount of time to finish the work and produce a high quality product. In-order to evaluate and assess the appropriate time for lane closures, it is important to estimate the capacity of the lanes. The capacity estimates can help in determining the optimized time for lane closure to minimize the user delays while providing the sufficient time to contractors in achieving the desired productivity and quality of work. There are different models, computer Software and wide variety of studies to evaluate and estimate the Workzone Capacity and associated user delay costs at work zones. These costs are primarily affected by traffic flows, vehicle speeds, and work zone capacities.

In-view of the above, this study is designed to estimate freeway capacity of workzones and discuss the associated user delay costs issues. For this study, the capacity at the work zones was measured as the mean queue discharge flow rate during forced-flow conditions. Forced-flow conditions were defined as congested conditions during which a sustained queue formed. There are several studies and approaches for collecting traffic volume data for estimating workzone capacity. For this study, it was decided to utilize a manual counting method for volume data. This would help provide the visual confirmation of queuing and intensity of work activity at workzones. Six sites located in Southern Ontario, were selected for this study. The data of these sites will be used for estimating the workzone capacity.

1.2 Research Objectives

This study is funded by Ministry of Transportation, Ontario under the Highway Infrastructure Innovation Funding Program (HIIFP), which embarked upon this research program to evaluate the possibility of refining the existing models and standards used by MTO for lane closures at various workzone set ups in southern Ontario. It is a joint collaborative partnership with the University of Toronto and the University of Waterloo. The research is directed at avoiding traffic delays and queues upstream from the work zone and to leave appropriate capacity for traveling public during road and pavement maintenance and rehabilitation activities. Like several other countries, provinces and states, Ontario also has policies or guidelines for lane closures. These guidelines for work schedule requirements of contractors are based on estimates of road capacity at work zones [Tighe 2006]. If these estimates are conservative relative to the actual traffic flow, then the contractor is closing the work zone earlier and for a longer period of time than necessary. Consequently, this cause longer construction window than necessary. It is therefore important to revisit the existing models and evaluate the possibility of suggesting changes in standard lane closure timings based on the estimated capacity values. Furthermore, it is necessary to quantify user delay costs.

In view of the above, the following objectives were established for this research:

- To determine traffic throughput on highways under various typical work zone configurations in Southern Ontario during congested conditions.
- Based on the different capacity values, refine model output for evaluation of user delay costs at the work zones.

The anticipated outcomes of this project are:

- Ranges or adjustment factors for per lane hourly mean capacity at work zones during congested conditions considering road alignment, traffic characteristics and environmental conditions.

- A matrix summarizing the recommended ranges or per lane hourly mean for various classes of highways in MTO's Southern Region.

1.3 Research Approach

The direction for this research was primarily provided by Ministry of Transportation, Ontario, in the form of Terms of reference (TOR) for this project. In-order to analyze the work zone traffic delays and user costs, it is essential to accurately estimate the workzone capacity for various road closure configurations. It is believed that the capacity is affected by various site characteristics. The Highway Capacity Manual (HCM 2000) has defined the capacity as "…the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period, under prevailing roadway, traffic and control conditions (HCM 2000)." The methodologies outlined in the HCM 2000 have widely been used for different agencies in calculating the highway capacity. A literature review conducted to analyze the default values of the HCM 2000 with reference to other input parameters of detailed site specific data.

Traffic delays caused by road construction and maintenance can often lead to driver frustration and excess user costs. User costs are those incremental costs incurred by traveling public having to drive slower and spend additional time in a queue, or take a detour or change driving maneuvers at work zones which result in excess costs in time, consumption of fuel, and wear and tear of vehicle parts. There are few economic analysis methods which can help estimate the user costs caused by Workzone congestions and accidents. These estimates can help decision makers in making informed decisions about effectiveness of various workzone strategies. This study will also provide a brief overview of the World Bank Highway Development Manual, version (HDM-4) model for use in estimating user delay costs.

This study focuses on estimating the freeway Workzone Capacity and associated User Delay Costs and factors that influence the Capacity and Costs. The procedure can be used as an incentive for the contractors to achieve the early completion of construction work by employing innovative work techniques and contracting strategies. Capacity estimation will also help concerned agencies in preparing the appropriate traffic management and control plans for Ontario setup.

Chapter 2
Literature Review

This chapter reviews selected relevant research involving workzone capacity and user delay costs. The literature review starts with the discussion about the capacity estimation as presented in the Highway Capacity Manual (HCM 2000). The later part of this chapter attempts to cover some of the other research work carried out by various researchers.

2.1 Workzone Capacity:

The Highway Capacity Manual (HCM2000) is the recognized document used by various North American agencies in estimating the workzone capacity. HCM 2000 defines the transportation facilities in two categories. Uninterrupted flow facilities are those facilities which have no fixed elements, such as traffic signals etc. "Traffic flow conditions in these types of transportation facilities result from interactions among vehicles in the traffic stream and the geometric and environmental characteristics of the roadway". Similarly the interrupted-flow facilities are those facilities, "have controlled and uncontrolled access points. These access points include traffic signals, stop signs, yield signs, and other types of control that stop traffic periodically or slow it significantly".

The HCM defines the capacity as " the maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental and control conditions; usually expressed as vehicle per hour, passenger cars per hour, or persons per hour." The "capacity analysis is the set of procedures for estimating traffic-carrying ability of facilities over a range of defined operational conditions" [HCM 2000]. The HCM present the analysis framework for short- term maintenance workzones and long term construction workzone. The primary difference between these two types of workzones is the type and nature of barriers used to demarcate the work area. Short term workzones uses traffic cones, drums and other temporary channeling devices, whereas long term workzones normally require portable concrete barriers for demarcation of work area. Capacity of long term construction sites are believe to be higher than short term maintenance sites due to two main reasons. Concrete barriers at long term sites provide a better physical demarcation between travel and work area and at long term sites the commuter traffic gain acquaintance with site conditions that result in improved traffic flow. Both these factors reflect positively on traffic flow when compared to two types of workzones. In Ontario, these workzones and temporary traffic arrangements in work areas are conducted as per the Ontario Traffic Manual, Book 7 [MTO-2001].

The workzone capacity analysis requires estimation of base (ideal) capacity of the section of the road under consideration and estimation of various traffic, weather and geometric adjustment factors that are believe to be affecting the capacity. The base conditions defined by HCM 2000 is the "Set of specified standard conditions which assume good traffic, weather and geometric conditions with no impediments to traffic flow". Placed below are the base conditions defined by HCM 2000 for uninterrupted flow facilities:

- Width of lane 3.6 m
- Lateral clearance of 1.8 m between travel lanes and nearest obstructions
- For multilane highways, the free-flow speed is 100 km/h
- No heavy vehicle, traffic stream only consist of passenger cars
- Zero grade

The HCM recommended base capacity value for short-term workzone is 1600 pc/h/ln regardless of lane closure configuration. Base capacity value for long term workzones is 1750 v/h/ln if there is no cross over with merge to a single lane. Capacity will reduce to 1550 veh/h/ln if traffic cross over is present. HCM suggested adjustments to base capacity values for other site specific prevailing conditions, such as intensity of work activity, effect of heavy vehicles, presence of ramps etc. HCM suggested an adjustment of +/- 10% for intensity of work activity. HCM 2000 provides following equation for estimating the work zones capacity (Equation 22-2, HCM 2000):

$$ca = (1{,}600 + I - R) * f_{HV} * N \quad (2.1)$$

Where:

ca = adjusted mainline capacity (veh/h)

f_{HV} = adjustment for heavy vehicles

I = adjustment factor for type, intensity, and location of the work activity

R = adjustment for ramps

N = number of lanes open through the short-term work zone

Presences of heavy vehicles believe to be reducing the traffic carrying ability of the traveling lanes. These vehicles occupy more roadway space and have lesser operating and maneuverability capabilities than passenger cars. HCM 2000 defines heavy vehicles as vehicles that have more than four tires touching the pavement. Trucks, buses, and recreational vehicles are the three groups of heavy vehicles (HCM 2000).

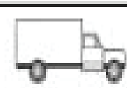
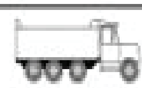
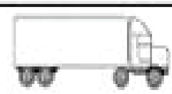
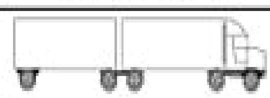
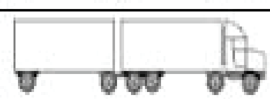
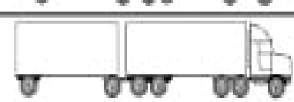
Typical configuration	Description
	Two or Three Axle Buses
	Two-Axle, Six-Tire, Single Unit Trucks
	Three-Axle Single Unit Trucks
	Four or More Axle Single Unit Trucks
	Four or Less Axle Single Trailer Trucks
	Five-Axle Single Trailer Trucks
	Six or More Axle Single Trailer Trucks
	Five or Less Axle Multi-Trailer Trucks
	Six-Axle Multi-Trailer Trucks
	Seven or More Axle Multi-Trailer Trucks

Figure 2-1 Typical Configurations of Heavy Vehicles (FHWA)

Adjustment for heavy vehicles (f_{HV}) can be calculated by Equation 22-1 of HCM 2000

$$f_{HV} = 1 / \{1+P_T(E_T-1)\} \quad (2.2)$$

Where:

f_{HV} = Adjustment factor for heavy vehicle

P_T = Proportion of heavy vehicles (%)

E_T = Passenger-car equivalent for heavy vehicles

HCM has also suggested adjustment factors for other important factors, such as lane width. For lane widths from 3.0 m to 3.4 m, the capacity may decrease by 9-14%. It is important to note that HCM dose not discuss the effect of interaction between various factors.

Al-Kaisy and Hall reported their findings on freeway capacity of long-term reconstruction sites of Ontario, Canada and presented site specific capacity models [Al-Kaisy 2002]. The researchers have collected data from six long term sites with different types of lane closures. The mean estimate of base capacity was found to be 2000 passenger cars per hour per lane (pcphpl). The researchers have developed two types of site specific capacity models after taking into account the several important factors affecting the capacity. The identified factors were heavy vehicles, driver population, light conditions, weather, work activity and lane configuration. The researchers found that the heavy vehicle and driver population have most significant effect on capacity. The study prescribed the base conditions as under:

1. Traffic predominantly consists of commuter drivers
2. Traffic is entirely composed of passenger cars
3. Daytime light conditions
4. No work activity on site
5. Clear weather conditions (no rain, no snow or extreme winds)
6. Right-side lane closure
7. Level terrain with grades no greater than 2 percent
8. Lane width of at least 3.7 meters.

The study estimated the base capacity values and considered the factors that have an impact on work zone capacity. Each individual factor was examined while controlling, as much as possible, the effect of other factors. The study than developed two mathematical models that could be used to estimate work zone capacity under the effect of various geometric, traffic, and environmental conditions. The study also attempts to investigate the combined effect of two or more variables on capacity. In the first multiplicative model, the base capacity is multiplied by adjustment factors to determine the impact of various variables. Solver optimization tool was used for this model with the variables, driver population, heavy vehicles, work activity, lane closure side, and rain. The model is as follows:

$$C = C_b \times f_{HV} \times f_{d1} \times f_{d2} \times f_w \times f_s \times f_r \qquad (2.3)$$

Where:

C = Work zone capacity (vphpl)

C_b = Base (ideal) work zone capacity (pcphpl)

f_{HV} = Adjustment factor for heavy vehicles (same as HCM 2000 formula for f_{HV})

f_{d1} = Adjustment factor for off-peak weekday driver population (off-peak= *fd1*, else=1)

f_{d2} = Adjustment factor for weekend driver population (weekend= *fd2,* else=1)

f_w = Adjustment factor for work activity (work activity= *fw*, no work activity=1)

f_s = Adjustment factor for side of lane closure (left lanes closed = *fs* , right closed=1)

f_r = Adjustment factor for rain (rain= *fr* , no rain=1)

The optimization procedure produced following values of various parameters:

$C_b = 2050$, $E_{HV} = 2.778$, $fd1 = 0.961$, $fd2 = 0.825$, $fw = 0.966$, $fs = 0.943$, $fr = 0.976$.

The coefficient of determination = 0.63.

For the second additive model, the multivariate linear regression was used. The variables used in regression were having binary values. For heavy vehicles the number or percentage was used. The additive model is shown as under:

$$C=1964- 20.9P_{HV}- 82D_1- 352D_2- 172W- 121S- 71R+ 55SD_1+ 185WD_2+ 58SD_2+ 107RD_2 \qquad (2.4)$$

Where:

C = Capacity in vphpl

PHV = Percentage of heavy vehicles in the traffic stream

D1 = Off-peak weekday driver population (off-peak=1, else=0)

D2 = Weekend driver population (weekend=1, else=0)

W = Work activity at site (work activity=1, no work activity=0)

S = Side of lane closure (left lanes closed=1, right lanes closed=0)

R = Rain (rain = 1, else = 0)

SD1, WD2, SD2, and RD2 = Interactive variables

R^2 = 0.68, Std. Error = 89

The study suggested multiplicative capacity model as generic capacity model having following format:

$$C=C_b \times f_{HV} \times f_d \times f_w \times f_s \times f_r \times f_l \times f_i \quad (2.5)$$

Where:

C = Work zone capacity (vphpl)

C_b = Base work zone capacity (pcphpl):

f_{HV} = Adjustment factor for heavy vehicles

f_d = Adjustment factor for driver population

f_w = Adjustment factor for work activity

f_s = Adjustment factor for side of lane closure

f_r = Adjustment factor for rain

f_l = Adjustment factor for light condition

f_i = Adjustment factor for non-additive interactive effects

The study presented by Sarasua, suggested a base capacity value of 1460 pcphpl after collecting 12 months of data in 2001-2002 from 22 South Carolina's short term interstate work zone sites. The study summarized the various workzone capacity definitions [Sarasua 2004]:

- Mean queue discharge flow rate from the resulting bottleneck at the end of a transition
- Hourly traffic volume under congested traffic conditions
- Traffic volumes for three-minute intervals during congested traffic conditions
- Flow rate at which traffic behavior quickly changes from un-congested to queued conditions

The model is similar as the earlier model proposed by [Krammez et al.1994] with a new base capacity value of 1460 pcphpl

An other study by Agyemang, attempted an investigation into estimation of capacity values by establishing a relationship in queue and drop in capacity [Agyemang 1991]. They collected the peak period data over 52 day period. The study recommended the capacity value under stable flow is 2300 pcphpl and 2200 pcphpl for post breakdown flow. The researchers plotted pre-queue peak flows and queue discharge flow to show that the two distributions have similarities.

Benekohal presented a methodology for estimation of operating speed and capacity in work zones on highways [Benekohal 2004]. The study discussed the operating factors that cause motorists to reduce their speed and resultantly adversely affect the capacity of work zones. 30 hours of data from 11 workzone locations were collected to propose a model to estimate the workzone capacity. Work intensity was quantified to establish a relationship between work intensity and consequent speed reduction in construction zones. Operating speed was computed by using speed flow curves. The capacity of workzone computed after the determination of operating speed. Model validated using the filed data collected from long term and short-term workzones located in Illinois, USA.

Jiang has collected data from Indiana freeway work zones and suggested a new definition of workzone capacity [Jiang 1999]. The study found that traffic congestion at work zones was characterized by sustained low vehicle speeds and fluctuated traffic flow rates. Work zone capacity was defined as the traffic flow rate just before a sharp speed drop followed by a sustained period of low vehicle speed and fluctuated traffic flow rate.

Krammes presented a study to estimate the work zone capacity of short-term and long-term workzones based on the 45 hours of field data [Krammes 1994]. The data was collected in Texas, USA between 1987 to 1991. The studies become the basis for HCM 2000 methodology. Five different lane configurations were analyzed. The results suggested an average capacity value of 1600 pcphpl for short-term workzones. The study suggested adjusting this value for the effects of heavy vehicle, intensity of workzone and the presence of ramps near the beginning of workzones. The equation presented by the study for estimation of Capacity is as under:

$$C = (1600 + I - R) * H * N \tag{2.6}$$

Where

C = Workzone Capacity (veh/h)

I = Adjustment factor for type, intensity, and location of the work activity (pcphpl)

R = Adjustment for ramps

N = number of lanes open through the work zone

Maze conducted a study and pointed out that "when a queue is formed the maximum flow in the entire work zone is controlled by the rate at which the vehicles discharge from the queue and this flow will be of lower value because of the capacity drop" [Maze 2000]. The data was collected for this study in Iowa on the Interstate 80 between U.S. 61 and Interstate 74. Two cameras were used for data collection, mounted on two trailers with 30-foot booms. The trailers remained on the site for 19 days. Congestion was observed for 4 days during this period. Result showed that under queuing conditions, the volume remained constant before and after queuing while the average speed dropped. In this case, there was no capacity drop observed. The maximum capacity of the lane closure was calculated by taking the average of the 10 maximum traffic volumes before and after queuing conditions. It was found that the capacities for the rural highway work zones in Iowa ranged from 1400 to 1600 pcphpl.

Kim presented a study for estimating the freeway work zone capacity [Kim 2001]. The study investigated various independent factors that contribute to capacity reduction in work zones and suggested a new methodology to estimate the work zone capacity. Traffic and geometric data were collected at 12 short-term work zone sites of Maryland, to prepare a model for estimating the capacity. The multiple regression model was developed and compared with HCM. The study suggested the capacity values from 1228 to 1790 vphpl which is indicative of the short term work zones.

2.2 User Delay Costs

Evaluation of delays related to work zones is important for all road users and transportation agencies. Workzones disrupt the traffic and cause delays for thousands of people traveling through these workzone areas. Therefore, these workzone results in additional cost for those drivers who pass through the construction zones at slower speeds. Slower speeds increase the travel time and consumption of fuel having to wait in the queues. User delay costs are those additional costs incurred by drivers, industries, businesses and economies as a whole which resulted because of delays caused by the workzones. This study discusses workzones and how they impact the user costs and how such costs can be used as an incentive for contractors to achieve faster completion times, thus reducing the amount of time contractors remain on the road. Using the value of user costs as an incentive to the contractors may encourage them to finish the work early. The methodology of formulating such a strategy can contribute in promoting economic growth by enhancing the effectiveness of the transport network and reducing congestion. This strategy will also encourage the contractors to develop new and innovative techniques for early completion of construction work.

2.3 Contractual Methods:

Currently there are three contractual methods commonly used by various agencies for encouraging the early completion of work thereby reducing the negative impacts of workzones on user delay costs:

- Incentive/disincentive (I/D)
- A+B contract
- Lane rental

Careful analysis of these methods is necessary before selecting the most appropriate methods for any particular project. Each method believed to have some advantages and related disadvantages.

2.3.1 Incentive/Disincentive

The incentive/disincentive (I/D) methods have some legal implications when the penalties are imposed on contractors for delays. Since this type of method penalizes parties for delays, a careful implementation and documentation is necessary to make this method a success. The disincentive provision combined with an incentive is less vulnerable to legal challenge [Gillespie 1998]. In most cases, contractors are easily able to save some contract time, and the I/D method was the least effective and most expensive overall method [Herbsman 1998]. The Incentive/Disincentive and lane rental procedures were more effective in reducing the delay in work zones [Benekohal 2003]. However, there was no consensus on the I/D or lane rental dollar amount to be used. The other suggested measures by the study includes include geometric design features such as designing shoulders on high-volume routes to accommodate future construction. However, most are non-structural measures affecting construction operations through incentive/disincentive contract clauses, and increased public coordination.

2.3.2 A+B Contract

A+B contract or Cost/Time method invites the bidding contractors to provide a bid for the project cost plus the amount of time planned to complete the project. The combination of lowest bid with earliest completion time wins the contract. This method found to be most economical and is receiving more support [Herbsman 1998]. Combining this method with I/D clause can improve the enforceability of the completion date by ensuring that the contractor is responsible for the completion date given in the bidding process [Gillespie 1998].

2.3.3 Lane Rentals

Lane rental is comparatively a new technique to minimize the road user costs. This method requires that the contractor be charged for the time that the lane is closed to traffic. The contractor will be charged for each time lanes were closed based on the predetermined fees that were part of the bidding documents [Herbsman 1998]. The time interval can be weeks, days, hours, or even smaller intervals. The contractor must determine the future cost for lane closure and incorporate it into his/her cost estimate." The costs are normally determined by taking into account the day of the week, time of day, annual average daily traffic (AADT), percentage of trucks, and any other possible parameters. This method can also be combined with Incentive/Disincentive method. If the actual number of days of lane closure is less than the specified number, an incentive is paid. If the contractor exceeds the number of days of lane closure allowed, a disincentive payment is deducted from the contract for each day in excess of the bid number of days. The intent is to force efficient scheduling of resources and timely completion of the work in order to reduce motorist delay.

2.4 Workzone Impact Assessment

As mentioned above, the workzones have significant impacts on a number of sectors including the environment and economy as a whole. The uncertainty in accurately estimating the travel times, imposes significant costs to business operations and overall performance of various organizations. These unexpected delays may reduce the marketability of various products hence this uncertainty is more harmful for businesses than the expected lengthy delays. Therefore an increasing amount of research and literature is emerging with respect to tackling the impacts of workzones. One of the major impacts of workzone is on the user delay costs. There are many methods to quantify the user delay costs. One commonly applied measure is to divide the total delay by the volume of traffic to figure out the average amount of delay encountered by a vehicle traveling through a workzone. These methods however disregard vehicle occupancy, time values and environmental impacts etc.

Determination of users cost in work zones requires identification of travel delay and queue delay. Travel delay is about the operating speed of vehicles and queue delay is related to queue length and its duration. Many studies suggested that the speed and queue values depend on work zone capacity; therefore these studies use capacity as a key input parameter for calculating the queue length, delay, and user delay costs. Due to increasing prices of fuel, the motorists today are more sensitive to delays, since delays cause them to bear extra expenses. Due to these reasons, transportation agencies today are facing increasing pressures to reduce the construction time, so the impact to traveling public and local businesses may be minimized. However, scheduling maintenance activities, merely in limited off-peak periods, may lengthen project duration and increase maintenance related costs.

2.5 Work Strategies

Work strategies may significantly impact the time it takes to complete the construction work. For example, Table 1 illustrates the productivity comparison of different construction windows in a concrete slab replacement [Lee 2000; 2004]. Reductions in productivity were attributed to repeated auxiliary activities, such as mobilization and traffic control set up, curing or cooling time, cleaning and demobilization, caused by a short construction window.

Table 2-1 Productivity Factors for Concrete Slab Replacement [Lee 2000; 2004]

<table>
<tr><th>Description</th><th colspan="2">Productivity Factor</th></tr>
<tr><td>Continuous Closure, Continuous Operation, 3 Shifts</td><td colspan="2">1.00*</td></tr>
<tr><td>Continuous Closure, Daytime, Weekday Operation</td><td colspan="2">2.80</td></tr>
<tr><td>Weekend Closure, 55 Hours Continuous Operation</td><td colspan="2">1.45</td></tr>
<tr><td>Nightly Closure, 10 Hours Operation</td><td>1.91</td><td rowspan="2">2.23 (Average)</td></tr>
<tr><td>Nightly Closure, 7 Hours Operation</td><td>2.55</td></tr>
</table>

*This is productivity benchmark. 2.8 represents that it will take 2.8 times longer to do the same work.

Distractions for drivers are often as hazardous as they decrease capacity caused by the work zone. For example, even if the work zone has been opened to traffic, the parked equipment along the highway causes a visual distraction, slowing traffic through the area.

2.6 Life Cycle Cost

There is a growing trend for transportation agencies to consider life cycle costs (LCC) of their capital assets including initial construction, maintenance and reconstruction of transportation infrastructure. LCC should also include the user delay costs associated with the maintenance and reconstruction processes [Raymond 2000; Tighe 2006]. The data collected through this research will also be used to provide decision makers with valuable information on user delay costs associated with work zones.

Reduction of speed through a work zone will cause slowing and queuing delays in a work zone. The slowing delay is associated with the approach to the work zone where drivers first reduce speed (and increase travel time) compared to normal free flow conditions. Reduced speed limits enhance safety for both the construction workers and the traveling public. Where the construction requires a lane closure on a multi-lane highway or freeway, vehicles in the affected lane will begin to merge to adjacent lanes. It is interesting to note that researchers have found that early merges reduce the throughput of vehicles through the work zone, whereas “late-merging” will increase road capacity by 18% and lead to 75% fewer merging conflicts [Stidger 2003].

Work zone layout affects the comfortable vehicle velocity for the driver. Rister analyzed the cost of construction delays and studied various factors [Rister 2002]. He found that the position of the work activity with respect to the through lanes will affect the speed of vehicles. In fact a work zone shift of one metre towards the through traffic will reduce vehicle speeds by two miles per hour [Rister 2002]. Also reduced throughput (vehicles per hour per lane) of 9 and 14 percent are observed if the lane widths are reduced to 3.75 metres and 3 metres respectively.

Queuing delays are very frustrating for drivers, and have been the focus of many studies. For instance, the Pollaczek-Khintchine formula describes the relationship between the time a vehicle spends in any given system, the road capacity and the mean queue length in a work zone [Heidemann 2001]. Through substitutions of variables, a crude model depicting stationary queues is derived. Transient queues where vehicles vary their speed and density approaching the construction zone are more realistic in most situations for partial lane closures [Heidemann 2001]. Munoz observed a two kilometre queue during peak hours of the vehicles exiting Freeway I-880 at I-238. They felt that the phenomenon could be partially explained using the kinetic wave model. Similar conditions may occur in partial lane closures in work zones during peak hours [Munoz 2003].

Constraints on contractors for the operation of work zones are typically either a ceiling on capacity or queue length. Strategies can be used to reduce delays, including encouraging drivers to take a different route, dynamic lane assignments, restrictive lane usage, and variable speed limits; however, implementation of these strategies can be difficult. Information relayed to drivers through changeable message signs (CMS) typically give drivers limited time to interpret and act on the message. Therefore, some will adhere to the recommendation while others will not. An investigation of several construction projects in California found that with sufficient public notice, traffic through a work zone was not severely impacted since many drivers decided to take alternative routes and avoid the work zone area completely. In fact, traffic volumes through the work zones were below the design capacity. As the construction continued, volumes increased as drivers learned that there was little congestion [Lee 2004].

This type of study requires an abundant amount of data to be acquired. Loop detectors, CCTV, and ramp metering are examples of equipment needed to understand the traffic volume around and within the work zones. Unfortunately, embedded detectors are usually interrupted around work zones, so automated data collection requires the installation of temporary measures.

While notice of lane closures is important to the driver, once notified that the current lane will terminate, drivers will typically merge to adjacent through lanes early. The effect is several hundred metres of laneway not being used efficiently. To effectively understand the impacts regarding the merge zone, computer based simulations are available. Past studies indicate late merge effectiveness for high volume facilities reduced forced merges and increased traffic flow by decreasing queue length [Fontaine 2005]. Simulation of vehicles merging found that variations in the free flow speed and lane configuration directly influenced the results. Of keen importance is that all scenarios tested with late merge resulted in an increase in vehicle throughput. An inverse relationship between percent heavy vehicles and demand volume was found. High sensitivity on the percent heavy vehicles was due to latent rate of acceleration, resulting in unused capacity. Limitations of these findings include the assumption that vehicles complied with traffic control and queue jumping and lane straddling was non existent. Finally, a facility closing two out of three lanes showed most promise using the late merge strategy but is rarely tested in the field as demand would often exceed capacity. Single lane closures showed modest improvements with reduced negative impacts of heavy vehicles.

This section covers some of the studies conducted for evaluating the user delay costs of workzones and other related economic and life cycle cost issues.

A more recent study by Chitturi, presented a methodology for computing delays and user costs in highway work zones based on the relationship between speed and capacity [Chitturi 2007]. The methodology requires adjustment of speed to account for the various workzone factors such as work intensity, lane width, and lateral clearance. These factors cause reduction in the speed of the traveling vehicles and resultantly reduce the number of vehicles that can pass through the workzone. The paper presented two applications, one with queuing and one without queuing and compares the results with field data. For the queuing site, capacity computed was 1012 vphpl while the field capacity was 1220 vphpl. The field data were compared to the results of the methodology. The methodology involved 12 different steps to compute the delays and user costs in highway workzones.

Step one involves finding the speed reductions due to narrow lane width (R_{LW}) and less than ideal lateral clearance (R_{LC}) from a table presented in the study. The reductions due to lane width adopted from another study of the author, while the reductions due to narrow right shoulder widths taken from the HCM.

Step two requires computation of work intensity ratio (WI_r) using following equation:

$$WI_r = (w + e)/ p \quad (2.7)$$

Where:

WI_r = Work intensity ratio

w = Number of workers working in a group in the work space (Value varies 0-10)

e = Number of large construction equipment in work space near workers (from 0- 5)

p = Lateral distance between the work space and the travel lane (varies from 0.3 to 2.7 m)

In third step, using WI_r computed in step two, it is required to compute speed reduction (R_{WI}) due to work intensity.

$$R_{WI} = \{SR_S \text{ in Short-term workzone and } SR_L \text{ in Long-term workzone}\} \quad (2.8)$$

$SR_S = 11.918+2.676 \ln (WI_r)$ = Speed reduction in Short-term workzone (mph)

$SR_L = 2.6625+1.2056 \ln (WI_r)$ = Speed reduction in Short-term workzone (mph)

In step four, Operating Speed (U_O) to be calculated, using the following equation:

$$U_o = FFS - R_{LW} - R_{LC} - R_{WI} - R_O \quad (2.9)$$

Where:

U_o = Operating Speed (mph)

FFS = Free flow speed

R_{LW} = Reduction in speed due to lane width (mph)

R_{LC} = Reduction in speed due to lateral clearance (mph)

R_{WI} = Reduction in speed due to work intensity (mph)

R_O = Reduction in speed due to all other factors that may reduce speed (mph)

Step five is about finding the capacity at operating speed (C_{UO}) from the speed flow curve. An alternative method for calculating CUO is also presented in the study.

Step six of the methodology talks about calculating Heavy Vehicle factor using following equation:

$$f_{HV} = 1/\ 1 + P_T(PCE-1) \quad (2.10)$$

Where:

f_{HV} = Heavy vehicle factor

P_T = Percentage of heavy vehicles (entered as decimal)

PCE = Passenger car equivalents (HCM recommended values)

Step seven requires calculating the adjusted capacity-at-operating-speed (C_{adj}) using:

$$C_{adj} = C_{Uo} * f_{HV} \quad (2.11)$$

Where:

C_{adj} = Adjusted capacity-at-operating-speed (vphpl)

C_{Uo} = Capacity-at-operating-speed U_o (pcphpl)

f_{HV} = Heavy vehicle factor

Step eight is only applied if demand is greater than adjusted capacity-at-operating-speed. In other case go directly to step 10. This step requires estimation of the queue length at the end of every hour using the following equation:

$$n_{i+1} = n_i + V_{i+1} - C_{adj} * N_{op} \quad (2.12)$$

Where:

n_i = Number of vehicles in queue at the end of i_{th} hour

n_{i+1} = Number of vehicles in queue at the end of $(i+1)_{th}$ hour

V_{i+1} = Total demand in $(i+1)_{th}$ hour (vph)

C_{adj} = Adjusted capacity-at-operating-speed (vphpl)

N_{op} = Number of lanes open in the work zone

The methodology requires computing l_{eff} (effective spacing between vehicles) using:

$$l_{eff} = (P_T * l_T + P_C * l_C) + \text{buffer space} \quad (2.13)$$

Where:

l_{eff} = Effective spacing between vehicles (feet)

P_T = Percentage of heavy vehicles (entered as a fraction)

l_T = Length of heavy vehicles (feet)

P_C = Percentage of passenger cars (entered as a fraction)

l_C = Length of passenger cars (feet)

Buffer space = Distance between vehicles when both are stopped (10 feet)

The stacked Queue length (Q_{Si}) than is calculated using following equation:

$$Q_{Si} = n_i * l_{eff} \quad (2.14)$$

Where

Q_{Si} = Stacked queue length at the end of i_{th} hour (ft)

n_i = Number of vehicles in queue at the end of i_{th} hour

l_{eff} = Effective spacing between vehicles (feet)

The next process is to determine the distance from the work activity area to the beginning of the transition taper (D).

If D > Q_{Si} / N_{op}, queue will not extend outside of the work zone. Then queue length at the end of the i_{th} hour is computed using following equation:

$$Q_i = Q_{Si} / N_{op} \quad (2.15)$$

Where:

Q_i = Queue length at the end of the i_{th} hour (ft)

Q_{Si} = Stacked queue length at the end of i_{th} hour (ft)

N_{op} = Number of lanes open in the work zone

If D < Q_{Si} / N_{op}, queue will extend outside of the work zone. Then queue length at the end of the i_{th} hour is computed using following equation:

$$Q_i = D + (Q_{Si} - D*N_{op})/ N_{nr} \tag{2.16}$$

Where:

Q_i = Queue length at the end of the i_{th} hour (ft)

D = Distance from the work activity area to the beginning of the taper (ft)

Q_{Si} = Stacked queue length at the end of i_{th} hour (ft)

N_{op} = Number of lanes open in the work zone

N_{nr} = Number of lanes open before the work zone

Queue length is measured from the beginning of the work activity area in this methodology.

Step nine Estimate the delay due to queuing using the following equation:

$$d_q = \sum_{i=0}^{t-1}\left(\frac{n_i + n_{i+1}}{2}\right) \tag{2.17}$$

Where:

t = Number of hours of queuing

n_i = Number of vehicles in queue at the end of i_{th} hour

n_{i+1} = Number of vehicles in queue at the end of $(i+1)_{th}$ hour

Step ten requires estimation of the delay due to slower speed in the work zone:

$$d_{spd} = \sum_i V_i * \left(\frac{L}{U_o} - \frac{L}{U_{\lim}}\right) \tag{2.18}$$

Where:

d_{spd} = Delay due to slower speed (veh-hours)

L = Length of the work zone (miles)

V_i = Demand in hour i (vph)

U_o = Operating Speed (mph)

$U_{\lim}$ = Posted speed limit inside the work zone (mph)

Steps eleven estimate the total delay using following equation:

$$d_{total} = d_{spd} + d_q \qquad (2.19)$$

Where:

d_{total} = Total delay experienced by the users (veh-hours)

d_{spd} = Delay due to slower speed (veh-hours)

d_q = Delay due to queuing (veh-hours)

The final step of the methodology attempts to compute Users Cost

$$UC = d_{total}\,((P_T * C_T) + (P_C * C_C * N_{occ})) \qquad (2.20)$$

Where

UC = Total user costs ($)

d_{total} = Total delay experienced by the users (in veh-hours)

P_T = Percentage of heavy vehicles

C_T = Hourly delay costs for trucks ($/hr)

P_C = Percentage of passenger cars

C_C = Hourly delay costs for each passenger in a car ($/hr/passenger)

N_{occ} = Average number of occupants in cars (passengers/car)

Steven presented a research paper on scheduling work zones for highway maintenance project considering a discrete time-cost relation [Steven 2007]. The paper describes how highway reconstruction and maintenance are disrupting the traffic flow and causes traffic congestion. The objective of the study is to optimize work zone schedule, where the objective total cost, including agency and road user costs, is minimized considering a discrete relationship between maintenance time and the associate cost. The decision variables include the numbers of work zones and breaks and their corresponding starting, ending times, and lengths. The study presented a Genetic Algorithm to solve the combinatorial, multi-dimensional optimization problem.

Another study by Salem suggested including user costs in the pavement type selection decision making process [Salem 2007]. The suggested that the proposed process can be improved by quantifying user costs and using the monetized user costs in pavement type selection process. The study suggests that “there is a growing awareness in the transportation community that the user costs may out weigh the initial construction and agency costs over the life of transportation facilities”. There are few agencies today actually incorporate user costs in analysis of transportation projects. This is mainly due to difficulty in determining real economic value of user costs and absence of a standard method for quantification of user costs. The study developed two new approaches to integrate user costs in Ohio DOT pavement type selection process.

Benekohal prepared a detailed report on Evaluation of Construction Work Zone Operational Issues [Benekohal 2003]. The report prepared for Illinois Department of Transportation (IDOT), Bureau of Design and Environment (BDE). Report discussed the need for preparing the traffic control plans for freeway reconstruction projects. The plan requires queuing analysis to determine the anticipated traffic backups. Based on the results of the queuing analysis, decision can be made regarding restrictions of construction operations to off-peak or night hours, using alternative routes, making temporary capacity improvements, or providing real-time information to motorists. The report also discussed various methods to reduce delay and inconvenience to motorists. Those methods include enforcing certain contractual procedures (such as lane rental and incentive/disincentive (I/D)) to shorten the duration of construction time. Apart from other important aspects, the study investigated various contract incentive/disincentive procedures for minimizing user delays. For the purpose of this study the data was collected from 13 sites and comparisons were made between field data and software results. The study used FRESIM, QUEWZ and Quick Zone software and UIUC Models were developed to determine capacity, speed reduction, delay, and queue length.

Chapter 3
Workzone Capacity

This chapter discusses the topic of Workzone Capacity and importance of calculating the capacity for various transportation operations and planning purposes. The chapter attempts to discuss some commonly used models and computer software to estimate the capacity. These capacity models apply certain correction factors to the base capacity for establishing the workzone capacity. The chapter also briefly describes some of the important factors or site characteristics affecting the capacity.

Traffic volumes on our roads are increasing but the growth in road miles are minimal. The road network is reaching a middle age that requires more maintenance and reconstruction work hence we have more work zones. These workzone create congestion due to capacity reduction of roadway section. The congestion results in unproductive and wasteful delays for both motorists and commercial vehicles. The delay also results in driver frustration, making some drivers willing to take unsafe risks in an effort to bypass delays [Maze 2000]. With the increasing gas prices, the drivers now become more sensitive to delays. Transportation agencies are therefore under growing pressure to provide a good level of service to motorists, by minimizing the total impact of workzones and reducing the user delay costs. Agencies are now required to properly quantify and systematically assess soft costs related to projects. This would help agencies in quantifying the work zone safety and mobility implications of alternative project options and design strategies. This assessment also helps agencies in identifying the projects with greater work zone impacts so the necessary resources can be allocated more effectively to those projects. The objective is to reduce the delay and improve safety in work zones. This can be achieved by developing optimized workzone strategies to reduce total cost, construction time and impact of work zone on throughput.

Many agencies are now preparing traffic control plans and lane closure strategies for workzones to determine the anticipated traffic delays at particular times of the day. Based on the results, a decision can be made to consider restricting construction operations to off-peak or night hours, using alternative routes, temporarily widening the roadway to increase capacity, or providing real-time information to motorists.

The lane closure strategies attempt to weigh the impacts of construction duration and inconvenience to the road users and figure out the balance where users face minimum inconvenience while contractors get appropriate time to finish the work productively. The quantitative value of workzone capacity is believed to be that balancing point or break even point. If the agencies can create such a situation where traffic demand remains below the capacity value than there will be less inconvenience to travelling public and this would be the acceptable situation for agencies in managing the workzones. Some researchers, [Elefteriadou 1995] showed however, that breakdown does not necessarily occur always at the same demand levels, but can occur when flows are lower or higher than the numerical value traditionally accepted as capacity. But the majority of research studies recognize the importance of accurately estimating the capacity of workzone.The capacity estimates can help in determining the optimized time for lane closure to minimize the user delays while providing the sufficient time to contractors in achieving the desired productivity and quality of work.

As per [HCM 2000] workzone is "an area of a highway in which maintenance and construction operations are taking place that impinge on the number of lanes available to moving traffic or affect the operational characteristics of traffic flowing through the area". The closure of some lanes for traffic during construction or maintenance activity creates many potential safety problems. Lane closures require the driver to make behavioral adjustments, such as reducing speed and/or changing lanes [Nawaz 2005]. On high-volume facilities, problems often occur when two or more lanes of traffic must be warned sufficiently in advance for motorists to travel safely through the one lane passing through the work-zone.

In Ontario, workzone traffic control operations are conducted as per the standard system provided by Ontario Traffic Manual (OTM) [MTO 2001]. The objective of this manual is to promote uniformity of treatment in the design, application and operation of traffic control in workzones. This would promote the safe driving behavior, achieved by a predictable roadway environment through the consistent, appropriate application of traffic control devices.

3.1 Workzone Traffic Control

The OTM Book 7, provides a basic design for workzone set up [MTO 2001]. This set up starts with advance warning signs through to the last traffic control device, where traffic returns to its normal path and conditions [OTM 2001]. A well-designed work zone normally contains following six distinct component areas:

- Advance Warning Area
- Approach Area
- Transition Area
- Longitudinal Buffer Area (LBA)
- Work Area
- Termination Area

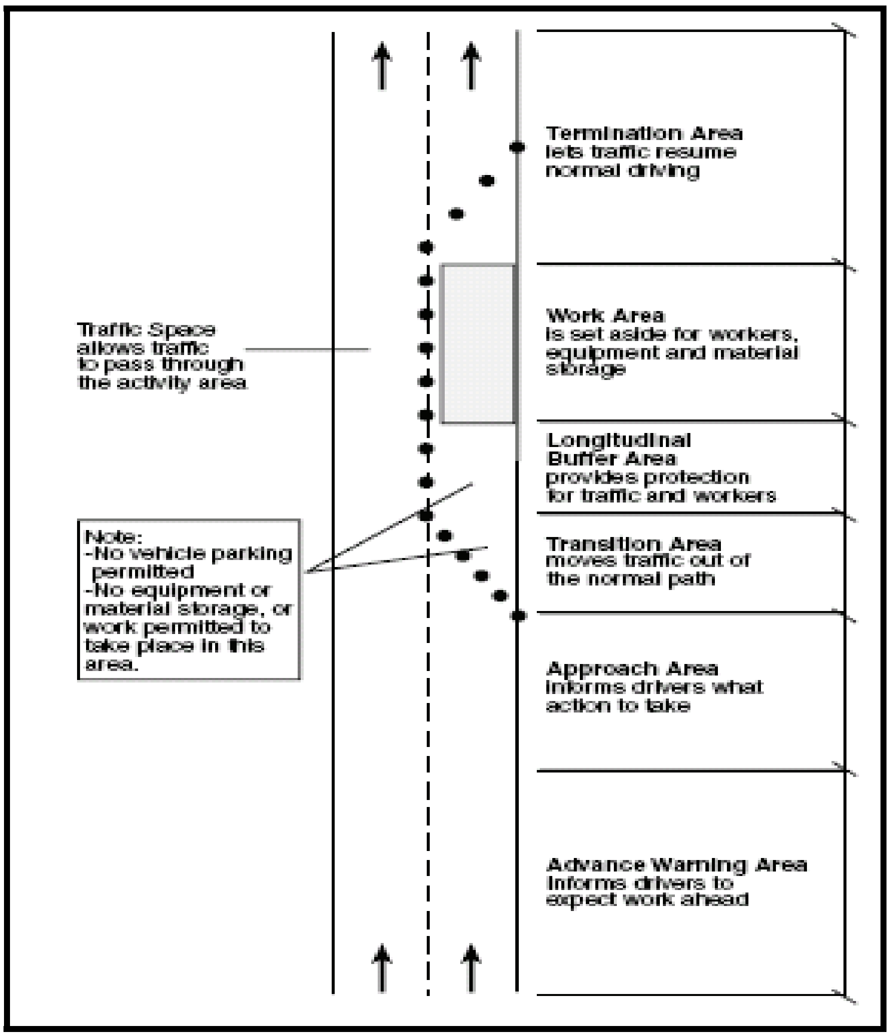


Figure 3-1Component Areas of a Temporary Workzone

Source: Ontario Traffic Manual (OTM Book 7)

There are various definitions of capacity at work zones. One common definition presented is the "mean queue discharge flow rate during forced-flow conditions" [Persaud 1991]. Forced-flow conditions were defined as congested conditions during which a sustained queue formed. When a queue is formed, the maximum flow in the work zone is controlled by the rate at which the vehicles discharge from the queue. The understanding of basic traffic flow characteristics is necessary to evaluate the capacity of a workzone. There could be different capacity values of a section of a facility if calculated the capacity using different definitions of capacity. The capacity values can be different as well for any site based on the location of the data collection point at site. It is believed that the capacity of transition area is generally more than the capacity of work area.

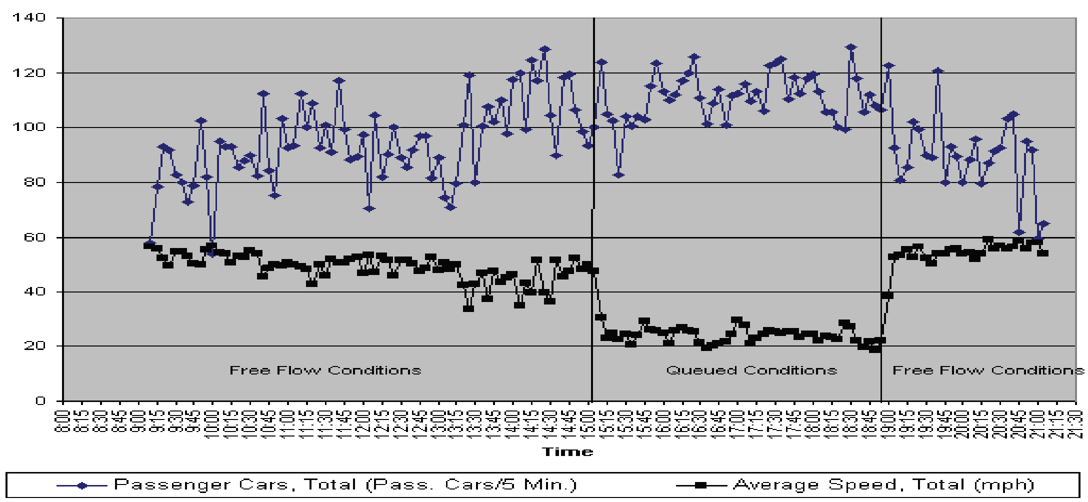


Figure 3-2 Workzone lane closure flow and speed over time

Transportation facilities are classified into two types of flow facilities. HCM 2000 has defined these two types of facilities as under:

3.2 Interrupted-flow facilities

Have controlled and uncontrolled access points that can interrupt the traffic flow. These access points include traffic signals, stop signs, yield signs, and other types of control that stop traffic periodically (or slow it significantly), irrespective of the amount of traffic.

3.2.1 Uninterrupted-flow facilities

Uninterrupted-flow facilities have no fixed elements, such as traffic signals etc. Traffic flow conditions result from the interactions among vehicles in the traffic stream and between vehicles and the geometric and environmental characteristics of the roadway.

This study involves estimating the workzone capacity of freeway short-term workzones and its impacts on user delay costs. A Freeway is an uninterrupted flow facility. The HCM describes the capacity analysis as the "set of procedures for estimating traffic-carrying ability of facilities over a range of defined operational conditions [HCM 2000]. The principal objective of capacity analysis is to estimate the maximum number of vehicles that a facility can safely accommodate during a specified time. However, facilities generally operate poorly at or near capacity; they are rarely planned to operate in this range. Accordingly, capacity analysis also estimates the maximum amount of traffic that a facility can accommodate while maintaining its prescribed level of operation. Operational criteria are defined by introducing the concept of level of service. Ranges of operating conditions are defined for each type of facility and are related to amount of traffic that can be accommodated at each service level"

The HCM further explains that the "stated capacity for a given facility is a flow rate that can be achieved repeatedly for peak periods of sufficient demand [HCM 2000]. Capacity is not the absolute maximum flow rate observed on such a facility. Driver characteristics vary from region to region, and the absolute maximum flow rate can vary from day to day and from location to location. Persons, passenger cars and vehicles per hour are measures that can define capacity, depending on the type of facility and type of analysis". The capacity of a transportation facility is regarded as a random variable instead of a constant value. [Brilon 2007] presented a study "Implementing the Concept of Reliability for Highway Capacity Analysis" and suggested the stochastic concept of highway capacity is more realistic the traditional method, which uses constant-value capacities. The researchers have worked on the field data of German freeways with unlimited speed conditions. The probabilistic approach allows better understanding of the variability of maximum highway traffic flows. The author introduced a new method for estimating the distribution functions of freeway capacity based on the statistics of life time data analysis. The capacity of a freeway section was shown to be best represented by a Weibull-distributed random variable. The researchers have suggested use of this new method for the economic appraisal of alternative freeway planning schemes or for assessment of traffic management strategies.

Flow characteristics in freeway work zones are more complex that a normal freeway segment. Traffic flow in workzone has some additional factors. It is very difficult to investigate the impact of those additional factors such as work intensity, presence of police, location of merging point, placement of warning signs etc. It is difficult to collect all related traffic data to analyze traffic flow characteristics at workzone at sites. Some factors are easier to identify and measure, such as percentage of heavy vehicle, length of workzones, lateral clearance and width of lanes. However, there are some other factors which are difficult to measure and quantify such as work intensity etc. Due to these difficulties, there is no standard method for estimating the workzone capacity. Various researchers have worked on different mathematical models and computer software in estimating the workzone capacity. Some of the well recognized research is discussed in the following section.

Krammes presented a model for estimating the freeway short-term workzone capacity. Data were collected from 33 Texas freeway short-term construction sites for 45 hours from 1987 to 1991 [Krammes 1994]. Five different lane closures configurations were used for collecting the field data. The capacity values showed considerable variability for each lane closure configuration. This variability was owing to differences in type and intensity of work activity, percentage of heavy vehicles, lane width and lateral clearance etc. The capacity was measured as the mean queue discharge entering a freeway bottleneck.

The average capacity for all the lane closure configurations was found to be 1600 pcphpl. This overall average capacity did not consider the effect of presence of ramps in the work zone. This average capacity value of 1600 pcphpl is used as the base capacity for the work zone capacity value. Adjustments were made for effects of heavy vehicles, intensity of work activity and presence of ramps. The proposed capacity model is as under:

$$C = (1600 \text{ pcphpl} + I - R) * H * N \quad (3.1)$$

Where:

C = Estimated workzone capacity (vph)

I = Adjustment for intensity of work activity (Range +/-10 of Base Capacity)

R = Adjustment for presence of ramps volume in pcphpl (+/- 800 pcphpl)
H = Adjustment for Heavy Vehicle
N = Number of lanes open through work zone

Adjustment for presence of entrance ramp applies when ramp is located within the taper or within 500ft downstream of the beginning of the full lane closure. Heavy Vehicle H calculated using the Highway Capacity Manual's methodology.

Al-Kaisy developed two different capacity models. Data were collected from six long-term reconstruction zones [Al-Kaisy 2003]. The capacity for long-term construction zone was found to be higher than that for short term work zones. This difference in capacity was attributed to the presence of concrete barriers and driver familiarity with the work zone. The models basically adjusted the base capacity value for site-specific conditions. Base capacity conditions were defined as the site condition where all drivers comprise of commuter drivers, passenger cars, daytime light, no work activity, clear weather, right side lane closure, level train with grades no greater than 2 percent, lane width of at least of 3.7 meters.

The study proposed the base capacity as 2000 pcphpl. A PCE of 2.4 was established for level grade. A reduction factor for commuter traffic was established as 7 % for weekdays and 16% for weekends. Reduction of 5% for night construction was established. The reduction for left lane as against right lane was proposed as 6%. The rain caused the reduction in capacity ranging from 4.4 % to 7.8%. The found a significant variability in establishing the effect of intensity of work activity. Their proposed reduction range is from 0.85% to 12.7%.

The study presented two models namely a multiplicative model and an additive model. Multiplicative model established by minimization of sum of squared errors. For additive model, the multivariate regression was used. The researchers after comparing the results of two models and validating them with other models and site observed data proposed multiplicative model as more suitable for estimating workzone capacity. The equation of the model is as follows:

$$C = C_b \times f_{HV} \times f_{d1} \times f_{d2} \times f_w \times f_s \times f_r \tag{3.2}$$

Where:

C = Work zone capacity (vphpl)

C_b = Base (ideal) work zone capacity (pcphpl)

f_{HV} = Adjustment for heavy vehicles (compute using the same HCM 2000 formula)

fd1 = Adjustment factor for off-peak weekday driver population (off-peak= *fd1*, else=1)

fd2 = adjustment factor for weekend driver population (weekend= *fd2,* else=1)

fw = Adjustment factor for work activity (work activity= *fw*, no work activity=1)

fs = Adjustment for side of lane closure (left lanes closed = *fs* , right lanes closed=1)

fr = Adjustment factor for rain (rain= *fr* , no rain=1)

Following values were generated for various factors using optimization techniques:

C_b = 2050, E_{HV} = 2.778, *fd1* = 0.961, *fd2* = 0.825, *fw* = 0.966, *fs* = 0.943, *fr* = 0.976.

Sarasua presented a phase-2 of the earlier study conducted in year 2003 [Sarasua 2006]. The study was about estimating the workzone capacity of freeway short term projects. In the phase-2 of the study, the data was colleted from 12 South Carolina short term workzone sites. Earlier model suggested a base capacity value of 1460 pcphpl. The model was similar as the earlier model proposed by [Krammez 1994]. Equation presented by earlier study is as follows:

$$C = (1460 + I) * f_{HV} * N \quad (3.3)$$

Where:

C = Estimated Capacity of Short-term Workzone (Veh/h)

I = Adjustment for intensity of work (Range +/- 10%)

f_{HV} = Heavy Vehicle Factor

N = Number of open lanes

The Heavy Vehicle factor calculated using equation: = 1 / (1 + (%HV*(PCE-1))

The phase-2 of the study expanded numerically derived relationships and contained analysis of other short-term lane closure configurations including 3-to-2 and 3-to-1 lane closures. The research attempted to determine the number of vehicles per lane per hour that can pass through short-term Interstate work zone lane closures with minimum or acceptable levels of delays.

The research suggested that the passenger car equivalents (PCEs) are different for various speed ranges. Therefore, modified PCEs for various speed groups were applied in calculating capacity in the phase-2 of the research. A model for calculating work zone capacity that incorporates base capacity, PCEs for various speed groups, adjustment factors related to specific work zone characteristics, and number of lanes open through the work zone, is recommended.

The researchers developed the following model in phase -1 of the study:

$$C_{WZ} = (1460 + I) * f_{HV} * N \tag{3.4}$$

Where

C_{WZ} = Estimated capacity of a short-term work zone (veh/h)

f_{HV} = Heavy vehicle adjustment factor

N = Number of lanes open through work zone

I = Adjustment factor for type, intensity, length, and location of work activity.

The model was based on data collected from 23 work zones with 2-to-1 lane closures across South Carolina. As a result of this model the threshold volume of 800 vphpl was increased to 1000 vphpl by the agency. The data collection activity of phase- 2 was conducted after the implementation of the new threshold levels. The data collected with the help of video cameras and radar speed guns. The length of queues recorded manually at these new 12 sites. The analysis of data indicated that the relationship between speed and flow rate appears to follow a multi regime distribution. The study used a procedure to estimate the passenger car equivalence (PCE) value for trucks and recreational vehicles (RVs) by measuring headways. It was found that the PCEs are indirectly proportional to speed (PCE value increase when Speed decrease), up to a certain level as shown in Table 3.1.

Table 3-1 PCE values for Speed ranges

Speed (mph)	PCE Value
0-15	2.47
15-30	2.22
30-45	1.90
45-60	1.90

The difference in PCE values was believed to be due to operating characteristics of trucks in freeway and forced flow conditions. The study suggested that the earlier Greenshields single-regime linear modeling approach for estimating capacity is not as reliable. The data on 85 percentile passenger car volumes suggested the following capacities:

- 2-to-1 lane closures = 1,426 pcphpl,
- 3-to-1 lane closures = 1,280 pcphpl
- 3-to-2lane closures = 1,791 pcphpl

The revised model after the phase-1 of the study has the following shape:

$$C_{WZ} = (C_B + I) * f_{HV} * N \qquad (3.5)$$

Where:

C_{WZ} = Estimated capacity of a short-term work zone (veh/h),

C_B = Base Capacity

f_{HV} = Heavy vehicle adjustment factor,

N = Number of lanes open through work zone, and

I = Adjustment for type, intensity, length, and location of work activity (Range ±10%)

(Value of I should be adjusted by -150 if a double-lane closure is present)

The study suggested that the workzone should be able to pass between 1200 to 1400 pcphpl at capacity flow. The researchers have suggested that the model will also work for long-term work zones.

The researchers have suggested that there are various other important factors such as terrain, work zone activity, and weather etc which are difficult to examine accurately. Existing models cannot yield the required accuracy with limited data available to train the models. Many researchers therefore attempted to estimate the capacity of work zone using the computer simulations.

3.3 Computer Models for Estimating Workzone and User Costs

There are many software packages and computer models available in the market for estimation of workzone capacity and user delay costs. The section reviews couple of popular software packages and a computer model used in the industry.

3.3.1 Queue and User Cost Evaluation of Work Zones (QUEWZ)

QUEWZ is a popular software package developed by Memmott for Texas Transportation Institute [Memmott 1984]. This software package is used for evaluation of freeway work zone lane closures with up to six lanes in each direction and any number of lanes closed in one or both of the directions. It is a menu driven program, which estimates the changes in traffic flow characteristics on freeway segments with lane closures. This software can compute the additional road user costs due to the lane closure.

QUEWZ uses capacity as a key input parameter for calculating queue length, delay and user delay costs. It analyzes traffic flow through lane closures, and help plan and schedule freeway workzone operations by estimating queue lengths and the additional road user costs. The costs are calculated as a function of the capacity through workzones, average speed, delay through the lane closure section, queue delay, changes in vehicle running costs, and total user costs. The planners can use this program to ensure the effectiveness of proposed traffic control plans. The program has few inbuilt default values, which can be changed by the user to best fit the requirements of any specific planning or designing task.

3.3.1.1 Default Values

Unless user specifies otherwise, program uses default values for following:

- Workzone Capacity (Parameters values can be adjusted for capacity)
- Speeds-Volumes relationship
- Cost update factor (Cost adjustment for inflation)
- Percentage of trucks (default value, 8 %)
- Critical length of queue
- Maximum acceptable delay to motorist
-

3.3.1.2 Inputs

The key inputs to this program are:

- Closure configurations (open/closed directional lanes, length of WZ, Capacity)
- Traffic volume approaching the freeway segment (directional hourly volume)
- Schedule of work activities (Start/end time of work activity and lane closures)

3.3.1.3 Outputs

This program has two output options with following components:

- Road User Costs
  - Traffic Volume
  - Capacity
  - Speed
  - Queue length
  - Diverted traffic
  - Hourly Road User Costs (VOC, travel time costs and emission costs)
- Lane Closure Schedule
  - Proposed schedule for lane closure which provides minimum impacts

Studies have suggested calculating the additional detour user cost due to presence of ramps. In that case this program some times not able to provide the accurate estimates.

3.3.1.4 Algorithm

This program uses the HCM 2000 model for short-term work zone capacity. The model uses the following equation to compute the capacity of the work zone:

$$C = (1600 + I - R) * H * N \qquad (3.6)$$

Where:

C = Estimated capacity of workzone (vph)

I = Effect of work intensity (+/- 10% of Base Capacity, default value = 0)

R = Effect of entrance ramps (0 to 160 vehicles; default value is 0)

H = Effect of Heavy vehicles (Default PCE value is 1.7)

N = Number of open lanes through the work zone

3.4 QuickZone

This Excel based software developed by United States Federal Highway Administration (FHWA) for estimation of work zone delay. The full version of this package released in 2005 and the package supports all four phases of the project development process (policy, planning, design and operation). This program is designed to quantify work zone impacts in terms of queues, user delay, travel behavior and costs. The program uses four modules namely, Input Data, Program Controls, Output Data and Open/Save. The maximum allowable queues and delays are calculated as part of the procedure in optimizing a staging/phasing plan and developing a traffic mitigation strategy. The procedure uses the PCE factor of 2.3 and the workzone capacity is fixed as 1200 pcphpl as input parameter

3.4.1.1 Input

The key inputs to this program are:

- Network (Description of Nodes and Links with attributes of Mainline and Detour)
- Project Information (Starting date and duration of the Project)
- Construction Phases Data (Duration and Cost)
- Work Zone Plan (St/End dates, affected links and resulting capacity reduction, mitigation strategies)

3.4.1.2 Output

- Project Delay Summary (multiple and single construction phase)
- Travel Behavior Summary (divides vehicles into one of four travel behaviors)
- Amortized Delay (yearly delay and infrastructure costs)
- Construction Costs and Summary (Costs and summary of inputs and outputs)

3.4.1.3 Algorithm

QuickZone process the information provided by the user as input data and estimates delay and mainline queue growth by comparing travel demand against capacity for every link on an hour-by-hour basis for the life of the project. The new MD-QuickZone provides the user the option to choose from UMCP Model, HCM 2000 or 1997 (discussed above with QUEWZ). UMCP Model used by Kim et al., 2001 has the following shape:

$$CAPACITY = 1857 - 168.1NUMCL - 37.0LOCCL - 9HV + 92.7LD - 34.3WL - 106.1WI - 2.3WG*HV \quad (3.7)$$

Where:

- Number of closed lanes (NUMCL)
- Location of closed lanes (right = 1, otherwise = 0) (LOCCL)
- Proportion of heavy vehicles (HV)
- Lateral distance to the open lanes (LD)
- Work zone length (WL)
- Work Intensity (WI)
- Work zone grade (WG)

The model uses the 1or 0 for medium and 1or 0 for heavy work intensity (WI).

3.5 IntelliZone

IntelliZone is an object-oriented computer model for estimation of freeway work zone capacity, queue length and delay [Xiaomo 2004]. The model operates on an interactive software system, called IntelliZone. This software works on pattern recognition and neural network models incorporating a large number of factors impacting the work zone capacity.

IntelliZone functions consist of following four interaction stages:

- Input (17 parameters for WZ capacity and 4 additional parameters for queue estimation)
- Analysis (Redial and BP neural network model used to estimate workzone capacity)
- Output (3 different types of outputs)
- TMP

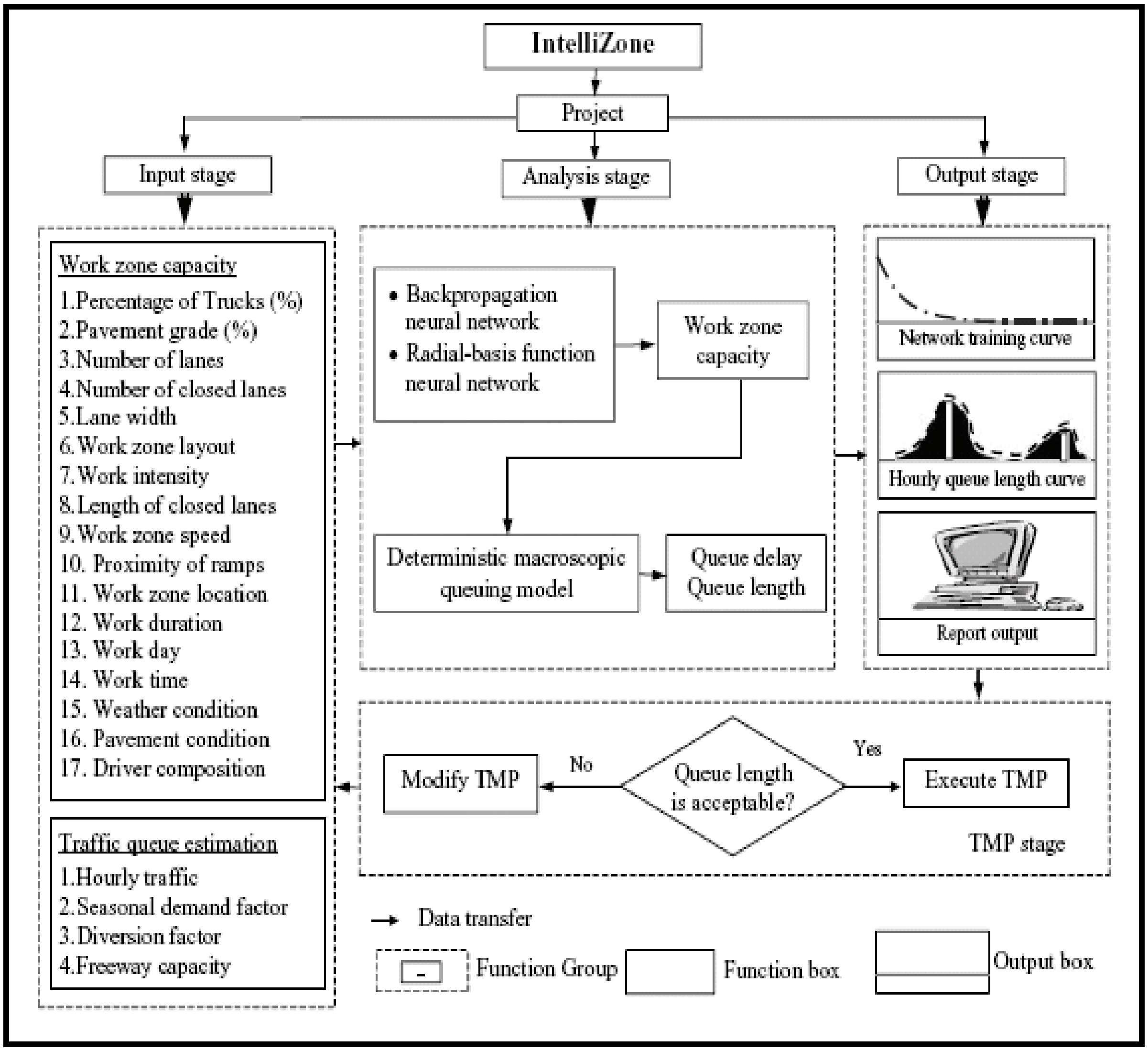


Figure 3-3: Functional Diagram of IntelliZone [Jiang 2004]

Source: *Computer-Aided Civil and Infrastructure Engineering* **(**2004) 144–156

This object-oriented model is an advanced intelligent decision support system for estimating workzone capacity and delay. The model uses IntelliZone software, which has the capability of handling multiple-segment and multiple-traffic flow strategies which can handle varying work zone scenarios. This software provides a highly interactive user interface with the tools for scenario analysis and control of work zone traffic effectively. The software ability to recognize patterns and use if neural networks, enables it accurately estimating the workzone capacity by incorporating large number of factors believe to be influencing the capacity.

Chapter 4
Factors Affecting Capacity

This chapter discusses about various factors believe to be affecting the workzone capacity. The understanding of these factors is important for capacity estimation. There is no consensus among researchers on any standard list of factors. This section presents a non exhaustive list of factors or site characteristics and consolidates them to show which factor(s) are investigated by more researchers. Some of the important factors will be discussed in more detail in the later section of this chapter.

There are wide variety of studies and mathematical models for estimating the workzone capacity. Most of these models apply certain correction factors to the base capacity for establishing the workzone capacity. Base capacity is defined in the HCM as the "Set of specified standard conditions which assume good traffic, weather and geometric conditions with no impediments to traffic flow" [HCM 2000. In reality at most workzone prevailing conditions differ from base conditions, therefore it is necessary to adjust the base capacity by applying the applicable reduction factors that are believe to be affecting the workzone capacity.

As mentioned above, workzone capacity is a function of a several interacting variables called site conditions. Various researchers have discussed wide variety of factors that are believed to be affecting the workzone capacity. They have collected the field data from various workzone and found which factors in work zones are important and are affecting the capacity of workzone. These factors include the geometric, weather, traffic and workzone activity related characteristics which can influence the workzone capacity. Many researchers have attempted to evaluate some of the factors individually and in combination for determining the relationship between various factors and effects of these factors on workzone capacity. Some of the factors can be easily identified and measured e.g. grade of the road, percentage of heavy vehicles etc while others are difficult to quantify, such as driver behavior and intensity of work etc.

This section presents a non exhaustive list of traffic, geometric; weather and workzone activity related factors and briefly explains some of the commonly used relevant factors investigated by various researchers in the estimation of workzone capacity.

1. Heavy Vehicles
2. Lane closure configuration
3. Presence of ramps
4. Width of the lanes
5. Physical barriers
6. Location and type of warning signs
7. Speed limit
8. Grade
9. Light Condition (Day versus Night)
10. Work Zone Configuration
11. Rain
12. Intensity of Work Activity
13. Driver population
14. Number of lanes open through workzone
15. Temporal variation
16. Day of the week
17. Location of closed lanes (Left or Right)
18. Lateral clearance
19. Presence of Police
20. Curvature
21. Length of workzone
22. Work duration
23. Traffic volume
24. Wind speed
25. Type of lane drop

Table 4-1: Factors investigated by various researchers

Factors	Al-Kaisy	Sarasua	Tiwari	Kim	Krammes	Adeli	Karim
	2003	2005	1985	2001	1994	2003	2003
Heavy Vehicle	Y	Y	Y	Y	Y	Y	Y
Driver	Y			Y		Y	
Light	Y					Y	Y
WZ	Y						Y
Weather	Y			Y		Y	
Work Activity	Y	Y	Y	Y	Y	Y	Y
Ramps	Y			Y	Y	Y	Y
Lane Width	Y				Y	Y	Y
Grade				Y		Y	Y
Length of				Y		Y	Y
Work Zone						Y	Y
Work Zone						Y	
Work				Y		Y	
Lateral				Y			
Pavement						Y	

4.1 Important factors Affecting capacity

The above table indicates, none of the studies conducted on the topic have considered all the independent factors; several studies did not include information on key independent factors that might affect capacity reduction in work zones. This section describes the important factors investigated by most of the researchers.

4.1.1 Heavy Vehicle

The HCM 2000 defines heavy vehicles as vehicles that have more than four tires touching the pavement. Trucks, buses and recreational vehicles are the three groups of heavy vehicles [HCM 2000]. The presence of heavy vehicles is believed to reduce the traffic carrying ability of the traveling lanes. These vehicles occupy more roadway space and have lesser operating and maneuverability capabilities than passenger cars. Furthermore, heavy vehicles accelerate and decelerate slowly and their presence makes other drivers in the traffic stream traveling around them more apprehensive. These observations of freeway conditions suggest that these impacts include longer and more frequent gaps both in front of and behind heavy vehicles [Krammes 1986]. Also, the speed of vehicles in the adjacent lanes and their spacing may be affected by these generally slower-moving large vehicles. These factors reduce the overall capacity of the work zone. In-order to accurately estimate and take into account the impact of this factor, researchers has converted the heavy vehicles mathematically into passenger cars with a conversion factor called "Passenger Car Equivalent" (PCE).

The term PCE was first used in HCM 1965 and was defined as "The number of passenger cars displaced in the traffic flow by a truck or a bus, under the prevailing roadway and traffic conditions." Today the definition remains the same as the PCE reflect the number of passenger cars that will occupy the space of these larger vehicles in a traffic stream. This was done by measuring the headway between two vehicles. The headway is the distance from the rear end of a leading vehicle to the rear of a other one. Traditionally, the traffic volume was calculated as vehicles per hour per lane (vphpl). This volume can be converted into passenger cars per hour per lane (pcphpl) by applying the PCE factor which takes into account the impact of heavy vehicles in estimating the capacity. The Highway Capacity Manual (HCM) provides estimates for freeway capacity that are calibrated to a set of conditions labeled as ‘‘ideal conditions’’ or ‘‘base conditions’’ [TRB, 2000]. Among these ideal conditions is the stipulation that the traffic stream is uniform and consists of passenger cars only [Al-Kaisy 2002]. In most instances, prevailing conditions are not ideal and the traffic stream usually contains a mix of different vehicles, i.e. trucks, buses, RVs, and passenger cars. The HCM capacity analysis procedures utilize passenger car equivalents (PCEs) to account for the presence of heavy vehicles in the traffic stream. Using these PCEs, a non-homogeneous mix of vehicles in a traffic stream can be expressed in a standardized unit of traffic. Though essential in carrying out capacity analyses, these PCEs have been the subject of an old and long argument about the definition of equivalency and the basis for deriving their numerical values.

Elefteriadou suggested that the PCE values are typically based on a limited number of simulations and on older simulation models [Elefteriadou 1997]. In addition, the impact of variables such as traffic flow, truck percentage, truck type (i.e., length and weight/horsepower ratio), grade, and length of grade on PCEs has not been evaluated in depth for all facility types. Generally, major differences in PCEs occurred for the longer and steeper grades. There was great variability in PCE values as a function of the weight/horsepower ratio as well as of vehicle length.

Al-Kaisy used an optimized approach to develop the PCE values for heavy vehicles by minimizing the variation in capacity (queue discharge flow rate) measured in passenger cars [Al-Kaisy 2002]. The results suggest that the effect of heavy vehicles is greater in queue discharge (capacity) flow than during free-flow operation. On level terrain, the study suggested PCE value of 2.4 versus 1.5 as provided by Exhibit 23-8 of the HCM 2000. For reconstruction sites on specific grades, the equivalency factors developed by the research (level terrain & 1 km 3% upgrade) and the current HCM PCE's can be used to interpolate an approximate equivalency factor.

Another study conducted by Hall, suggested that the effect of heavy vehicles on traffic is greater during congestion than during under saturated conditions [Hall 2002]. Two sites located in Ontario, were used for the research and a new approach was proposed to quantify this effect by deriving passenger car equivalents (PCEs) using queue discharge flow (QDF) capacity as the equivalency criterion. Results strongly suggest that the research hypothesis is true and that the approach developed by this research is both plausible and feasible. The mean PCE factor at the first site was 2.36 versus 1.5 in the Highway Capacity Manual (HCM) 2000.

Sun presented a study about PCEs within highway work zones that were based upon the speed and the percentage of trucks [Sun 2007. The paper suggested that the PCEs designated for highway work zones have their own distinct characteristics. The 3 dimensional charts were developed (Fig: 4.1) to help identify the PCE value as speed varies given the same percentage of truck traffic or as the percentage of truck traffic changes given the same speed. The study suggested that the "PCE calculated by the simple method (the ratio of the headways) were usually underestimated, while those derived from the normal congested traffic conditions were overestimated. The study claimed that the previous studies only focus on the functions of PCE, regardless of the criteria (speed, density, or volume). Therefore a new method is developed with closed loop calibrations to compute the PCE.

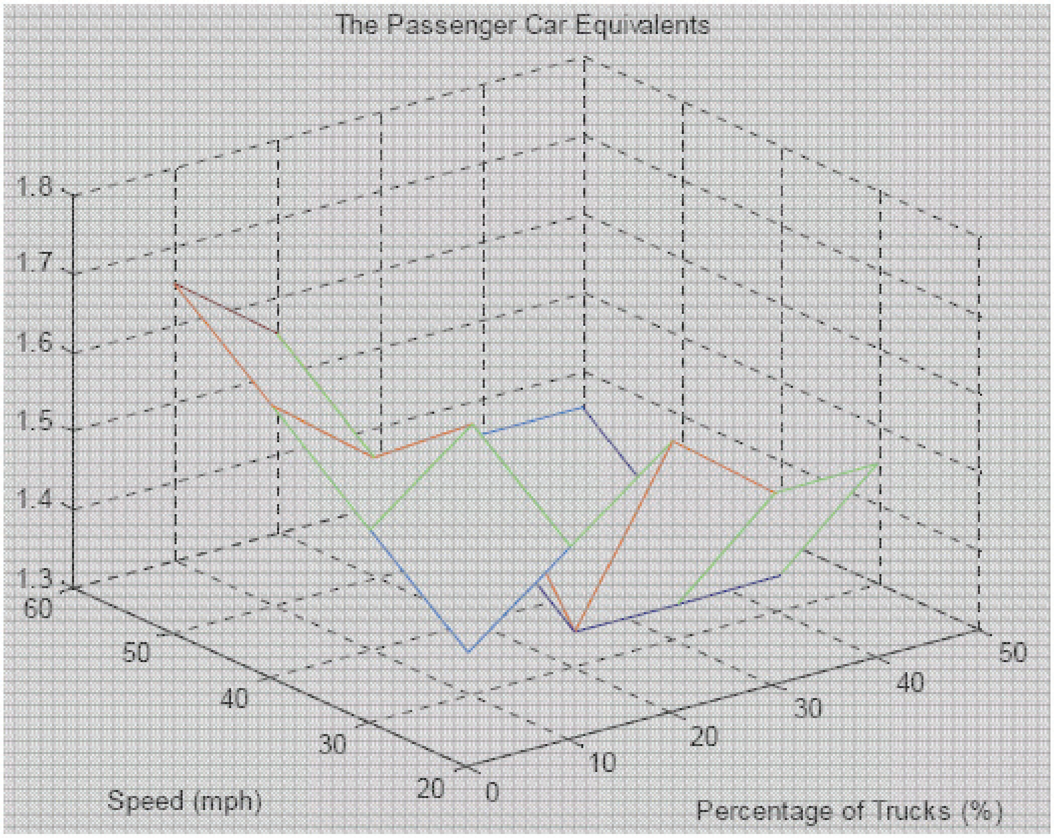


Figure 4-1 PCE for Short-term Workzone

Sarasua used a procedure to estimate PCE by measuring headways from data collected from the 35 work zone sites, investigated PCE variability [Sarasua 2006]. The study suggested that the PCEs are indirectly proportional to speed, up to a bracketed threshold speed. PCE values were calculated for the following ranges:

- Less than 15 mph, PCE for trucks = 2.47
- From 15 to 30 mph, PCE for trucks = 2.22
- From 30 to 45 mph, PCE for trucks = 1.90
- From 45 to 60 mph, PCE for trucks = 1.90

4.1.2 Driver Population

Driver population has a significant impact on the capacity of freeway workzones. The traffic behavior is believed to be different during peak periods and non-peak periods. Peak periods largely consist of commuter drivers having a good familiarity with the driving conditions of a particular road section. Therefore, they can proceed through the work zone with shorter headways, and higher flows. Various studies suggested appropriate adjustment factors to account for the driver population. [Al-Kaisy 2002] investigated some sites in Ontario and suggested that the reconstruction zone capacity was highest during peak hours, i.e. when traffic consists mainly of commuter drivers. The study found that the effect of the driver population factor on the capacity of the reconstruction site was highly significant. The study suggested a capacity reduction of around 7 % during off-peak hours when compared with that during peak hours. Reduction was even higher during weekends, and is around 16% compared to weekdays peak-hours.

Heaslip described that "Research suggests the implementation of a driver familiarity adjustment factor for use in the Highway Capacity Manual work zone capacity equation similar to the factor used in the general highway capacity equation is appropriate [Heaslip 2007]. The value of and thereby the influence of the proposed factor is based on assessment of driver familiarity, driver adaptability, driver aggressiveness, and driver accommodation tendencies that are unique demographic groups defined by locality, region, driver experience, and/or driver age". The study suggested adjustment factors ranges from 0.8 to 1.25 (Table 4.2) based on the data collected from two sites.

Hall in his study refers the driver population as "the mix of driver types in a traffic stream by trip purpose [Hall 2001]. The study conducted to examine the affect of driver population on capacity. Personal attributes such as gender, age, or education are considered beyond the scope of that research. Two categories of drivers are identified: commuters and recreational drivers. Two aspects of driver characteristics are viewed as being related to the trip purpose. The first is the familiarity of drivers with the facility and its environs, which is thought to affect the efficiency of facility use by drivers. The second and less evident aspect is the value of time perceived by drivers for a specific trip purpose and its potential effect on driver behavior and, consequently, on the efficiency of use of a highway facility. Commuter drivers are believed to be the most familiar with the road, and therefore, they tend to use the highways in the most efficient way during their commutes to and from work. On the other hand, tourists (recreational drivers) who are not familiar with the road and the region tend to use freeways in the least efficient way. Drivers for other trips, such as trips for shopping or social purposes, are thought to fall between the two main categories given above in terms of their familiarity with the road and the effect on freeway capacity. Research results confirmed that the driver population factor has a significant effect on the capacity of freeway reconstruction zones". The study suggested that on the basis of a reference factor of 1.0 for commuter traffic, the driver population factor for the afternoon peak traffic was 0.93 and about 0.84 on weekends in both directions of travel.

4.1.3 Light Conditions

In order to minimize the user delays on highway maintenance or reconstructions sites, the construction activities are taking place during nights when the traffic flows are at its lowest. But the darkness has significant effect on workzone capacity. It is therefore important to accurately estimate the affect of darkness on capacity. There are very limited studies available on the topic. Brilon conducted a study to examine the affect of darkness on freeway capacity [Brilon 1995]. The study suggested a range of 13% to 25% capacity reduction on regular freeway sections due to darkness. Few other studies have also attempted to investigate the affects of darkness which lead to poor driver visibility. The range of reduction factor is not consistent among various studies and the literature suggested the traffic planners to use best site judgment in applying the reduction factor. The HCM suggested capacity reduction of 13% and 19% for six and four lane facilities respectively [HCM 2000]. Al-Kaisy suggested that freeway capacity at reconstruction sites decreases during darkness by roughly 5%, for a facility with good illumination [Al-Kaisy 2000]. This decrease was statistically significant.

4.1.4 Work Zone Configurations

Work zone capacity might be affected by work zone configurations such as the number of open and closed lanes and the location of these lanes. It is believed that the per-lane work zone capacity might decrease as the number of closed lanes increases, and it might increase as the number of opened lanes increases. After closure of one or more lanes, the remaining open lane(s) have less capacity than normal lanes due to merging. Various researchers have suggested that the right lane closures result in lower capacity than left lane closures because the right lane generally carries more traffic, resulting in more vehicles merging into the open lane. Kim collected traffic data in seven types of work zone configurations and found that there was significant variation in the range of observed work zone capacities according to the lane closure configuration [Kim 2001. Their regression model shows that location of closed lane was significant to capacity at 5% significant level. Sisiopiku found that a large portion of speed reduction in work zone might be due to the number of open lanes [Sisiopiku 1999]. Al-Kaisy found that in some work zone sites location of closed lanes was significant [Al-Kaisy 2002]. However, in some other sites, it was not significant. The study suggested that this factor could be responsible for a capacity difference of around 6%.

4.1.5 Weather Conditions

Several studies have discussed about the affects of inclement weather on freeway workzone capacity. The Freeway capacity is affected by a variety of weather conditions including rain, snow, wind and fog etc. Al-Kaisy investigated the effect of weather at various sites and suggested that the wet snow, freezing rain were partly responsible for a significant drop in capacity [Al-Kaisy 2000]. They found that the light rain was responsible for a drop in work zone capacity of 4.4% to 7.8% at Sites. Study suggests that more extreme weather conditions could have a greater effect on capacity. The HCM describes that “adverse weather can significantly reduce not only capacity but also operating speeds” [HCM 2000]. The HCM proposed a capacity reduction of 10-20% for weather conditions and suggest that the higher reductions are also possible for severe weather conditions.

4.1.6 Intensity of Work Activity

The intensity of work activity affects the workzone capacity. HCM refers the work activity as the number of workers on site, the number and size of work vehicles in use, and the proximity of work to the travel lanes in use. Various studies suggest that it is very difficult to accurately quantify the affects of work activity as it is more of a qualitative or subjective term. Studies suggest that the base capacity of a workzone may be adjusted by up to ±10 percent for work activity that is more or less intense than normal. But it is also difficult to define what constitutes the normal intensity. HCM, therefore suggests that this factor should be applied on the basis of professional judgment, recognizing that 1,600 pc/h/ln is an average over a variety of conditions.

Al-Kaisy suggested a range of capacity drop from 1.85% to 12.5%. [Chitturi 2004] described that “the work intensity in a work zone is characterized by two main factors: number of workers and construction equipment in the closed lane that is adjacent to the open lanes and proximity of the workers and equipment to the nearest open lane (how far the crew and equipment are from the traveled lane) [Al-Kaisy 2002]. To quantify the reduction in speed due to the work activity, a ratio called the work intensity ratio is developed, which is obtained by dividing the sum of the number of workers and equipment in the active work area in the closed lane by the distance between the active work area and the open lane:

$$WI_r = (w + e) / p \quad (4.1)$$

Where:

WI_r = Work intensity ratio,

w = Number of workers in active work area (varies from 0 to a maximum of 10)

e = Amount of equipment in active work area (varies from 0 to a maximum of 5)

p = Distance between active work area and open lane (ft) (varies from 1 to 9 ft)

4.1.7 Presence of Ramps

Ramps near the work zone reduce the workzone capacity. Studies suggest that ramps within the workzone area have a significant impact on capacity. Krammes suggested that the "work zone capacity can be reduced by the average volume of entrance ramps located within the taper area or within 152 m (500 ft) downstream of the beginning of a full lane closure, but by no more than one half of the capacity of one open lane through the work zone" [Krammes 1994].

The HCM suggest that the "presence of entrance ramps within the taper area approaching the lane closure or within 150 m downstream of the beginning of the full lane closure, the ramp will have a noticeable effect on the capacity of the work zone for handling mainline traffic [HCM 2000]. This arises in two ways. First, the ramp traffic will generally force its way in, so it will directly reduce the amount of mainline traffic that can be handled. Second, the added turbulence in the merging area due to the entrance ramp may itself reduce the capacity slightly. If at all possible, ramps should be located at least 450 m upstream from the beginning of the full closure to maximize the total work zone throughput. If that cannot be done, then either the ramp volume should be added to the mainline volume to be served or the capacity of the work zone should be decreased by the ramp volume (up to a maximum of half of the capacity of one lane, on the assumption that at very high volumes mainline and ramp vehicles will alternate)". The HCM proposed following equation to compute the resulting reduced capacity.

$$ca = (1,600 + I - R) * f_{HV} * N \quad (4.2)$$

Where:

ca = Adjusted mainline capacity (veh/h);

f_{HV} = Adjustment for heavy vehicles

I = Adjustment factor for type, intensity, and location of the work activity (+/- 160 pc/h/ln)

R = Adjustment for ramps, as described in the preceding paragraph

N = Number of lanes open through the short-term work zone.

4.1.8 Lane width

Lane width also has a significant affect on workzone capacity. As per the HCM, this factor decreases the capacity of both short-term and long-term work zones. HCM suggested a decrease of 9-14% for lane widths of 3.0 to 3.4 meters. The base value for lane widths as per HCM is 3.6 meters or greater. Any lane having lesser width than the given base value, result in reduction in the base free-flow speed (e.g., 120 km/h).

4.1.9 Work Zone Grade

Work zone grade affect the capacity and speed, particularly in the presence of heavy vehicles. The HCM provided good material on affect of grades on capacity [HCM 2000]. The manual suggested level terrain with maximum grade of 2% as a base value for capacity calculation. It also indicated that the affect of heavy vehicles in traffic stream is greatly influenced by the grade of the particular road section. It is suggested that the " extended segment analysis can be used where no one grade of 3 percent or greater is longer than 0.5 km or where no one grade of less than 3 percent is longer than 1.0 km." A 3% grade will increase passenger car equivalent factors for trucks from 2.4 to the range of 2.7–3.2. Positive grades have greater impacts if they are located within the workzone area.

Chapter 5

Freeway Workzones and Associated Economic Concepts

There is growing awareness today among transportation agencies in making user delay costs and life cycle cost analysis are an important part of the road construction analysis and the alternative project selection process. The soft costs affect the road construction projects in number of ways. Earlier these costs have not been considered in the planning or design process due to the lack of unified standards in quantifying such costs etc. Now there are some generally accepted methods and tools to quantify such costs on a more reliable basis. This chapter covers some of the pertinent economic topics.

Among nine world regions, North America's urban density is lowest but there is highest number of passenger cars per person. North America is also placed second highest in length of roads per 1000 people in the world. North American also makes the highest number of motorized vehicles trips on the road [UITP 1995]. About 20 percent of the U.S. National Highway System is under construction during the peak summer roadway season. Fifty percent of all highway congestion is attributed to nonrecurring conditions and work zones are estimated to account for nearly 24 percent of nonrecurring delays. Work zones account for two percent of roadway crashes and more than 1,000 fatalities per year [Francis 2008]. These facts and figures accentuate the need for a more serious effort in North America handling these transportation issues innovatively, so as to minimize the impacts of construction. North American agencies need to properly quantify and systematically assess soft costs related to projects, because of the magnitude of the impacts of these costs.

The growing congestion on roads with an increasing need to maintain the already aging road network pose a more complex challenge for agencies to properly account for all the pavement maintenance and reconstruction alternatives wisely. Proper quantification of soft costs would help agencies; quantify the work zone safety and mobility implications of alternative project options and design strategies. This assessment will also help identify the projects with greater work zone impacts so the necessary resources can be allocated more effectively to those projects.

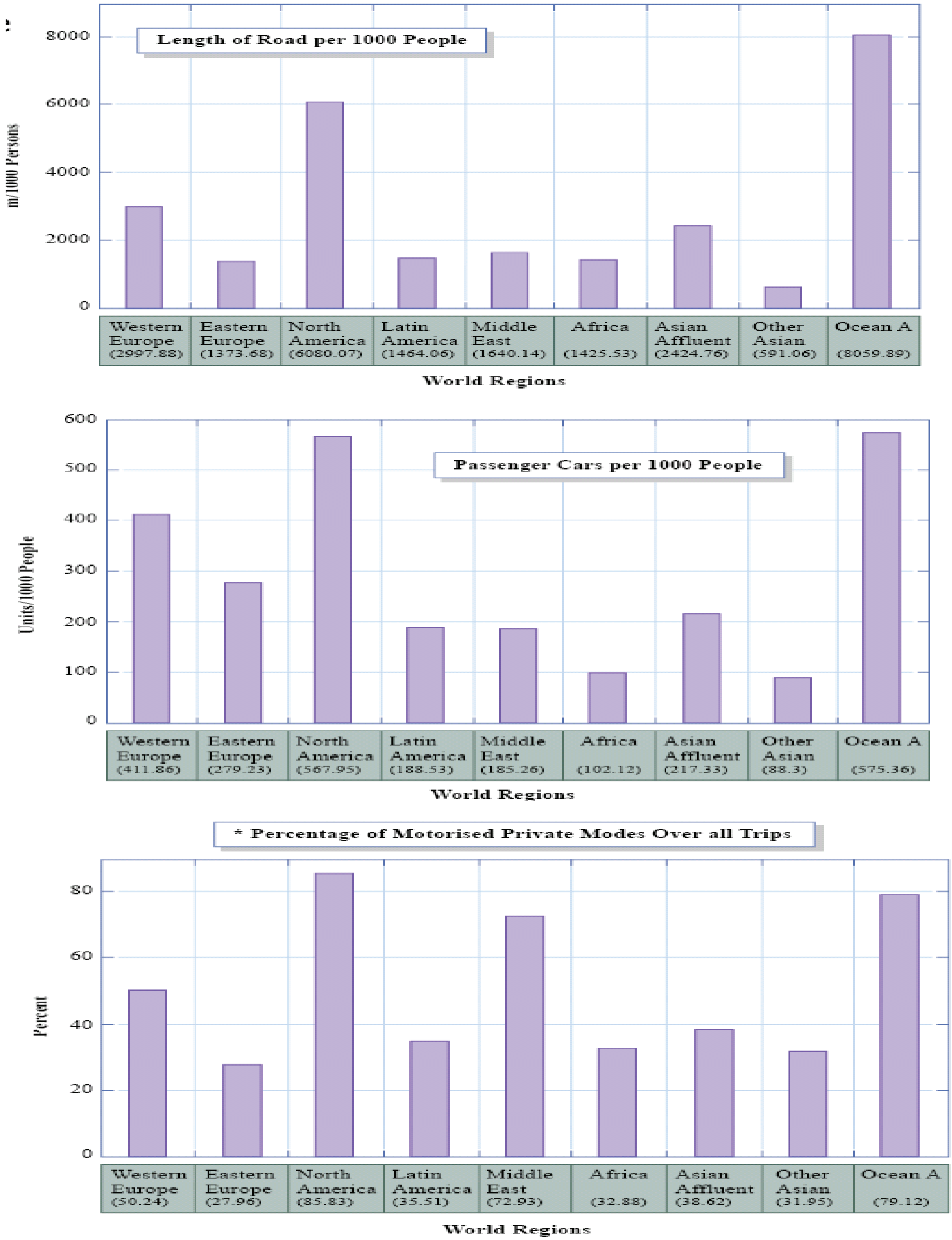


Figure 5-1 World Transportation [UITP, 1995]

5.1 Workzone Impact Assessment

Workzone impact assessment requires an understanding of safety and mobility impacts of construction workzones. The assessment can help agencies identify system deficiencies and develop the solutions to mitigate those deficiencies. The assessment can also serve as a good decision making framework for decision makers in making appropriate adjustments to the traffic management plans to minimize the negative impacts of construction projects. The FHWA has developed a comprehensive document on workzone impact assessment process to help agencies develop policies, processes and procedures for assessing and managing the work zone impacts of road projects throughout the different program delivery stages [FHWA, 2006].

The workzones have significant impacts on a number of sectors including the environment and economy as a whole. The uncertainty in accurately estimating the travel times, impose significant costs to business operations and overall performance of various organizations. These unexpected delays may reduce the marketability of various products hence this uncertainty is more harmful for businesses than the expected lengthy delays. Therefore an increasing amount of research and literature is emerging with respect to tackling the impacts of workzones. One of the major impacts of workzone is on the user delay costs. There are many methods to quantify the user delay costs. One commonly applied measure is to dividing the total delay by the volume of traffic to figure out the average amount of delay encountered by a vehicle traveling through a workzone. These methods however disregard vehicle occupancy, time values and environmental impacts etc.

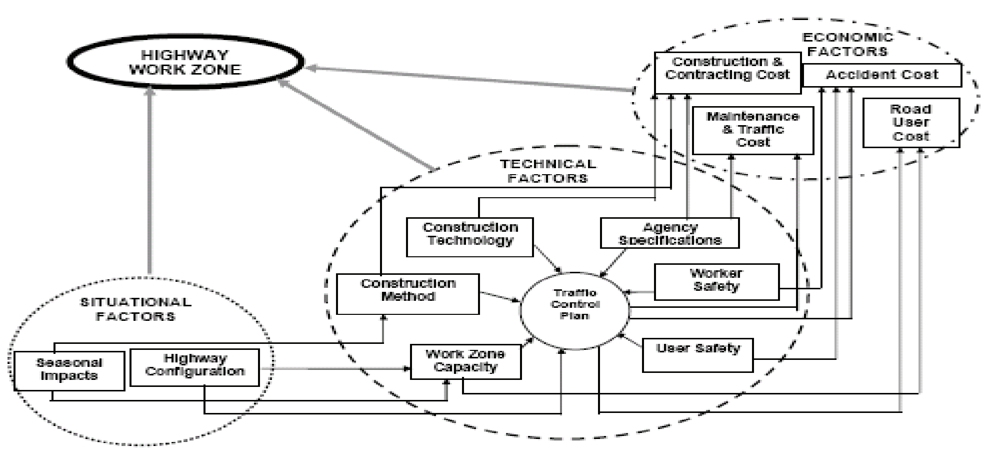


Figure 5-2 Situational, Technical, and Economic factors impacting workzone [Tighe 2006]

Determination of users cost in work zones requires identification of travel delay and queue delay. Travel delay is estimated using the operating speed of vehicles and queue delay is related to queue length and duration. Many studies suggest that the speed and queue values depend on work zone capacity; therefore these studies use capacity as a key input parameter for calculating the queue length, delay, and user delay costs. Due to increasing prices of fuel, the motorists today are more sensitive to delays, since delays cause them extra expenses. Due to these reasons, transportation agencies today are facing increasing pressures to reduce the construction time, so the impact to traveling public and local businesses may be minimized. But it is not easy to accurately estimate or quantify the economic impacts of delays on the economy. The delays caused by workzones not only result in additional user costs traveling through these workzone but it may also affect the businesses in-terms of additional logistics costs, inventory costs, reliability costs, just-in-time processing costs, and reductions in market areas for workers, customers, and incoming/outgoing deliveries [NCHRP 2001].

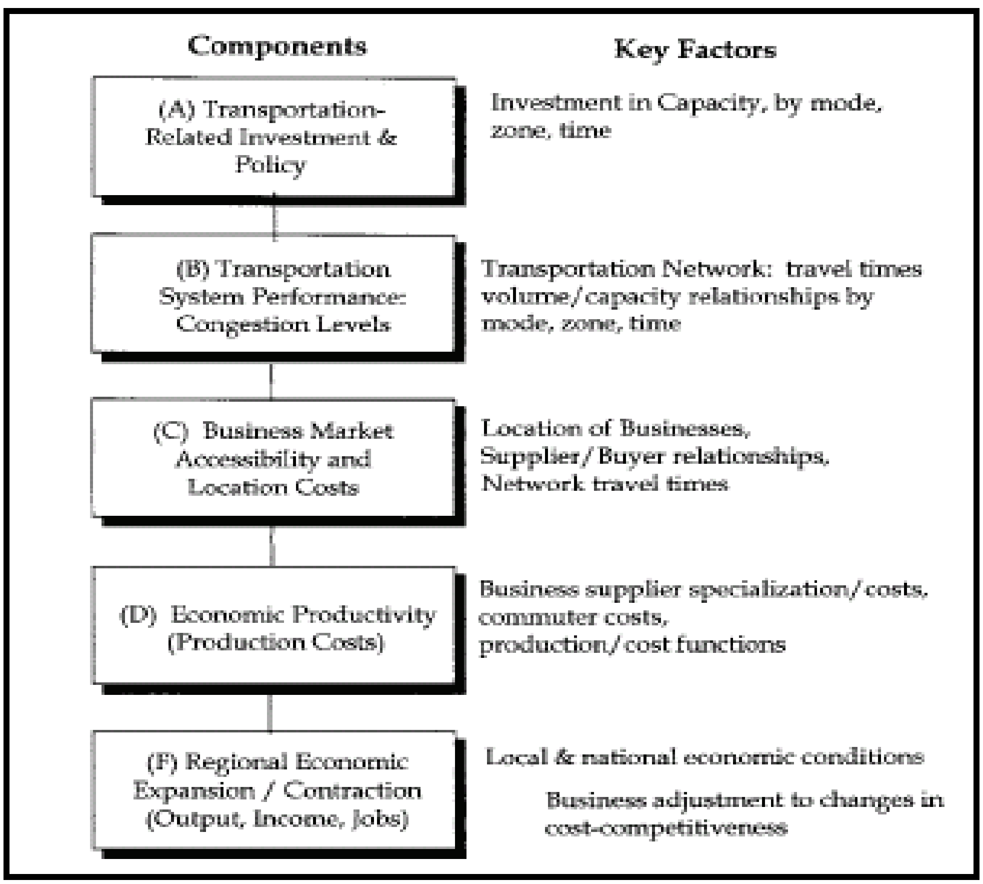


Figure 5-3 Components of the economic impacts of congestion [NCHRP 2001]

5.2 Life Cycle Cost

There is a growing trend for transportation agencies to consider life cycle costs (LCC) of capital assets including initial construction, maintenance and reconstruction of transportation infrastructure. LCC should also include the user delay costs associated with the maintenance and reconstruction processes [Raymond 2000; Tighe 2006]. Life Cycle Cost Analysis (LCCA) is a very good tool for transportation agencies to estimate the pavement maintenance and rehabilitation costs in advance and carryout the economic assessment of different alternatives on the basis of all estimated costs expected over the economic life of each alternative. Therefore LCCA can be used during the design stage to select the most appropriate alternative having the minimum lowest cost of the project over the life span or service life of any project. The idea behind life-cycle cost analysis (LCCA) is that capital investment decisions should be based on costs over the lifetime of the investment, including operations and maintenance, and not just on initial capital cost [Lee 2002]. The lowest long-run cost is not necessarily achieved by the lowest initial capital expenditure, even when future costs are discounted. LCCA is defined as "a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future cost, such as maintenance, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment" [FHWA 1996]. This definition of LCCA has also been used as the definition of "Benefit Cost Analysis (BCA)". The "Benefit–cost analysis (BCA) is a framework for evaluating the desirability of transportation capital and maintenance investments [Lee 2002]. Life-cycle cost analysis (LCCA) has been used for similar purposes, so it may be helpful to compare these two methods for scope and consistency. It is concluded that LCCA is a restricted form of BCA that can be applied in situations where benefits are assumed to be equal for all alternatives. Under these conditions, the project alternative with the lowest discounted cost is preferred. LCC analysis requires conversion of all future costs into present, the one common point in time. Therefore it requires the consideration of time value of money and all future cash flows are discounted back to the present. The formula for adjusting present value is presented as under:

$$PV = [1/(1+r)^t]\, A_t \qquad (5.1)$$

Where:

PV = Present value (present dollars)

r = Discount rate (%)

t = Time (number of years)

A_t = Amount of benefit or cost in year t (future dollars)

An example calculation using formula (5.1) is shown in (5.2) below:

A $1000 benefit ten years from now, using a discount rate of 5% would be worth $614 in-terms of present dollars.

$$PV = \{1/(1+0.05)^{10}\}1000_{10} = \$\,614 \quad (5.2)$$

Consideration of the correct discount rate is very important in terms of economic evaluation of projects, because a higher discount rate will result in lower present value of a future dollar. Benefit Cost Analysis (BCA) compares the discounted value of projects and can be calculated with the following formula:

$$PV = \sum_{t=0}^{N}\left(\frac{1}{(1+r)^t}\right)(Benefit_t - Cost_t) \quad (5.3)$$

Life Cycle Cost Analysis (LCCA) is the subset of BCA and can be used when all design alternatives yield same benefits. The formula for calculating LCCA is as under:

$$PV = \sum_{t=0}^{N}\left(\frac{1}{(1+r)^t}\right)Cost_t \quad (5.4)$$

The definition of LCCA according to the FHWA is“a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future cost, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment” [FHWA 2004]. The procedural steps are defined as:

- Establish alternative pavement design strategies for the analysis period
- Determine performance periods and activity timing
- Estimate agency costs
- Estimate user costs
- Develop expenditure stream diagrams
- Compute net present value
- Analyze results
- Reevaluate design strategies

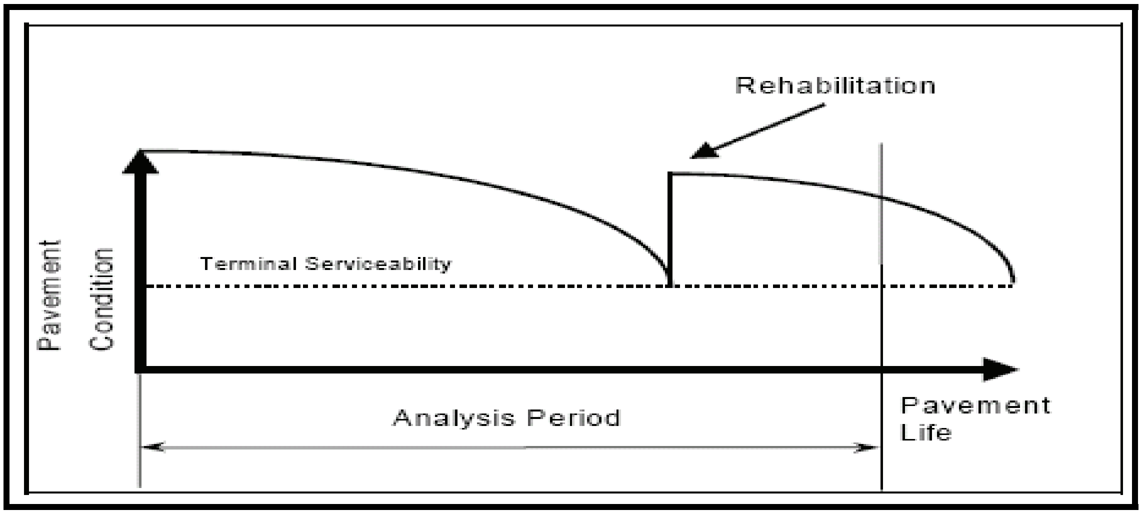


Figure 5-4: Analysis period for pavement design alternatives [FHWA, 1998]

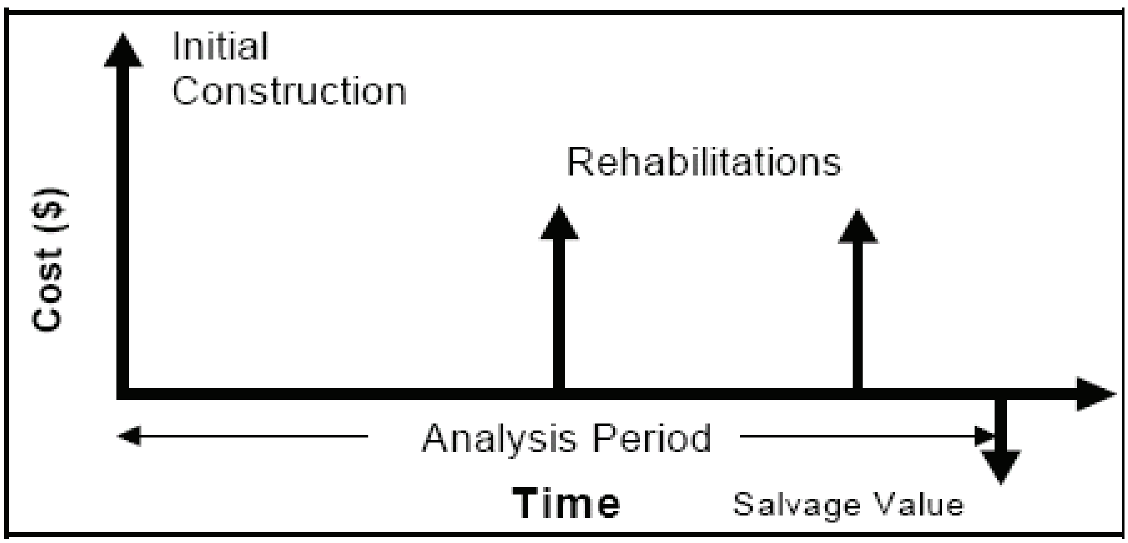


Figure 5-5: Typical expenditure diagram [FHWA, 1998]

Furthermore, LCCA Pavement Design is used to evaluate the long-term economic efficiency between alternative investment options. Economic analysis focuses on the relationship between costs, timings of costs, and discount rates employed. Once all costs and their timing have been developed, future costs must be discounted to the base year and added to the initial cost to determine the NPV for the LCCA alternative" [FHWA, 1998].

Parker presented guidelines for LCCA of public projects. In the final report on the subject the authors talked about the several formats of economic indicators for the analysis of LCCA. The equations of four most common indicators are summarized in Table 5. 1. [Parker 2003]

Table 5-1 Summary of Economic Indicators [Parker 2003]

Eq. No	Indicator	Abbreviation	Equation
1	Net Present Value	NPV	$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+d)^t}$
2	Benefit-Cost Ratio	B/C	$\frac{PVB}{PVC} = \sum_{t=0}^{T} \frac{B_t / (1+d)^t}{C_t / (1+d)^t}$
3	Equivalent Uniform Annual Costs	EUAC	$EUAC = NPV\left[\frac{1(1+d)^t}{(1+d)^t - 1}\right]$
4	Internal Rate of Return	IRR	$\sum_{t=0}^{T} \frac{B_t - C_t}{(1+IRR)^t} = 0$
NPV = Net present value of future costs and benefits, IRR = Internal Rate of Return, B/C = Benefit/Cost PVB = Present value of future benefits, PVC = Present value of future costs d = Discount Rate , t = time of incurrence (year), T = Lifetime of the project or Analysis period (years) B_t= Benefits to be gained at time t, C_t= Costs to be incurred at the time t			

The most appropriate indicators could be any one of the four depending upon the level, context, and degree of uncertainty of some parameters in the analysis. Where the discount rate is uncertain, the appropriate format would be IRR. Similarly for those analyses where the analysis period is not know the preferred choice of indicators would be EUAC. NPV is the most commonly used indictor for a wide variety of analysis scenarios. The NPV is the cost in present dollars considering initial costs and future costs taking into account inflation.

The study also provides the LCCA procedure in following steps:

- Define project's alternatives
- Decide on the approach: Probabilistic vs. Deterministic
- Choose general economic parameters: Discount Rate, Analysis Period
- Establish expenditure stream for each alternative:

- Design rehabilitation strategies and their timings
- Estimate differential agency costs
- Estimate differential user costs
- Estimate differential societal costs

- Compute Net Present Value for each alternative
- Compare and interpret results/ Sensitivity Analysis
- Re-evaluate design strategies if needed.

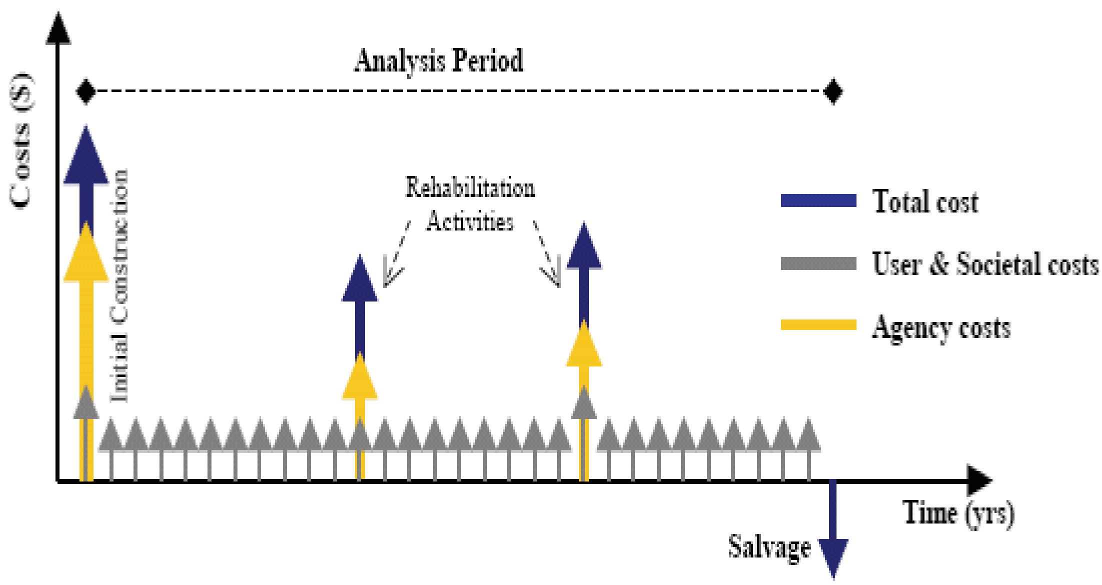


Figure 5-6: Conceptual cash flow diagram of a project [Parker 2003]

The analytical framework of LCCA can account for all the current or future tangible and intangible costs of the alternative projects for the analysis purposes. These costs may be related to the agency costs, user of the facility costs and the social costs. Some of the cost components are difficult to estimate particularly those which are termed as intangible costs. The other costs are real or direct costs called the expenditures and these are easy to estimate. Due to these reasons there was no consensus in transportation agencies in incorporating the standard cost components in LCCA for transportation projects.

5.2.1 User Delay Costs

With the staggering increase in vehicle-miles of travel, motorists are increasingly exposed to work zones. About 20 percent of the U.S. National Highway System is under construction during the peak summer roadway season. Fifty percent of all highway congestion is attributed to nonrecurring conditions and work zones are estimated to account for nearly 24 percent of nonrecurring delay. Work zones account for two percent of roadway crashes and more than 1,000 fatalities per year [Francis 2008]. These figures clearly indicate the need for transportation agencies to consider the user delay costs in the project selection process to minimize the workzone delay. In-order to undertake an effective LCCA with User delay costs included is to account for all the maintenance / rehabilitation costs of a roadway and the additional user costs resulted because of the workzones. Reasonably accurate estimation of frequency and duration of these work zones throughout the life of the project is very important for determining the reasonably accurate economic worth of alternative projects. It is also important to consider all possible competing alternatives for any construction project. The LCCA provides a means of comparing alternative concepts over the life span of projects. This ensures that the most cost effective option for the project is selected.

The LCCA provides a framework for the assessment of workzone operations related costs. This would require a thorough understanding of the User Delay Costs resulting from the construction or maintenance activities of transportation facilities. User delay costs are those additional costs incurred by drivers, industries, businesses and economies as a whole which resulted because of delays caused by the workzones. There are many methods to quantify the user delay costs. One commonly applied measure involves dividing the total delay by the volume of traffic to figure out the average amount of delay encountered by a vehicle traveling through a workzone. These methods however, disregard vehicle occupancy, time values and environmental impacts etc. Determination of users cost in work zones requires identification of travel delay and queue delay. Travel delay is calculated based on non construction operating speed of vehicles and the queue delay is related to queue length and duration. Many studies suggested that the speed and queue values depend on work zone capacity; therefore these studies use capacity as a key input parameter for calculating the queue length, delay, and user delay costs. Due to increasing prices of fuel, the motorists today are more sensitive to delays, since delays directly result in extra expenses. Due to these reasons, transportation agencies today are facing increasing pressures to reduce the construction time, so the impact to traveling public and local businesses may be minimized. However, scheduling maintenance activities, merely in limited off-peak periods, may lengthen project duration and increase maintenance related costs.

User delay costs include the costs borne by the users of the transportation facility and can be divided into following categories:

- Additional Travel Time Costs
- Vehicle Operating Costs (VOC)
- Accidents Costs
- Environmental Costs

There can be an opportunity cost associated with the cost components but due to difficulty in estimating the opportunity costs in workzone scenarios, it is mostly ignored in practice.

5.2.1.1 Additional Travel Time Costs

It is the value of road user's time, having to spend more than normal time at workzone due to reduction in speed and detours. The workzone delay is a result of following [Carr 2000]:

- Speed delay : Due to slower speed of vehicles in the workzone
- Backup delay : Delay due to queues formed at the upstream of workzone
- Diversion delay: Delay due to traveling on detour route around the workzone

This travel time delay can be divided into three categories [FHWA 1998]:

5.2.1.1.1 Speed Change Delay

Time laps between initial speed to workzone deceleration speed and back to approach speed

5.2.1.1.2 Reduced Speed Delay

Time required in traveling through workzone at reduced speed. It depends on the difference between the approach speed and work zone speed, as well as the total distance of the work zone.

5.2.1.1.3 Stopping Delay

Time required to come to a complete stop and then accelerate back to approach speed.

5.2.1.1.4 Queue Delay

Time required driving through a queue [Wilson 2003].

5.2.1.2 Vehicle Operating Costs (VOC)

The VOCs may include the fuel, tires, maintenance, depreciation and other costs resulted from the additional operation that a vehicle has spent in the workzone. VOC has the following sub components [FHWA 1998]:

Speed Change VOC : Due to drop in speed from normal to workzone speed
Stopping VOC : Due to stop position and acceleration again to approach speed
Idling VOC : Due to stop and go situation traveling through queue

5.2.1.3 Accident Costs

These are the costs associated with the workzone related accidents.

5.2.1.4 Environmental Costs

Due to the difficulty in accurately quantifying the environmental costs, most agencies consider the addition of additional travel time costs, vehicles operating costs and accidents costs as the user delay costs. There are various methods in calculating the user delay costs; the following formula is just the simplification of the concept behind user delay costs:

$$RUC = VOC + AC + VOT \qquad (5.5)$$

Where:

RUC = Road User Cost

VOC= Vehicle Operating Cost

AC = Accidents Costs

VOT = Value of Time

Slowing delays result from a reduced traveling speed through the construction area and queuing delays result from traffic backups as a result of traffic volume exceeding the roadway capacity [Raymond 2000]. The first part of the speed delay can be evaluated as the difference between the longer travel time during construction and the normal travel time without construction, with the following equation adopted from the [HCM 1994]:

$$D_S = \left(\frac{L}{V_{(reduced)}} - \frac{L}{V_{(normal)}} \right) \tag{5.6}$$

Where:

D_s = Slowing delay due to reduced speed (hr)

L = Length of the construction zone (km)

$V_{(reduced)}$ = Reduced speed in the construction zone (km/hr)

$V_{(normal)}$ = Normal speed (km/hr)

The second part of the delay caused by queuing can be calculated with the following equations [Raymond et. al 2000]:

$$Q_V = (HV \times CAP) \times t \tag{5.7}$$

$$D_Q = Q_V/CAP \tag{5.8}$$

Where:

Q_v = Volume of vehicles in a queue

HV = Hourly volume of vehicles (vphpl)

CAP = Hourly capacity (vphpl)

t = Time (hours)

D_Q = Queuing delay (hours)

5.2.1.5 MTO procedure of calculating User Delay Costs:

Ministry of Transportation Ontario (MTO), GDM Chapter-B 2002 provide the nine step procedure (exhibit B7-6) for calculating the queue and delay for each hour of analysis period [MTO 2002]. Some of values used in the analysis are as under:

- Base capacity of short term workzone = 1600 veh/h/lane
- Adjustment to capacity:
  - Intensity of work activity (+/- 10%)
  - Presence of Ramp (+/- 50% of lane capacity for ramp within 450 m of lane closure)
- Vehicular length = 7.5 m (Basic vehicular length)
- Delay Cost

- Passenger Car = $10/h/veh

- Heavy Vehicle = $50/h/veh

- Mixed Traffic = $15/h/veh

The analysis has the following steps:

Table 5-2 Steps for calculating UDC [MTO 2002]

Calculation required	Information Required
Workzone Capacity	- Basic Capacity - Number of Lanes at Workzone - Intensity of Construction Activity - Presence of Interchange On-Ramp
Queue(Veh)	- Traffic Volume - Percentage of Heavy Vehicle - Workzone Capacity
Hourly Delay (Veh-h)	- Queue
Total Vehicle Delay (Veh-h)	- Hourly Delay
Last in Queue	- Queue - Traffic Volume - Workzone Capacity
Total Affected Vehicles	- Traffic Volume - Last in Queue
Average Vehicle Delay (min)	- Total Vehicle Delay - Total Affected Vehicles
Queue Length	- Queue - Number of lanes upstream of - Vehicle length
Delay Cost	- Total Vehicle Delay - Hourly Delay Cost

Step 1: Determine Workzone Capacity

$Capacity_{WZ} = (Capacity_{BL})\ (N)\ (I)$ (5.9)

Where:

$Capacity_{WZ}$ = Workzone Capacity (veh/h)

$Capacity_{BL}$ = Base capacity (veh/h/lane)

N = number of lanes open through the short-term work zone

I = Adjustment for intensity of work activity

When actual capacity is not available, the estimated capacity can be calculated as under:

$Capacity_{WZ} = Capacity_{BL}\ (N)$ (5.10)

Step 2: Determine Queue:

Determination of queue requires conversion of heavy vehicle mathematically into passenger car units through the use of Passenger Car Equivalent (PCE) factors. Adjustment for heavy vehicles can be calculated based on PCE values for various terrain scenarios as under:

Table 5-3 Passenger-Car Equivalents for Freeway Segments

Factor	**Terrain**		
	Level	**Rolling**	**Mountainous**
ET (Trucks and Buses)	1.5	2.5	4.5
ER (RVs)	1.2	2.0	4.0

Adjustment for Heavy Vehicles (f_{HV}) can be calculated using the following equation:

$f_{HV} = 1 / \{1+P_T(E_T-1)+ P_R(E_R-1)\}$ (5.11)

Where:

f_{HV} = Adjustment factor for heavy vehicle

P_T = Proportion of Trucks, expressed as a decimal

P_R = Proportion of RVs, expressed as a decimal

E_T = Passenger-car equivalent for Trucks

E_R = Passenger-car equivalent for RVs

The equation for converting the truck volume into PCE value is as follows:

$V_{arrival} = (V_{truck} / f_{HV}) + V_{car}$ (5.12)

Where:

$V_{arrival}$ = Arrival rate with PCE for truck volume (veh/h)

V_{truck} = Truck Volume (veh/h)

f_{HV} = Heavy Vehicle adjustment factor

Vcar = Passenger Car Volume

The equation for determination of queue is as under:

$Q_t = V_{arrival}$ - CapacityWZ + Q_{t+1} (5.13)

Where:

Q_t = Queue (veh) for t hour when $V_{arrival}$ is greater than $Capacity_{WZ}$

$Capacity_{WZ}$ = Workzone capacity (veh) for t hour

$V_{arrival}$ = Arrival rate with PCE for truck volume (veh/h) for t hour

Q_{t+1} = Queue (veh) for the previous hour (If Q value is negative, set 0)

Step 3 & 4: Determine Hourly Delay and Total Delay:

Hourly Delay = (Q_t - Q_{t+1})/2 (5.14)

Where:

Hourly Delay = Vehicle delay (veh/h) while in queue in t hour

Total Delay = Σ (Hourly $Delay_t$) (5.15)

Where:

Total Delay = Total hours vehicles delayed for analysis period

Hourly $Delay_t$ = Vehicle delayed (veh/h) in t hour

Step 5: Determine Last in Queue:

It is the value denoted as the theoretical number of vehicles anticipated to face queuing delay during the last hour that queue delays are experienced.

Last in Queue = [(Q_{t+1} + $V_{arrival\ for\ period\ t}$) ($V_{arrival\ for\ period\ t}$)]/ $Capacity_{WZ}$ (5.16)

Where:

Last in Queue = Final vehicle experiencing queue in the last period when Q=0 for t hour (veh)

Q_{t-1} = Queue (veh) for t-1 hour

$V_{arrival\ for\ period\ t}$ = Arrival rate with PCE for truck volume (veh/h) for t hour

$Capacity_{WZ}$ = Workzone capacity (veh) for t hour

Step 6: Determine Total Affected Vehicles:

Total Affected Vehicles = Σ ($V_{arrival}$) + Last in Queue (5.17)

Where:

Total Affected Vehicles = Vehicles experiencing queue (veh)

$V_{arrival}$ = Arrival rate with PCE for truck volume (veh/h) when Q>0

Last in Queue = Final vehicle experiencing queue in the last period when Q=0 for t hour (veh)

Step 7: Determine Average Vehicle Delay:

Average Vehicle Delay = {(Total Delay) (60)}/Total Affected Vehicles (5.18)

Where:

Average Vehicle Delay = (min.)

Total Delay = Sum of hourly delay for the analysis period (veh-h)

Total Affected Vehicles = All vehicles experiencing queue (veh)

Step 8: Determine Queue Length:

Queue Length = (Q_t)(L)/ (1000)(N) (5.19)

Where:

Queue Length = (Km) for t hour

Q_t = Queue (veh) for t hour

L = Vehicle length (m)

N = Number of lanes upstream of workzone

Step 9: Determine Delay Cost

Delay Cost = (Total Delay)[(%Truck)($Cost_t$)+(1-%Truck)($Cost_{pc}$)] (5.20)

Where:

$Cost_t$ = Delay cost for trucks ($/hr)

$Cost_{pc}$ = $_{Delay}$ cost for passenger car ($/hr)

When the % Truck is not known, the procedure suggests using the following equation:

$$\text{Delay Cost} = (\text{Total Delay})\ (Cost_{mixed}) \quad (5.21)$$

Where:

$Cost_{mixed}$ = Delay cost for mixed traffic ($/hr)

5.3 Highway Development and Management (HDM-4)

The Highway Development and Management (HDM-4) tool is the extension of the earlier Highway Design and Maintenance Standards Model (HDM-III) which was developed by the World Bank in 1994 to provide system of combining the technical and economic appraisals of road projects. It is a decision support system to analyze various investment alternatives of road projects. This software and has the analysis, documentation and presentation features that help agencies in justifying the increased road maintenance and rehabilitation budgets. Various world organizations use HDM-4 as road investment appraisal method for different environments and conditions. The model has the reputation of providing the reasonable results if calibrated properly for local conditions.

The HDM-4 has the features to analyze the effects of traffic congestion on speed and impacts of road maintenance and construction work on road users. It also takes into account the road user effects (RUE) and has the modeling capability for estimating the delays and length of queues based on the length of workzones. The HDM-4 provides the mechanistic models of road deterioration and maintenance. It also provides the Vehicle Operating Costs (VOC) models for various regions. The new model has the capability of determining the total transportation cost of alternative strategies. The scope of HM-4 covers the following:

- Network strategy analysis
- Programming and budgeting
- Project Analysis
- Research Applications

The model requires calibration to work appropriately for different regions and environments.

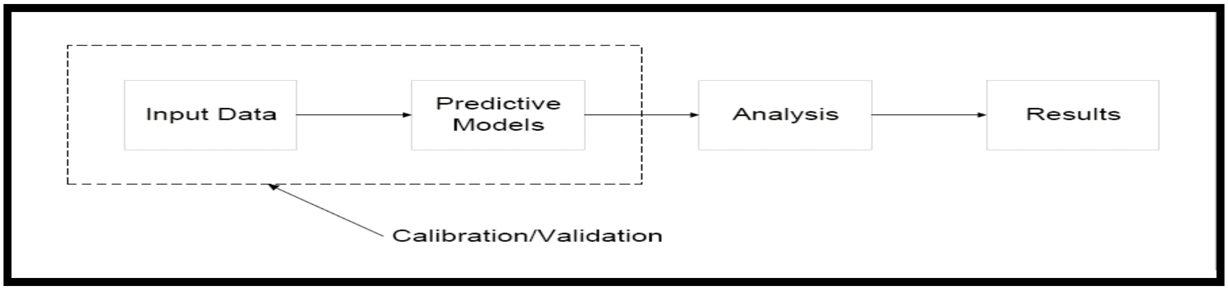


Figure 5-7 Analysis steps [Bennett 1998]

The application of HDM-4 covers the following functions of highway management process:

- Planning
- Programming
- Preparation
- Operations

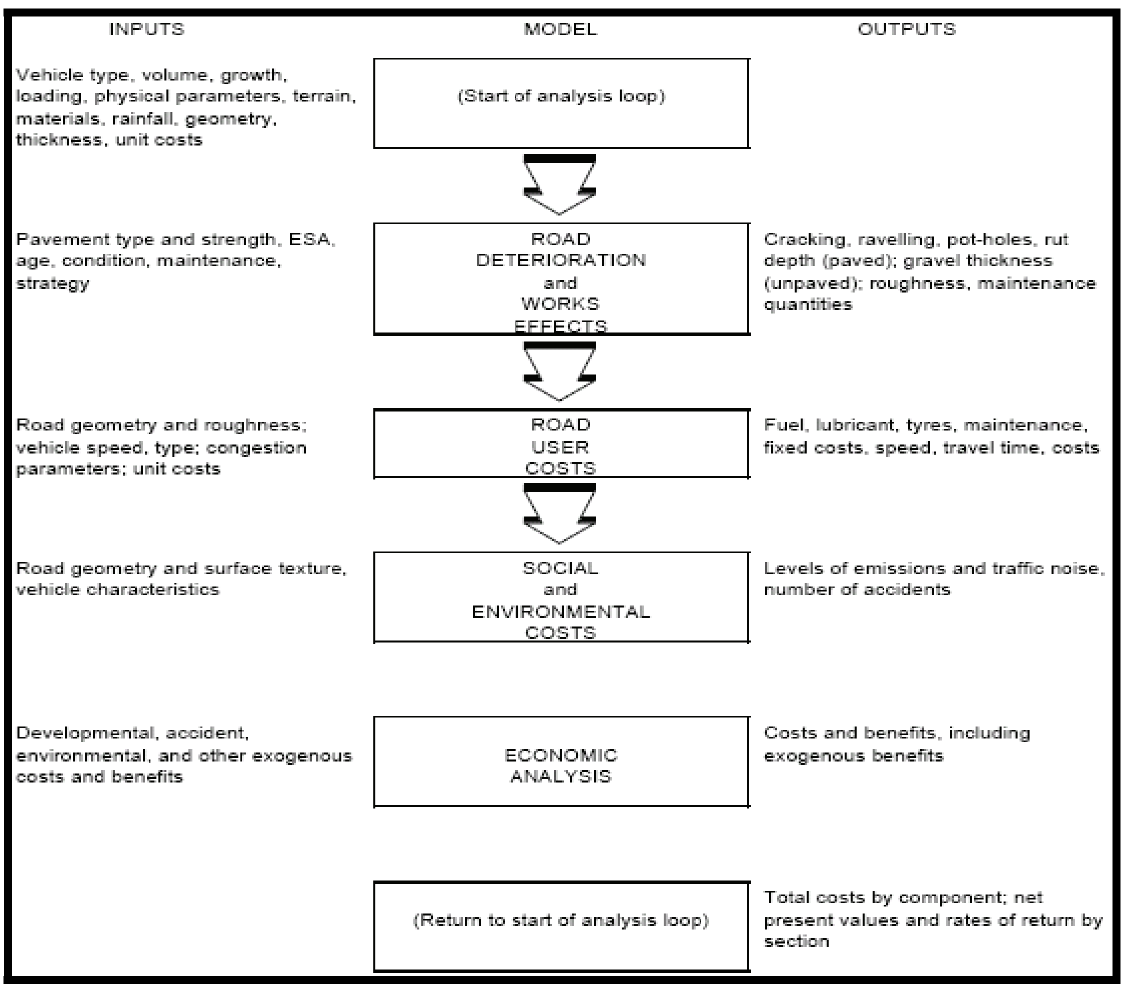


Figure 5-8: HDM -4 Approach [Bennett 1998]

The analytical framework of HDM-4 is designed on the concept of pavement life cycle analysis. The accuracy of results depends on the quality and detail of calibration activity performed on the default models to suite the local conditions. The model covers the following road user cost components:

- **Vehicle Operation Costs** (fuel, tires, oil and depreciation etc.),
- **Costs of travel time** (Passenger and Cargo)
- **Road accidents cost to the economy**
- **Social and Environmental Cost**

The HDM-4 provides the ability to calculate economic benefits of various road investments alternatives or options for a user-defined analysis period. The future costs are discounted to the base year for the economic analysis.

Chapter 6
Methodology and Data Collection

This chapter discusses the five step methodology for estimating the workzone capacity. The first three steps of the methodology will be covered in detail in this chapter while the next two steps will be covered in the next two chapters.

Our road network is reaching a middle age and requires more maintenance and reconstruction work hence there are more work zones. These work zones disrupt traffic flow as they reduce the number of lanes for traffic. This reduction in the traffic carrying ability of traffic lanes lead to traffic congestions that has serious social, economical and environmental implications. The vehicles traveling through the workzones require additional travel time and effort to traverse through the workzones. Changing driving maneuvers result in excess costs to motorists in terms of time, fuel consumption, and wear and tear of vehicle parts.

Transportation agencies are therefore under enormous pressure to deal with growing congestion problem while facing the increasing need to perform rehabilitation and reconstruction work on existing roads. The multifaceted challenges for the agencies are forcing them to compress schedules, finish projects early, while performing the work at night and maintain the safety and mobility of traffic at all times. This can be achieved by developing optimized workzone strategies to reduce total cost, construction time and impact of work zone on throughput.

Like many other North American agencies, the Ministry of Transportation Ontario (MTO) is utilizing conservative lane closure strategies and standards. The lane closure strategies should weigh the impacts of construction duration and inconvenience to the road users and find out the balance where users face minimum inconvenience while contractors get appropriate time to finish the work productively. This desired balance can be achieved if demand does not exceed the road capacity at all times. It is therefore important to accurately estimate the capacity so as to decide about the most appropriate time and method for lane closures. These capacity estimates can help in determining the optimized time for lane closure to minimize the user delays while providing the sufficient time to contractors in achieving the desired productivity and quality.

In-view of the above, Ministry of Transportation Ontario has embarked upon a research project under the Highway Infrastructure Innovation Funding Program 2007 to evaluate the existing workzone capacity estimation methods for suitability on Ontario setups. The study will attempt to estimate the capacity of freeway workzones and discuss about the associated user delay costs issues. For this study, it was decided to conduct the manual counting of volume data. This would help provide the visual confirmation of queuing and intensity of work activity at workzones.

Having acquired a wide range of data from diverse sites, the next steps of the project involve analysis, model creation and model validation. A general overview of this process can be seen in Figure 6.1, which had been adapted from Meyer and Millers book, "Urban Transportation Planning".

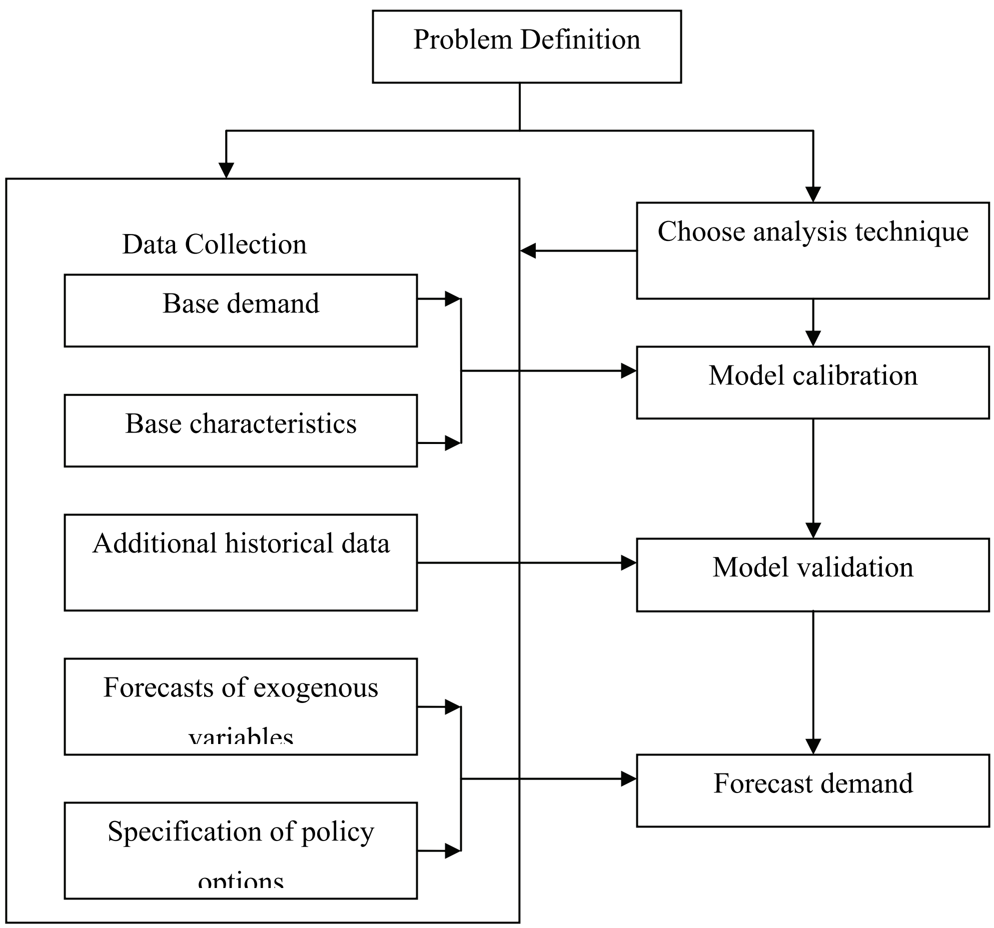


Figure 6-1 Demand Analysis Process [Meyer 2001]

This figure shows a problem definition, which in the case of this project is determining the capacity of highway work zones. After having chosen to use on-site data collection to determine the analysis, the project was able to determine both the demand and site characteristics of high work zone projects. The next step of this project can be seen in Figure 6.1 as the "Model Calibration" stage. Once this is completed, it can be compared to historical data for highway capacity in order to validate the model. Finally, this model can be applied to Ontario roads to help forecast how the lane will behave under different conditions.

By using the system described above, the model will give MTO a tool that can be used to determine the capacity of Highway Work Zones. Knowing this information will prove to be useful in a number of different ways. First and foremost it will help determine appropriate lane closure times. Additionally, this work will provide data to the database of Ontario road systems, which can be used in future studies. Finally, by understanding the capacity of workzones, the costs associated with user delay can be evaluated.

6.1 Major steps

The five major steps adopted for the project are discussed below:

6.1.1 Selection of Sites

The Ministry of Transportation Ontario (MTO) have provided the list of sites that meet the conditions of this research i.e. are on a major highway and experience congestion regularly. It was expected that the locations will likely be 400 series and other King's Highways in Southern Region as these have the greatest traffic volumes [MTO 2004].

Table 6-1 2004 Highway Distance (km) by Designation [MTO 2004]

Designation	Length (Km)	% Of Total
Freeways (King's Excluding Hwy 407)	1,744.1	10.5
Other King's Highways	9,833.0	59.3
Secondary Highways	4,802.4	29.0
Tertiary Roads	201.4	1.2
Totals	**16,580.9**	**100.0**

Ministry of Transportation (MTO) provided the list of 30 projects to project team for data collection in August of 2007. The projects were selected based on their availability within the timeframe of the assignment and suitability with project objectives. MTO's criteria for site selection were based on the following suitability criteria:

- Sites with extended lane closure: Longer than just for periodical movement of machinery
- Presence of partial lane closure: Reduction of traffic lanes (i.e 2-to-1, 3-to-2 or 3-to-1)
- Adequate amount of traffic demand

A list of 30 sites provided by the Ministry of Transportation (MTO) for the data collection purpose for this project. The list also includes the contact information of the Contract Control Officers (CCOs) and a brief description of work. There were equal number of short-term workzones (shave & pave contracts) and long term workzone (reconstruction sites) selected for this project by MTO. The sites were located in southern Ontario region.

Since the project team was comprised of two Research Assistants, it was decided to distribute the sites on the basis of geographical proximity. The sites were then divided into two areas located near the eastern part of the region and the western part of the region for the ease of Research Assistants to coordinate and visit the sites in a stipulated time.

The lists of short-term and long-term sites received from MTO are provided in tables 6.2 and 6.3.

Table 6-2 Short Term Sites (Shave and Pave Projects)

S.N	Location	Hwy	Dir.
1	20 m east of Simcoe Rd. 10	9	E/B
2	Bullnose at 407 to 407 structures. At Steels Avenue.	400	N/B
3	407 Structure to just North of Hwy 7 (Core)	400	N/B
4	1.3 Km South of Hwy 9 for 1.0 Km	400	S/B
5	Deceleration lane. Lower Big Chute to N of flyover	400	N/B
6	Quarry Rd. Bt Taylor Docks from end of last patch N.	400	N/B
7	100 m E of Whites Rd. bridge structure. Express	401	WB
8	Bullnose Westerly on Hwy 2A to W of 401-Collector	401	WB
9	Markham Rd. to 1st bridge joint of Markham Rd.Br.	401	EB
10	Birchmount to Victoria Park Br. Express	401	WB
11	404/DVP to 1st Br. Joint at Leslie St. Collectors	401	WB
12	Lane 1 & 2 from 3 to 4.1 Kms East of Guelph Line	401	EB
13	Rouge River St. to Maj. Mackenzie. S of M.Mack & 404	404	NB
14	Niagara Region from Mountain Road to Hwy 420	QEW	SB
15	QEW from Thorold Stone Rd. to Mountain Rd.	QEW	NB

Table 6-3 Long Term Sites

S.N	Location	Hwy	Dir.
1	Hwy 6/York Rd I/C. Hwy 403 to Hwy 5 (Hamilton)	6	N
2	1 Km N of RR 24 N'ly to 1Km S of H9(Orangville)	10	S
3	S.Jct of H48 to S of Beaver River Br (Beaverton)	12	S
4	From N of Whites Creek Br. To N. Jct. Hwy 48	12	N
5	Park Rd. to H 35/115 and Stevenson Rd. (Oshawa)	401	E,W
6	Avenue to Leslie St. transfer EB Collectors	401	E
7	Westney to Salem Rd- 410 EB & WB (Ajax)	401	E
8	From Wilson to King St. (Oakville)	403	
9	Hwy 401 to QEW SB Exp. Lanes, Toronto	427	S
10	Glendale Rd. to Mountain Rd. (Hamilton)	QEW	S
11	Red Hill Creek I/C (Hamilton)	QEW	
12	QEW/Hurontario I/C (Mississauga)	QEW	W
13	Price Corners to Coldwater, Simcoe Country	12	
14	Grand River to Fergus Avenue, Kitchener	8	N
15	Waterloo Rd. 1 to Waterloo Rd. 5, New Hamburg	7	E,W

6.1.2 Coordination for site access

Since all sites were working sites, it was important to discuss all the safety protocols with the site supervisors and coordinate about the site visits well in advance. This would followed by gaining the permission from relevant personnel to access each site.

After receiving the list of project sites from MTO, the project team started contacting the Contract Control Officers (CCOs) for site visits. The CCOs of all the sites were contacted to confirm the work schedule, accessibility issues and mobilization methodology. Since all the sites were active work sites, it was important to determine availability of a safe location for data collection with a clear line of site. As an agreed technical requirement, it was decided to collect traffic data at the end of taper area. While all of the sites suggested by MTO were evaluated, only some of them were deemed appropriate for a site visit. It should be noted that this was not a straight forward task as many of the contacts provided by MTO were not always prompt at returning calls and keeping the research team up to date. This resulted in several sites finished the work without visits. However, regardless of these experiences, good quality data was collected and this is described herein.

6.1.3 Data collection

As mentioned above, it was decided for this study to conduct the manual counting of volume data using 15 minute intervals during the congestion periods. While manual counting vehicles may not be the most efficient method, image recognition software or roadside radar equipment are expensive, vulnerable to technical problems, and not available to the Principal Investigators. A digital camera was used to capture traffic congestion conditions to confirm the data collection methods used in the field. The manual method would also help provide the visual confirmation of queuing and intensity of work activity at workzones.

For this study, the capacity at work zones was measured as the mean queue discharge flow rate during forced-flow conditions. Forced-flow conditions were defined as congested conditions during which a sustained queue formed. Queued conditions were identified as stop vehicles or slow moving traffic with about 10-20 km/h. Results from previous studies have indicated that once a traffic queue forms at a work zone, the maximum flow occurs at the end of the merge taper [IBI 2007] therefore it was decided to count the traffic volume passing the end of the taper during queued conditions.

The data collection activity requires collecting the data at each site for 2-3 days while some through lanes are closed for work. Site characteristics form was developed for recording of site data for this project.

While all of the sites suggested by MTO were considered, only some of the sites were deemed to be appropriate for a site visit. This was either based on the construction schedule, timing, availability and/or whether queuing was present. Nine sites provided data with sustained queuing condition. The remaining sites did not provide any data due to absence of forced flow condition. On an average about three days were spent on each site collecting data. Manual methods were used for data collection, using 15 minute interval counts during congestion periods. A digital camera and camcorder were used to capture traffic congestion conditions and for later use once back in the office. Apart from the traffic data, the site characteristics were also recorded in the site characteristics form that was developed as shown in Table 6-5. Some sites photos and video were also taken to provide useful information to study.

6.1.4 Data Analysis

The collected traffic data and site characteristics details were analyzed for estimation of the freeway workzone capacity. Capacity analysis includes establishing the mean traffic density values at the peak times with 95% confidence interval. The regression analysis tools and some of the well known models were used to estimate the capacity values for each site. Testing the model provided into the impact of independent variables on capacity. At all work zones visited, traffic, weather and geometric characteristics of the sites were recorded on the site characteristics form. Site characteristics varied drastically from location to location. Of the information recorded, the most vital to this study were the number of traffic lanes of the highway and the number of traffic lanes that remained open during the construction. Data were recorded on sites with 2 lanes narrowed to 1, 3 lanes narrowed to 1, 4 lanes narrowed to 2. There are a number of other elements recorded in site characteristics that will provide useful information to this study. Based on the model used to analyze traffic flow and user costs, additional information will be taken from these data sheets. Completed site characteristics forms along with the maps of sites and recorded volume data can be found in later part of this document.

Table 6-4 Site Characteristics Form

Date	
Hwy No:	
Location	
Weather	
Starting Time	
End Time	
Day of Week	
Time of Day	
Assigned Lane	
Lane Width (m)	
Direction of Traffic	
Shoulder Type	
Lane Closure	
OPP Presence	
Time of OPP Presence	
Facility Type	
Driver Population	
% Heavy Vehicles	
Grade of Road	
Speed Limit (km/hr)	
Curve of Road	
Length of Work Zone	
Duration of Closure	
Interchange	
Type of Traffic Control	
Pavement Condition	
Distractions	
Other Comments	

Chapter 7
Data Analysis

The data that was collected for Sites that exhibited the desired characteristics, the volume of vehicles traveling through the zone were recorded and have been used for analysis in the thesis. These vehicles were categorized into Passenger Vehicles and Heavy Vehicles. In addition to this information, other raw data such as speed, site characteristics and other pertinent information was recorded. This chapter presents the analysis of the raw data collected on each site to create a model for Workzone Capacity.

Data was collected at 15 minutes intervals whereby vehicle were counted in-terms of Passenger Cars per hour per lane (pcphpl) and the Heavy Vehicles per hour per lane (hvphpl). Initially the heavy vehicles were assigned a PCE (Passenger Car Equivalent) of 2.0 and than the total volume was calculated. Subsequently regression analysis was performed with the PCE values of 1, 1.5, 2, 2.5 and 3. The calculated information was then used to create a graph to figure out the PCE value with lowest error. After these regressions were complete the model with the lowest percentage error was chosen.

Although the data were collected from seventeen different sites, after detailed review of the data and site characteristics following sites were considered appropriate for data analysis having met most of the suitability criteria of this project. The following sections describe the Site Characteristics and data analysis of these sites. Detailed information on these sites is found in Appendix A to R.

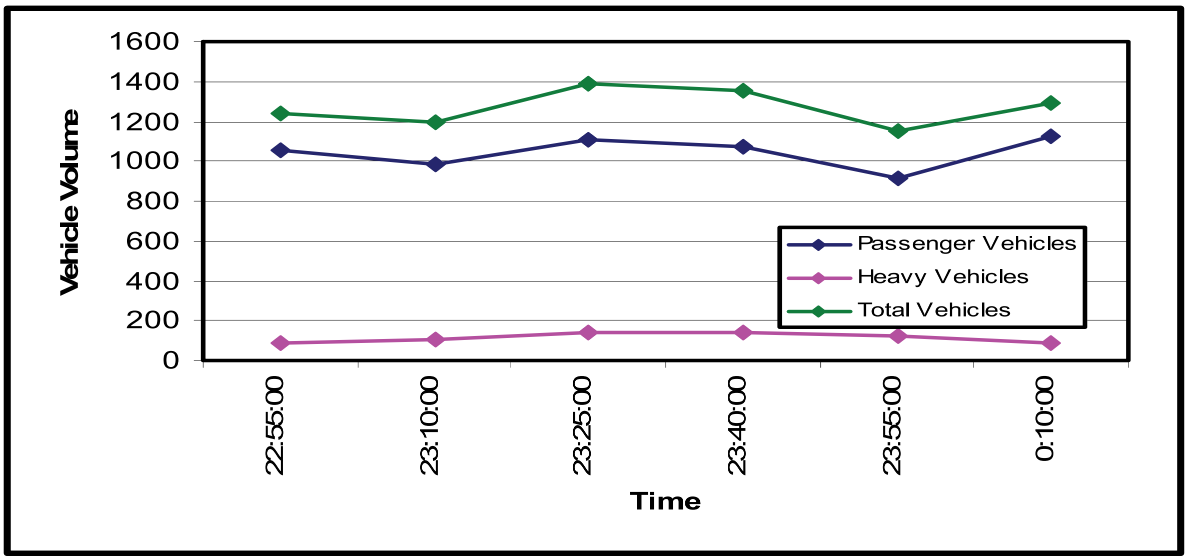
Table 7-1 Selected sites for Data Analysis

S.N	Location	Contract No.	Site Visit Dt.
A	Highway 400, North bond, North of Highway 89	2006-2024	Nov 02, 2007
B	QEW, North bond, Thorold Stone to Mountain Road	2007-2252	Sept22, 2007
C	Highway 401, East bond, Oshawa	2005-2014	Sept27,2007
D	Highway 401, East bond, Oshawa	2005-2014	Oct09,2007
E	Highway 401, East bond, Oshawa	2005-2014	Oct12,2007
F	Highway 427, South bond, onramp onto QEW East bond	2007-2028	Sept20, 2007
G	Highway 427, South bond, onramp onto QEW East bond	2007-2028	Sept21, 2007
H	Highway 427, South bond, onramp onto QEW East bond	2007-2028	Sept24, 2007
I	QEW, North bond, St. Catharine	2007-2027	Oct02, 2007

7.1 Site A: Highway 400, Northbound, North of Highway 89

This facility is six lane divided freeway facility located on Highway 400. Due to the short-term emergency work of the median repair, the workzone was active for full three days starting with the Friday night lane closure. The northbound lanes experienced forced flow condition on Friday night only. The summary of the traffic data collected is as follows:

Traffic Data	**Value**
Average Passenger Vehicle Flow (APVF)	1044
Standard Deviation (SD-APVF)	80.99
Average Heavy Vehicle Flow (AHVF)	113
Standard Deviation (SD-AHVF)	23.96
Average Total Flow (ATF)	1271
Standard Deviation (SD-ATF)	92.25

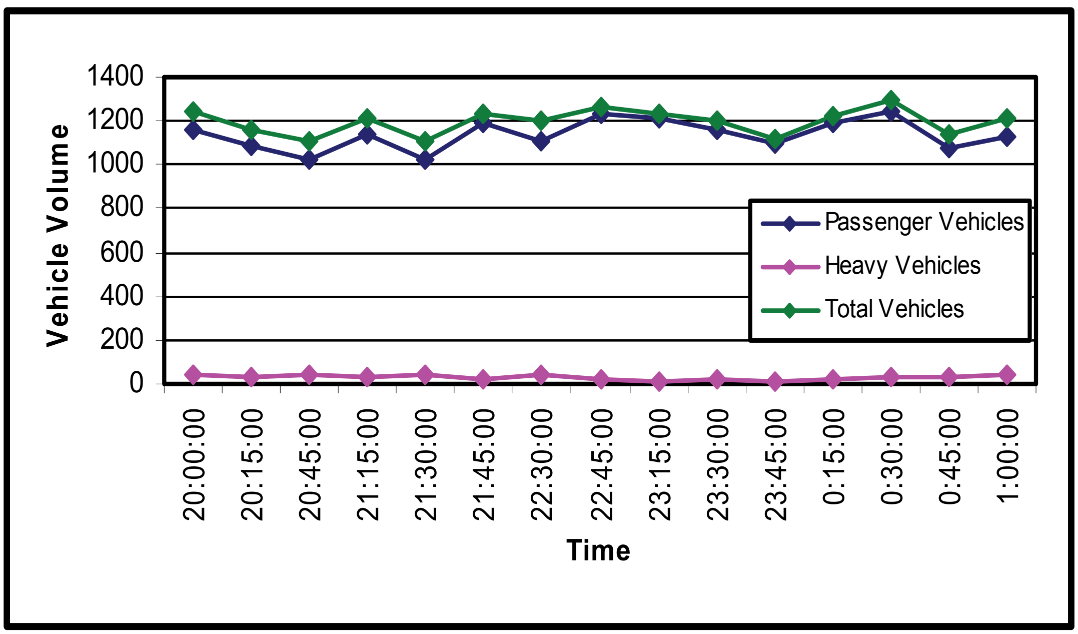


This workzone used a barrel to separate the workzone from the active roadways. The workzone resulted in a queue of approximately 200 m downstream from the end of taper. The lighting condition at this site were poor and a big proportion of heavy vehicle consisted of recreational vehicles, buses and cargo trucks.

7.2 Site B: Queen Elizabeth Way (QEW), Northbound, Thorold Stone to Mountain Road

This site was located near Niagara Falls on the Toronto-bound QEW. This is a six lane freeway facility with 3-to-1 (3 total lanes with one lane open) lane configuration. This short-term workzone was under forced flow condition on late Saturday night. Since the taper end was located within the 500 m of the ramps, the flow data is adjusted as per the HCM 200 guidelines to account for the presence of ramp within the workzone area.

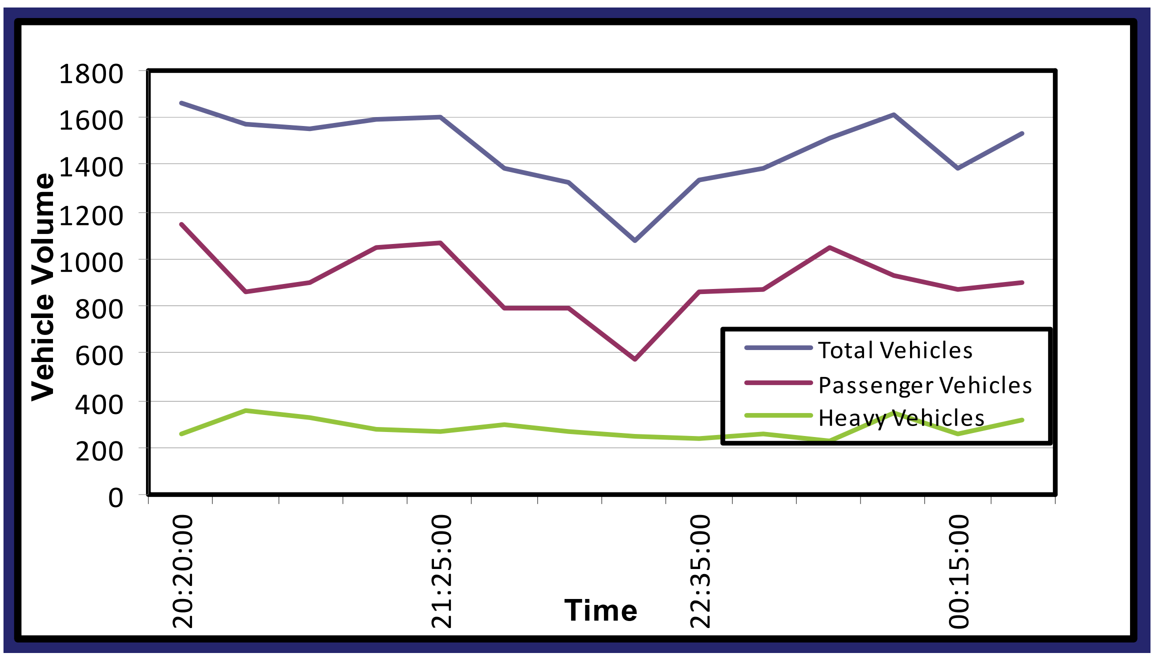
Traffic Data	**Value**
Average Passenger Vehicle Flow (APVF)	1138
Standard Deviation (SD-APVF)	68.48
Average Heavy Vehicle Flow (AHVF)	30
Standard Deviation (SD-AHVF)	12.08
Average Total Flow (ATF)	1197
Standard Deviation (SD-ATF)	59.63



7.3 Site C: Highway 401, Eastbound, Oshawa

This six lane divided freeway facility is located near Oshawa on Highway 401 East. This workzone was located after a hill where the queue length was recorded approximately 1.8 Km. The truck population consisted mostly of trucks and the total volume of heavy vehicle at this site was more than 30%.

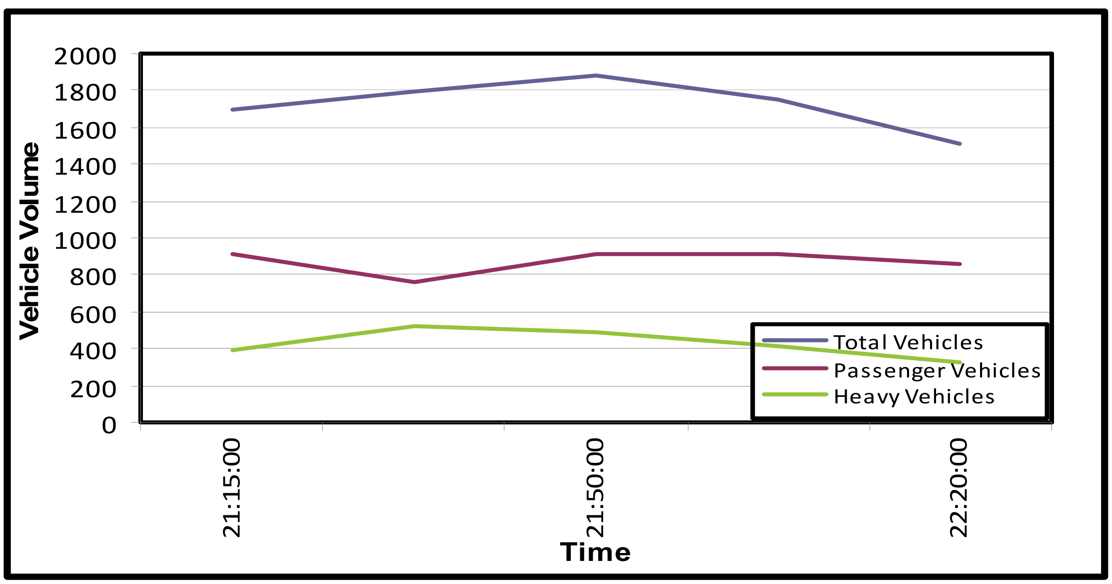
Traffic Data	**Value**
Average Passenger Vehicle Flow (APVF)	908
Standard Deviation (SD-APVF)	141
Average Heavy Vehicle Flow (AHVF)	282
Standard Deviation (SD-AHVF)	40
Average Total Flow (ATF)	1473
Standard Deviation (SD-ATF)	154



7.4 Site D: Highway 401, Eastbound, Oshawa

This is the same location discussed earlier as Site C but was recorded on a different date. Additionally, traffic was recorded in the South bond lane while the North bond lanes were closed. During this closure, the forced flow condition consisted of about an hour and fifteen minutes.

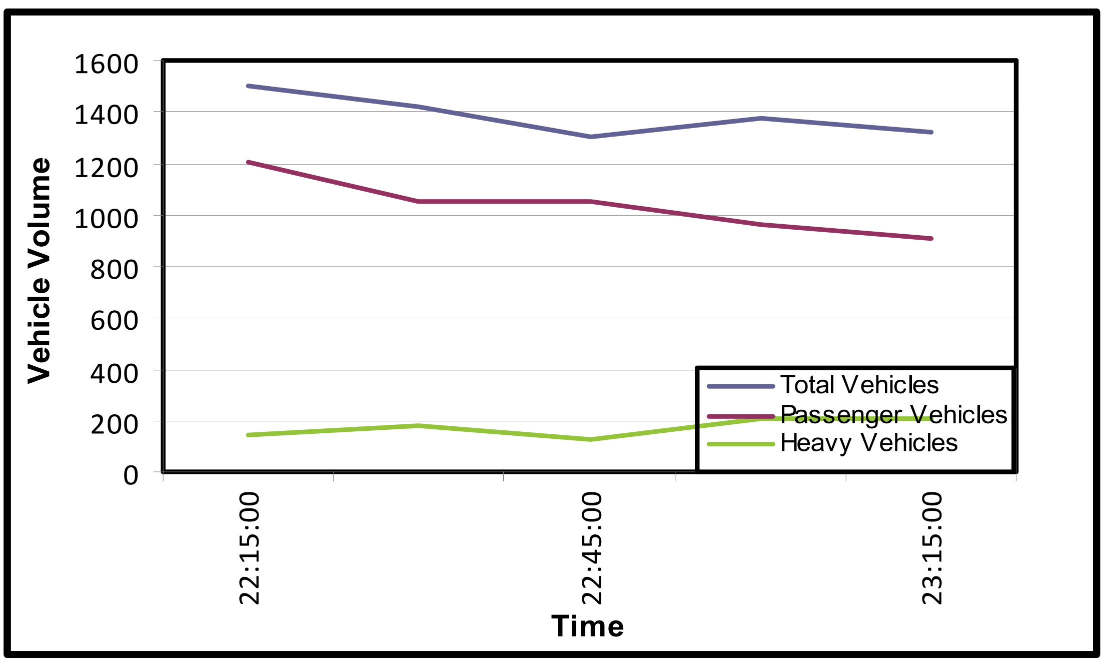
Traffic Data	**Value**
Average Passenger Vehicle Flow (APVF)	870
Standard Deviation (SD-APVF)	67
Average Heavy Vehicle Flow (AHVF)	429
Standard Deviation (SD-AHVF)	77
Average Total Flow (ATF)	1727
Standard Deviation (SD-ATF)	137



7.5 Site E: Highway 401, Eastbound, Oshawa

Site E data was also collected at the same construction zone as Site C and D, however it was collected in the West bond traffic lanes only. The forced flow during this visit was recorded for an hour and fifteen minutes. It was important to note that during this time, the North bond lanes were closed and traffic was all in the South bond lane.

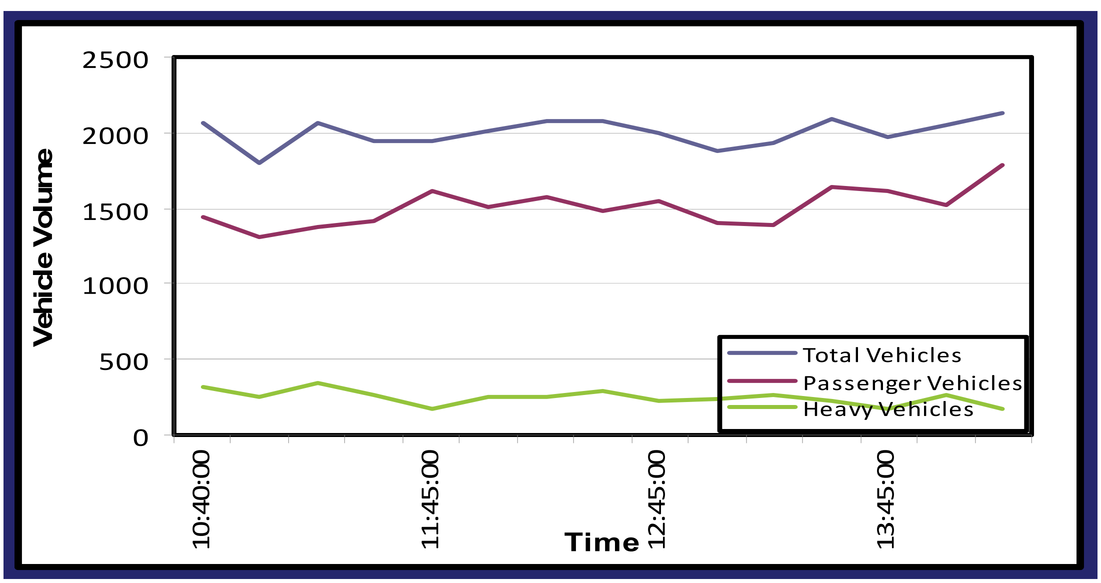
Traffic Data	**Value**
Average Passenger Vehicle Flow (APVF)	1035
Standard Deviation (SD-APVF)	113
Average Heavy Vehicle Flow (AHVF)	174
Standard Deviation (SD-AHVF)	37
Average Total Flow (ATF)	1382
Standard Deviation (SD-ATF)	79



7.6 Site F: Highway 427, Southbound, onramp onto QEW East bond

This site was located at on onramp location on the QEW East bond at Highway 427 South bond. This was a long-term construction site whereby the left lane was closed to traffic. The traffic control was arranged with the concrete barriers and pavement markings. The forced flow condition lasted at this site for about 3.75 hours. This was a busy site with a high intensity of work activity within the construction zone as compared to other construction sites visited for this project. The length of queue was about 2.5 Km from the start of construction zone.

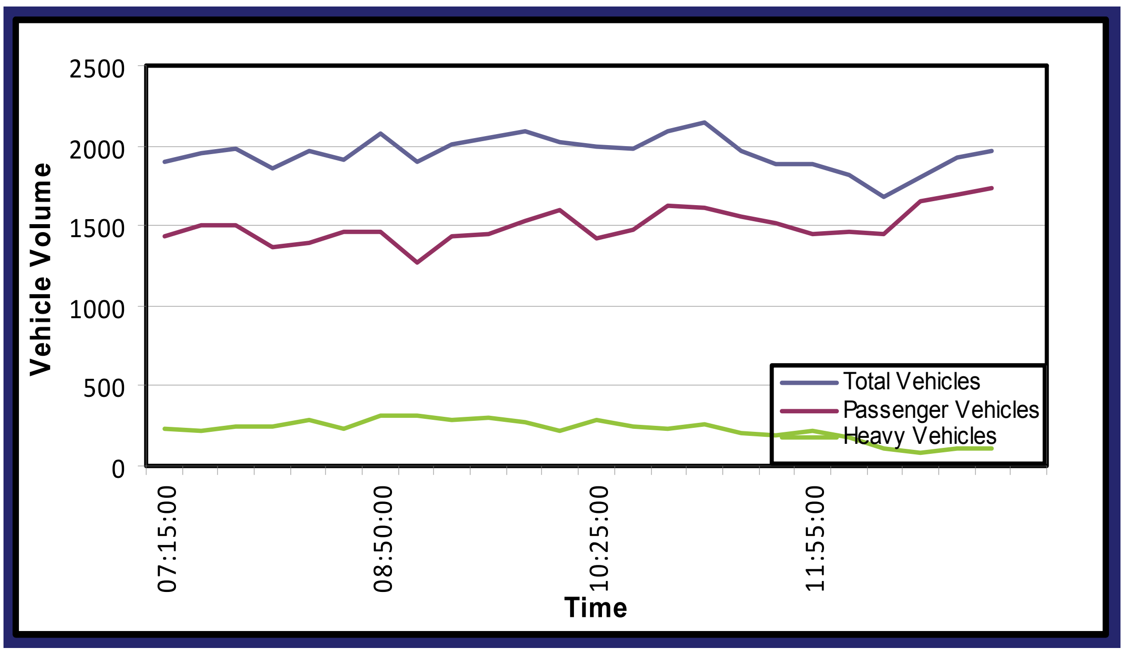
Traffic Data	**Value**
Average Passenger Vehicle Flow (APVF)	1515
Standard Deviation (SD-APVF)	125
Average Heavy Vehicle Flow (AHVF)	241
Standard Deviation (SD-AHVF)	55
Average Total Flow (ATF)	1997
Standard Deviation (SD-ATF)	89



7.7 Site G: Highway 427, Southbound, onramp onto QEW East bond

This site has experienced more than six hour of forced flow condition starting Friday morning. The traffic population consisted of commuter vehicles having good familiarity with site conditions at this long term construction site.

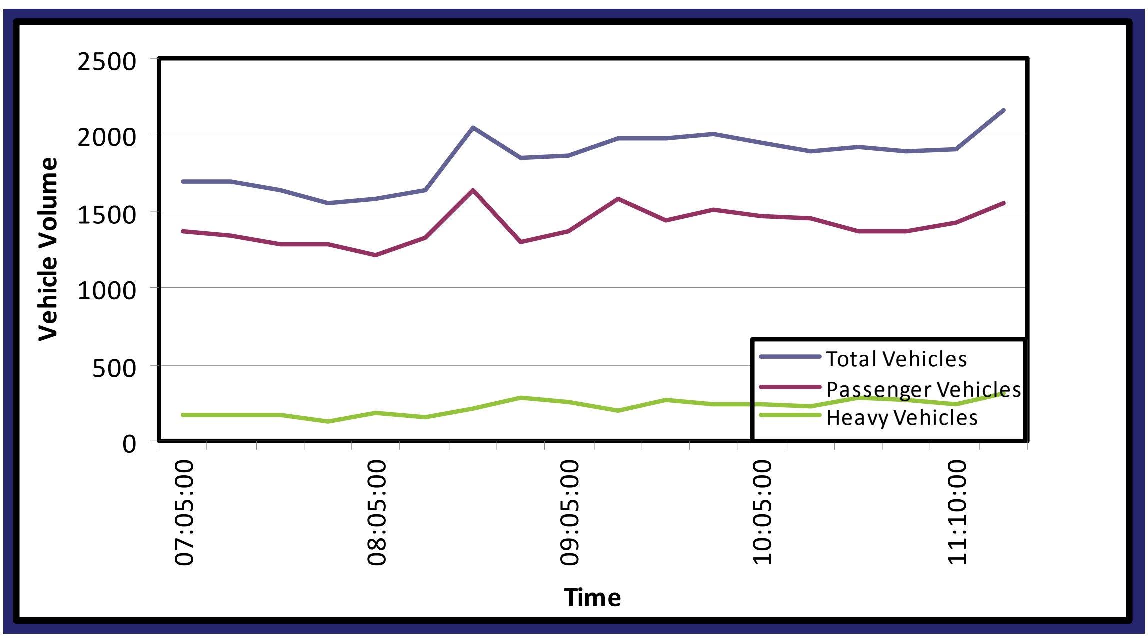
Traffic Data	Value
Average Passenger Vehicle Flow (APVF)	1501
Standard Deviation (SD-APVF)	108
Average Heavy Vehicle Flow (AHVF)	225
Standard Deviation (SD-AHVF)	66
Average Total Flow (ATF)	1951
Standard Deviation (SD-ATF)	105



7.8 Site H: Highway 427, Southbound, onramp onto QEW East bond

Site H involves data collection at the same location as Sites F and G but occurred on Monday morning starting 7:00 a.m. The forced flow lasted for about 4.5 hours with 2.5 Km long queues. The construction activity was focused on downhill of the ramp.

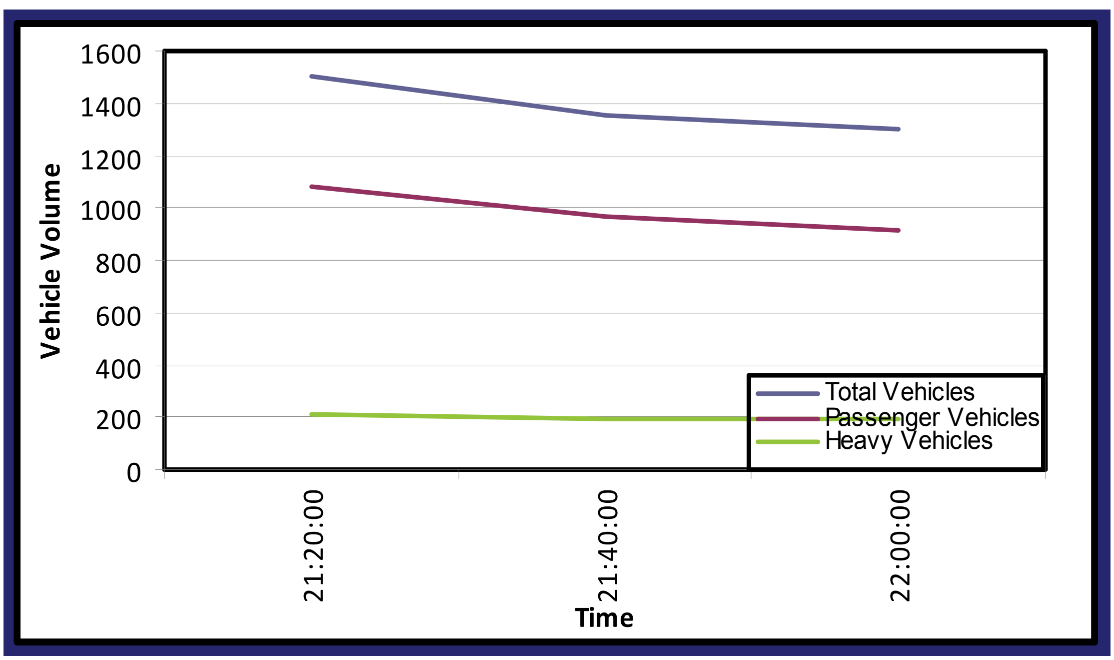
Traffic Data	**Value**
Average Passenger Vehicle Flow (APVF)	1404
Standard Deviation (SD-APVF)	111
Average Heavy Vehicle Flow (AHVF)	221
Standard Deviation (SD-AHVF)	47
Average Total Flow (ATF)	1847
Standard Deviation (SD-ATF)	169



7.9 Site I: Queen Elizabeth Way, Northbound, St. Catharine

This four lane divided freeway facility is located in St. Catharine's, Ontario on the QEW North bond. The forced flow at this site was very short and went back to freeway flow condition within 45 minutes. Periods of forced flow emerged momentarily while workers were adjusted the barrels for traffic control.

Traffic Data	**Value**
Average Passenger Vehicle Flow (APVF)	951
Standard Deviation (SD-APVF)	103
Average Heavy Vehicle Flow (AHVF)	206
Standard Deviation (SD-AHVF)	16
Average Total Flow (ATF)	1363
Standard Deviation (SD-ATF)	95



7.10 Traffic Data

As described in previous sections, the forced flow traffic data from nine freeway construction sites were collected and investigated for developing the mathematical model for estimating workzone capacity. Apart from the traffic data, information on different elements of the work zone was also gathered. This information helped to understand the impact of these variables or site characteristics on capacity model.

Table 7-3 summarizes the traffic data collected from nine sites in-terms of passenger vehicles and heavy vehicles. The table also lists seven important variables associated with each site. If the listed variable was present, it is indicated with number 1. Zero indicates the absence of the listed variable at the particular site.

Table 7-2 Summary and Site Characteristics

Site	1	2	3	4	5	6	7	8	9	10
	PV	HV	VPHPL	Wnd.	3L	LLC	Bar.	OPP	>3%	Night
A	1392	113	1505	0	1	1	1	0	0	1
B	1517	30	1547	1	1	1	1	1	0	1
C	908	282	1190	0	1	0	1	0	0	1
D	870	429	1299	0	1	1	1	0	0	1
E	1035	174	1209	0	1	0	1	1	0	1
F	1508	247	1755	0	0	1	0	0	0	0
G	1501	225	1726	0	0	1	0	0	0	0
H	1404	221	1625	0	0	1	0	0	0	0
I	988	199	1187	0	0	1	1	0	0	1

Notes: 1) PV = Passenger Vehicle
2) HV= Heavy Vehicle
3) VPHPL = Vehicles Per Hour Per Lane
4) Wnd. = Weekend
5) 3L = Three lanes
6) LLC = Left Lane(s) Closed
7) Bar. = Barrels
8) OPP = Ontario Police Presence
9) >3% = 3% Grade
10) Night = Night construction

7.11 Traffic Mix

The presence of heavy vehicles is believed to reduce the traffic carrying ability of the traveling lanes. These vehicles occupy more roadway space and have lesser operating and maneuverability capabilities than passenger cars. These observations of freeway conditions suggest that these impacts include longer and more frequent gaps both in front and behind heavy vehicles [Krammes 1986]. These factors reduce the overall capacity of the work zone, therefore it is important to carefully evaluate the traffic mix for preparation of capacity model. Figure 7-3 show the traffic mix of all the nine sites.

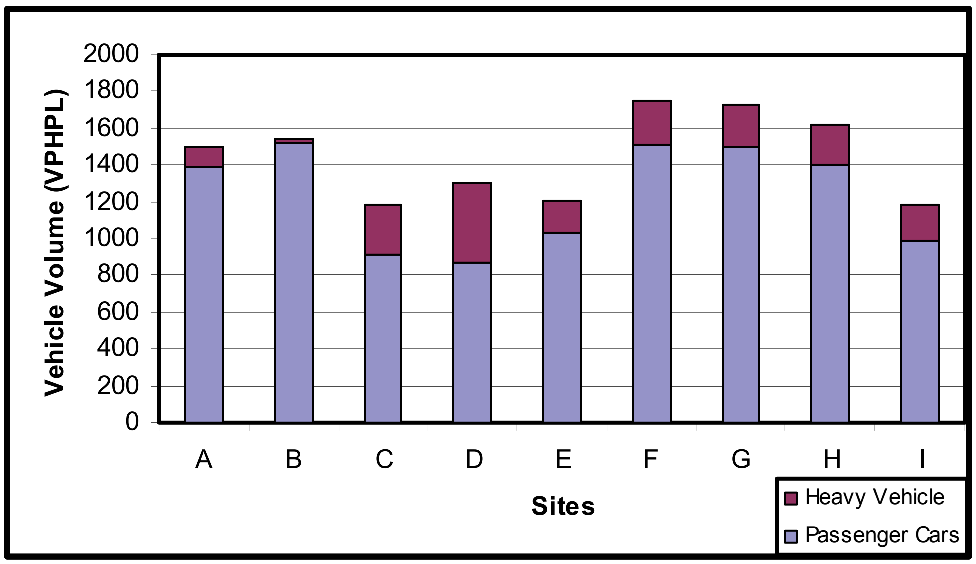


Figure 7-1 Traffic Mix

7.12 Data Analysis

There are various methods for investing and analyzing the data for preparing the capacity model. This study has used a simplified method for computation and presented a mathematical model which is easier to compute and understand. This is necessary if it will be adopted by a Department of Transportation for design and management purposes. Data from the nine sites were aggregated and then used in developing the additive model. Table 7-4 shows result of regression analysis conducted on the data presented in table 7-3 and indicates statistically significant elements for the creation of a capacity model.

Table 7-3 Data Analysis

PCE	Significant Elements	Value	Lower 95%	Upper 95%	Low	High	Range	Total Range
1	Base Case	1702	1507	1897	1507	1897	389	1007
	Barrels	-379	-618	-141	890	1756	866	
1.5	Base Case	1585	1443	1727	1443	1727	284	966
	3 Lanes	259	108	411	1551	2138	587	
	Left lanes closed	232	112	352	1556	2079	523	
	Barrels	-531	-683	-379	761	1348	587	
2	Base	1720	1509	1930	1509	1930	422	1194
	3 Lanes	255	30	480	1538	2411	872	
	Left lanes closed	214	35	392	1544	2322	778	
	Barrels	-547	-772	-322	736	1609	872	
2.5	Base	2049	1841	2256	1841	2256	416	1090
	Barrels	-419	-674	-164	1167	2092	925	
3	Base	2164	1898	2430	1898	2430	532	1290
	Barrels	-432	-758	-106	1140	2324	1184	

Note: PCE = Passenger Car Equivalency factor

The analysis of traffic data with seven important site variables were conducted using the PCE values of 1.0, 1.5, 2.0, 2.5 and 3.0. PCE value of 1.5 was showing the lowest total range of 966. Table 7-5 computes the root mean square error (RMSE) for each site with PCE value 1.

Table 7-4 All Sites with PCE 1

	1	2	3	4	5	6	7	8	9	10	11	12
Site	**PV**	**HV**	**VPHPL**	**Wnd.**	**3L**	**LLC**	**Bar.**	**OPP**	**>3%**	**Night**	**CC**	**RMSE**
A	1392	113	1505	0	1	1	1	0	0	1	1323	33124
B	1517	30	1547	1	1	1	1	1	0	1	1323	50176
C	908	282	1190	0	1	0	1	0	0	1	1323	17689
D	870	429	1299	0	1	1	1	0	0	1	1323	576
E	1035	174	1209	0	1	0	1	1	0	1	1323	12996
F	1508	247	1755	0	0	1	0	0	0	0	1702	2809
G	1501	225	1726	0	0	1	0	0	0	0	1702	576
H	1404	221	1625	0	0	1	0	0	0	0	1702	5929
I	988	199	1187	0	0	1	1	0	0	1	1323	18496
											Sum	14237
											Sqrt	42

Note: 1) PV = Passenger Vehicle

2) HV= Heavy Vehicle

3) VPHPL = Vehicles Per Hour Per Lane

4) Wnd. = Weekend

5) 3L = Three lanes

6) LLC = Left Lane(s) Closed

7) Bar. = Barrels

8) OPP = Ontario Police Presence

9) >3% = 3% Grade

10) Night = Night construction

11) CC = Calculated Capacity

12) RMSE = Root Mean Square Error

Table 7-6 below is showing the RMSE for all the PCE values starting from 1 to 3. One of the examples of calculating the RMSE for PCE 1 is presented above in table 7-5

Table 7-5 RMSE with other PCE values

PCE	RMSE
1.0	42
1.5	13
2.0	19
2.5	45
3.0	57

All the RMSE values against the PCE values are presented in the graph to determine the optimal value of PCE having the lowest error based on the data collected in this research. With the help of graph presented below in Figure 7-3, the suggested PCE value is determined to be 1.6 as this best describes the conditions for Ontario.

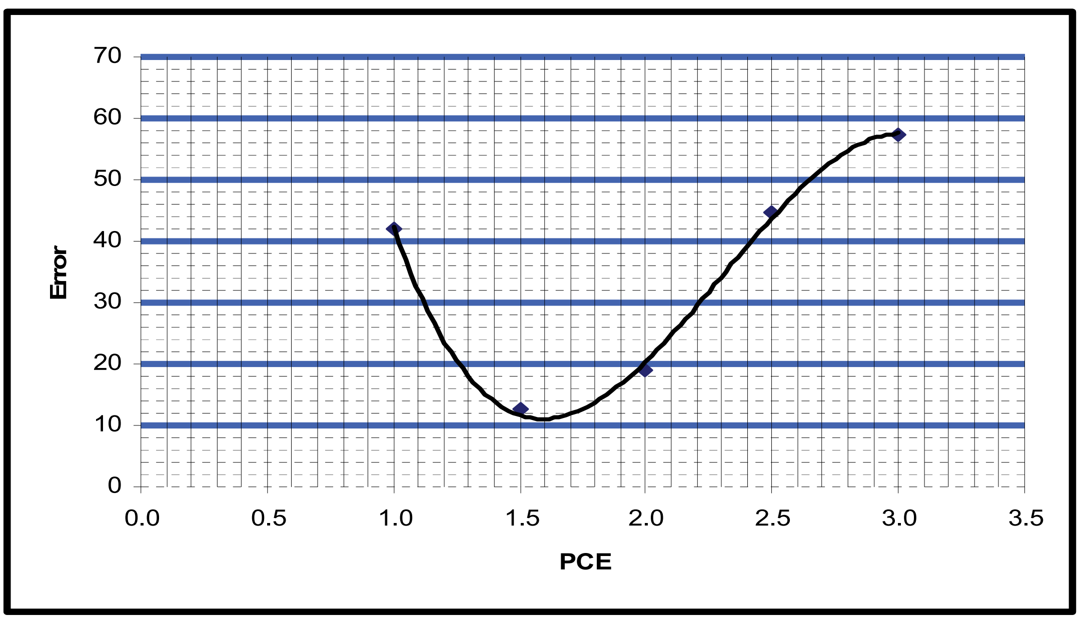


Figure 7-2 Graph of PCE values and resulting RMSE values

The multivariate linear regression was used to develop the additive model with PCE values from 1 to 3 and the new PCE value of 1.6. The model with the lowest error was selected. The variables included in the regression had binary values (0 and 1). The variables having statistically significant effect were included in the model. Table 7-6 shows that the PCE value of 1.6 is having the lowest total range with the base capacity value of 1612. Note that this value is very close to the base capacity value of 1600 suggested by the HCM 2000.

Table 7-6 PCE Values with Significant Elements

PCE	Significant Elements	Value	Lower 95%	Upper 95%	Low	High	Range	Total Range
1	Base	1702	1507	1897	1507	1897	389	
	Barrels	-379	-618	-141	890	1756	866	1007
1.5	Base	1585	1443	1727	1443	1727	284	
	3 Lanes	259	108	411	1551	2138	587	
	Left lanes closed	232	112	352	1556	2079	523	
	Barrels	-531	-683	-379	761	1348	587	966
1.6	Base	1612	1474	1750	1474	1750	276	
	3 Lanes	258	110	406	1584	2156	572	
	Left lanes closed	228	112	345	1586	2095	509	
	Barrels	-534	-682	-386	792	1364	572	**958**
2	Base	1720	1509	1930	1509	1930	422	
	3 Lanes	255	30	480	1538	2411	872	
	Left lanes closed	214	35	392	1544	2322	778	
	Barrels	-547	-772	-322	736	1609	872	1194
2.5	Base	2049	1841	2256	1841	2256	416	
	Barrels	-419	-674	-164	1167	2092	925	1090
3	Base	2164	1898	2430	1898	2430	532	
	Barrels	-432	-758	-106	1140	2324	1184	1290

Note: PCE = Passenger Car Equivalency factor

7.13 Proposed Model

The proposed model developed as a result of linear regression of the raw data resulted in a base capacity of 1612 vphpl, with adjustments for 3 lanes, left lane(s) closed and, the use of barrels. The mathematical model developed is as follows:

$$Ca = Cb + f_{3L} + f_{LL} - f_B \quad (7.1)$$

Where:

Ca= Workzone Capacity

C_b = Base Capacity (1612 vphpl)

f_{3L} = Adjustment for 3 lanes (258 if f_{3L}=1)

f_{LL} = Adjustment for Left lanes closed (228 if f_{LL}=1)

f_B = Adjustment for Barrels (-534 if f_B=1)

7.14 User Delay Cost Calculations

Evaluation of user delays related to work zones is important for all road users and transportation agencies. Workzones disrupt the traffic and cause delays for thousands of people traveling through them. Therefore, workzones result in additional costs for drivers due to slower speeds, queuing, increased travel times and increased fuel consumption. User delay costs are those additional costs incurred by drivers, industries, businesses and economies as a whole because of delays caused by the workzones. Various transportation agencies calculate user delay costs to help them determine the appropriate incentives for contractors to achieve earlier construction completion times, thus reducing the amount of time the lanes are closed. The methodology developed in this research is based on a simplified approach and it is intended to formulating a strategy that can contribute toward promoting economic growth by enhancing the effectiveness of the transport network and reducing congestion. This strategy also is developed to encourage contractors to develop new and innovative techniques for completing the work so a high quality product is produced with limited delays.

This study has used a simplified method to calculate the user delay cost based on real time data collected in this research. It is based on the premise that workzones reduce traffic flow and result in an economic impact to road users. Table 7-8 converts the heavy vehicles to passenger cars with PCE value of 1.6 for the calculation of user delay cost.

Table 7-7 Traffic Count

SITE	Passenger Cars	Heavy Vehicle	VPHPL	PCE	PCPHPL
A	1392	113	1505	1.6	1573
B	1517	30	1547	1.6	1565
C	908	282	1190	1.6	1359
D	870	429	1299	1.6	1556
E	1035	174	1209	1.6	1313
F	1508	247	1755	1.6	1903
G	1501	225	1726	1.6	1861
H	1404	221	1625	1.6	1758
I	988	199	1187	1.6	1306

Note: VPHPL = Vehicle per hour per lane
PCE = Passenger Car Equivalency
PCPHPL = Passenger car per hour per lane

The passenger cars per hour per lane values presented in table 7-8 above are than compared with the normal capacity of the freeway road sections.

Table 7-8 Reduced Capacity

SITE	PCPHPL	Normal	Reduction	FF Time	Total Reduction
A	1573	2135	562	1.5	843
B	1565	2135	570	3.75	2138
C	1359	2135	776	3.5	2715
D	1556	2135	579	1.25	723
E	1313	2135	822	1.25	1027
F	1903	2135	232	3.75	869
G	1861	2135	274	6	1644
H	1758	2135	377	4.5	1698
I	1306	2135	829	0.75	621

The total passenger cars per hour per lane traffic count is compared with the normal capacity of basic freeway segments of 2135 pcphpl to determine the total reduction in the capacity. The maximum service flow rate at freeway segments at level of service (LOS) D is taken as 2135 pcphpl as per the suggested flow provided in the HCM 2000. This flow rate corresponds to freeway flow speed of 110 Km/hour.

Table 7-9 User Delay Cost

SITE	Reduction	Delay Cost	Cost	Forced Flow Time	Total Cost
	(Hr)	$/H	$/Hr	Hr	$/day
A	562	10	5622	1.5	8433
B	570	10	5700	3.75	21375
C	776	10	7758	3.5	27153
D	579	10	5786	1.25	7233
E	822	10	8216	1.25	10270
F	232	10	2318	3.75	8693
G	274	10	2740	6	16440
H	377	10	3774	4.5	16983
I	829	10	8286	0.75	6215

The total reduction in pcphpl used to determine the per hour delay cost using the unit cost of $10/hour for the passenger cars as suggested by MTO. The reduction is than converted to a total reduction using the total time site has experienced the forced flow condition during the construction in a day. This has helped calculating the total user delay cost for each site.

7.15 Existing Workzone Capacity Models

In-order to analyze the model it is important to evaluate some of the existing models for correctness and validity. For this project three existing models are selected for analysis. The collected traffic data and site characteristics information were used with these three models to test the old models with the new data.

The selected models are as under:

1. Al-Kaisey and Fred Hall Multiplicative Model
2. Al-Kaisey and Fred Hall Additive Model
3. Highway Capacity Manual (HCM) Model

7.15.1 Al-Kaisey Multiplicative Model

$C = C_b \times f_{HV} \times f_{d1} \times f_{d2} \times f_w \times f_s \times f_r$ (7.2)

Where:

C = Work zone capacity (vphpl)

C_b = Base (ideal) work zone capacity (pcphpl)

f_{HV} = Adjustment factor for heavy vehicles (compute using the same HCM 2000 formula for f_{HV})

fd1 = Adjustment factor for off-peak weekday driver population (off-peak= *fd1*, else=1)

fd2 = adjustment factor for weekend driver population (weekend= *fd2,* else=1)

fw = Adjustment factor for work activity (work activity= *fw*, no work activity=1)

fs = Adjustment factor for side of lane closure (left lanes closed = *fs* , right lanes closed=1)

fr = Adjustment factor for rain (rain= *fr* , no rain=1)

Table 7-11 provides a summary of the data collected at nine sites and the heavy vehicle (HV) is converted into passenger vehicle (PV) mathematically with the passenger car equivalency (PCE) factor of 2.4.

Table 7-10 Traffic Data

SITE	PV	HV	VPHPL	% HV	PCE
					2.4
A	1392	113	1505	0.075	1663
B	1517	30	1547	0.019	1589
C	908	282	1190	0.237	1585
D	870	429	1299	0.330	1900
E	1035	174	1209	0.144	1453
F	1508	247	1755	0.141	2101
G	1501	225	1726	0.130	2041
H	1404	221	1625	0.136	1934
I	988	199	1187	0.168	1466

The multiplicative model was developed using the solver optimization tool in Microsoft Excel. The variables included in this model are driver population, proportion of heavy vehicles, work activity at site, side of lane closure, and rain [Al-Kaisy 2002].

Table 7-12 provides the summary of variables used in Al-Kaisey's Multiplicative models with the suggested values variables used in the model.

Table 7-11 Factors for Multiplicative Model

Cb	Base Capacity	2000				
PCE	Level Ground	2.4	3% Grade	3.0		
Driver Population	Weekday Peak Hr	1.0	Weekday Off peak	0.96	Weekend	0.825
Light Condition	Daytime	1.0	Nightime	0.96		
WZ Configuration	Right Lane Closed	1.0	Left Lane Closed	0.94		
Weather	No Rain	1.0	Moderate Rain	0.95	Heavy Rain	0.90
Work Activity	No Work Activity	1.0	Work Activity	0.94		

As indicated in table 7-12 the base capacity value of 2000 was used for this model and a PCE value of 2.4 for level ground. The variable interaction values are presented in table 7-13.

Table 7-12 Variable Interactions for Multiplicative Model

Variable Interactions	
No Interactions	1.0
Left Lane & Weekday off peak	1.03
Weekend & Work Activity	1.08
Left Lane & Rain	1.02
Weekend & Rain	1.05

The data collected from nine sites with Al-Kaisy's proposed values for multiplicative model were used to calculate the capacity for each site. The calculated capacity values were compared with the observed capacity values. The percentage error was determined with the help of difference between the calculated and observed capacity. The average error using Al-Kaisy's multiplicative model was found to be 19%.

Table 7-13 Calculations for Multiplicative Model

	1	2	3	4	5	6	7	8	9	10	11
SITE	**% HV**	**PCE**	**DP**	**Light**	**WZ**	**Weather**	**WA**	**Inter.**	**CC**	**OC**	**% Err**
A	0.075	2.4	0.961	0.96	0.94	1.0	0.943	1.03	1524	1663	8
B	0.019	2.4	0.825	0.96	0.94	1.0	0.943	1.08	1476	1589	7
C	0.237	2.4	0.961	0.96	1.0	1.0	0.943	1.0	1306	1585	18
D	0.330	2.4	0.961	0.96	0.94	1.0	0.943	1.03	1152	1900	39
E	0.144	2.4	0.961	0.96	1.0	1.0	0.943	1.0	1448	1453	0
F	0.141	3.0	0.961	1.0	0.94	1.0	0.943	1.03	1369	2101	35
G	0.130	3.0	1.0	1.0	0.94	1.0	0.943	1.0	1406	2041	31
H	0.136	3.0	1.0	1.0	0.94	1.0	0.943	1.0	1394	1934	28
I	0.168	2.4	0.961	0.96	0.94	1.0	0.943	1.03	1364	1466	7
										Average Error	**19**

Note:

1) % HV = Percentage Heavy Vehicle
2) PCE = Passenger Car Equivalency
3) DP = Driver Population
4) Light = Light condition at site
5) WZ = Workzone configuration
6) Weather = Weather condition at site
7) WA = Intensity of Work Activity at site
8) Inter. = Variable Interaction value
9) CC = Calculated Capacity
10) OC = Observed Capacity
11) % Err = Percentage error

7.15.2 Al-Kaisey Additive Model

$C = C_b - 20.9P_{HV} - 82D_1 - 352D_2 - 172W - 121S - 71R + 55SD_1 + 185WD_2 + 58SD_2 + 107RD_2$ (7.3)

Where:

C = Capacity in vphpl

C_b = Base Capacity (pcphpl)

P_{HV} = Percentage of heavy vehicles in the traffic stream

D_1 = Off-peak weekday driver population (off-peak=1, else=0)

D_2 = Weekend driver population (weekend=1, else=0)

W = Work activity at site (work activity=1, no work activity=0)

S = Side of lane closure (left lanes closed=1, right lanes closed=0)

R = Rain (rain = 1, else = 0)

SD1, WD2, SD2, and RD2 = Interactive variables

Data of nine sites tabulated in Table 7-15 show the traffic counts in terms of passenger vehicle and heavy vehicle. The heavy vehicle figures are converted into passenger vehicles mathematically using passenger car equivalency (PCE) factor of 2.4 for calculating the capacity for each site using Al-Kaisy's additive model.

Table 7-14 Raw Data for Additive Model

SITE	Passenger Vehicle	Heavy Vehicle	VPHPL	% Heavy Vehicle	PCE 2.4
A	1392	113	1505	0.075	1663
B	1517	30	1547	0.019	1589
C	908	282	1190	0.237	1585
D	870	429	1299	0.330	1900
E	1035	174	1209	0.144	1453
F	1508	247	1755	0.141	2101
G	1501	225	1726	0.130	2041
H	1404	221	1625	0.136	1934
I	988	199	1187	0.168	1466

Note: VPHPL = Vehicle per hour per lane

PCE = Passenger Car Equivalency

Table 7-16 presented the values for the variables used in the additive model and the values for variable interactions. Al-Kaisy suggested that the combined effect of two variables may not be additive, i.e. equivalent to the sum of individual effects. The combined effect of any two variables is less than the sum of the individual effects.

Table 7-15 Factors for Additive Model

Workzone Capacity	C	vphpl
Base Capacity	Cb	1964
% HV	P_{HV}	-20.9
Driver population (Off-peak=1)	D_1	-82
Driver population (Weekend=1)	D_2	-352
Work activity (Yes=1)	W	-172
Side of Lane closed (Left=1)	S	-121
Rain (rain = 1, else = 0)	R	-71
Variable Interactions		
No Interactions		1.0
Left Lane & Weekday off peak	SD_1	55
Work Activity & Weekend	WD_2	185
Left Lane & Rain	SD_2	58
Rain & Weekend	RD_2	107

Table 7-16 Calculations for Additive Model

SITE	P_{HV}	PCE	D1	D2	W	S	R	SD_1	WD_2	SD_2	RD_2	CC	OC	% Error
A	0.075	-1.6	1	0	1	1	0	1	0	0	0	1642	1663	1.2
B	0.019	-0.4	0	1	1	1	0	0	1	0	0	1504	1589	5.4
C	0.237	-5.0	1	0	1	0	0	0	0	0	0	1705	1585	-7.6
D	0.330	-6.9	1	0	1	1	0	1	0	0	0	1637	1900	13.8
E	0.144	-3.0	1	0	1	0	0	0	0	0	0	1707	1453	-17.5
F	0.141	-2.9	1	0	1	1	0	1	0	0	0	1641	2101	21.9
G	0.130	-2.7	1	0	1	1	0	1	0	0	0	1641	2041	19.6
H	0.136	-2.8	1	0	1	1	0	1	0	0	0	1641	1934	15.2
I	0.168	-3.5	1	0	1	1	0	1	0	0	0	1640	1466	-11.9
													Average Error	**4.4**

Notes: $P_{HV,}$ PCE, D_1, D_2, W, S, R, SD_1, WD_2, SD_2, RD_2 described in Table 7-16 above

CC= Calculated Capacity, OC = Observed Capacity

7.15.3 HCM 2000 - Mathematical Model

$C = (Cb + I - R) * f_{HV} * N$ (7.4)

Where:

C = Workzone Capacity (vphpl)

Cb = Base Capacity (1600 pcphpl)

I = Adjustment for Work Activity (+ / - 10%)

R = Adjustment for Ramp

f_{HV} = Adjustment for Heavy Vehicle

N =Number of open lanes

The data of nine sites used with the HCM model with PCE value of 1.5. Table 7-19 present the data with the traffic volume.

Table 7-17 Raw Data for HCM Model

SITE	PV	HV	VPHPL	%HV	PCE 1.5
A	1392	113	1505	0.075	1562
B	1517	30	1547	0.019	1562
C	908	282	1190	0.237	1331
D	870	429	1299	0.330	1514
E	1035	174	1209	0.144	1296
F	1508	247	1755	0.141	1879
G	1501	225	1726	0.130	1839
H	1404	221	1625	0.136	1736
I	988	199	1187	0.168	1287

The HCM propose to adjust the base capacity value with 10% as the adjustment for intensity of work activity. The base capacity value is proposed as 1600 pcphpl. Since all the nine sites were active workzones, the 10% of the base capacity value is adjusted accordingly. The presented data already taken into account the adjustment for presence of ramps within the workzones. Hence the value indicated against R is showing zero value in the table 7-19. All nine sites were comprised of one open lane as indicated in table 7-19.

Table 7-18 Calculations for HCM Model

SITE	I	R	f_{HV}	N	CC	OC	% Error
A	-160	0	0.964	1	1388	1562	11.1
B	-160	0	0.990	1	1426	1562	8.7
C	-160	0	0.894	1	1287	1331	3.3
D	-160	0	0.858	1	1236	1514	18.3
E	-160	0	0.933	1	1343	1296	-3.7
F	-160	0	0.934	1	1345	1879	28.4
G	-160	0	0.939	1	1352	1839	26.5
H	-160	0	0.936	1	1348	1736	22.3
I	-160	0	0.923	1	1329	1287	-3.3
						Average Error	**12.4**

The summary of all three models presented in table 7-20. The comparison indicates that Al-Kaisy's additive model have the lowest error of 4.4 when tested with the data collected at nine sites. Hence the additive model for this research is determined to be most appropriate for use in Ontario.

Table 7-19 Summary of Models

SITE	Al-Kaisey (Multiplicative Model)			Al-Kaisey (Additive Model)			Highway Capacity Manual (HCM2000)		
	CC	OC	% Error	CC	OC	% Error	CC	OC	% Error
A	1524	1663	8.3	1642	1663	1.2	1388	1562	11.1
B	1476	1589	7.1	1504	1589	5.4	1426	1562	8.7
C	1306	1585	17.6	1705	1585	-7.6	1287	1331	3.3
D	1152	1900	39.4	1637	1900	13.8	1236	1514	18.3
E	1448	1453	0.3	1707	1453	-17.5	1343	1296	-3.7
F	1369	2101	34.8	1641	2101	21.9	1345	1879	28.4
G	1406	2041	31.1	1641	2041	19.6	1352	1839	26.5
H	1394	1934	27.9	1641	1934	15.2	1348	1736	22.3
I	1364	1466	6.9	1640	1466	-11.9	1329	1287	-3.3
Average Error			19.3			4.4			12.4

Chapter 8
Conclusion and Recommendations

8.1 Conclusion

This study was conducted with the support of Ministry of Transportation Ontario (MTO). In total, sixteen construction workzone sites were visited. Overall, for the purpose of the research good quality data was collected from nine sites which were necessary for this research to propose a model for estimation of Workzone Capacity. The remaining sites did not offer any data due to lack of forced flow condition. However, the data collected can be used in future to better understand non-forced flow conditions and other site characteristics.

The new mathematical model with PCE value of 1.6 is developed for Ontario lane closure set ups for freeway facilities. The analysis also found that Al-Kaisy Additive model is showing the reasonable results when tested with collected traffic data. The model is showing 4.4 % error which is very close to the proposed model established during this project. The model is shown as under:

$$Ca = Cb + f_{3L} + f_{LL} - f_B \quad (8.1)$$

Where:

Ca= Workzone Capacity

C_b = Base Capacity (1612 vphpl)

f_{3L} = Adjustment for 3 lanes (258 if f_{3L}=1)

f_{LL} = Adjustment for Left lanes closed (228 if f_{LL}=1)

f_B = Adjustment for Barrels (-534 if f_B=1)

This model was developed using the data collected from nine freeways construction sites. More extensive research is needed to develop a more reliable model for Ontario with data from large number of sites having different site characteristics. The research team for this project has faced various problems in collecting the data from various sites which has resulted in limiting the ability to conduct an extensive data analysis required for such research projects.

Various studies have used different PCE values for developing the models. This study is proposing the PCE value of 1.6 for the model. This PCE value has resulted in the lowest error among the other PCE values used for developing the model. This PCE value is also very close to PCE value of 1.5 proposed by HCM 2000.

One of the observations of the research team was that the existing lane closure times can be extended to expedite the construction activity. More than 50% of the visited construction sites did not show any forced flow condition, which shows that MTO needs to re-examine the lane closure time based on the capacity models. The extended closure times may result in increased productivity of construction activity on site and it may also result in producing better quality work. On long-term sites the lane closure time can be adjusted based on the sites visits during the typical peak hours to determine the optimal lane closure strategy.

Few of the visited sites where there was no forced flow condition provided other interesting observations. It was observed that adverse weather was contributing significantly on traffic intensity. The effects of light, rain and snow need to be analyzed carefully while preparing the traffic management plan for construction workzones. It was also observed that MTO needs to enforce the Ontario Traffic Manual more effectively to reduce the impact of workzone on traffic flow. At some of the sites it was observed that the passenger vehicles were having problems tracking construction signs when heavy vehicles were in front of them.

With the staggering increase in vehicle-miles of travel, motorists are increasingly exposed to work zones. About 20 percent of the U.S. National Highway System is under construction during the peak summer roadway season. Fifty percent of all highway congestion is attributed to nonrecurring conditions and work zones are estimated to account for nearly 24 percent of nonrecurring delay. It is therefore important to appropriately quantify the user delay costs associated with the construction workzone. These cost estimates can help transportation agencies make informed decisions when selecting the competing projects. This study has used a simple method to calculate the user delay cost related to nine construction sites. The result of this study indicated the total user delay cost of nine sites investigated to the tune of $122,795 per day. This is indicative of the need to consider the user delay costs in the project selection process to minimize the workzone delay. In-order to undertake an effective LCCA with User delay costs included is to account for all the maintenance / rehabilitation costs of a roadway and the additional user costs resulted because of the workzones. Reasonably accurate estimation of frequency and duration of these work zones throughout the life of the project is very important for determining the reasonably accurate economic worth of alternative projects.

8.2 Recommendations:

For future projects it is recommended to start the data collection activity at the beginning of the construction season so the data can be collected from larger number of sites. Due to smaller construction window, it was difficult to visit more construction sites having varying nature of site characteristics. Since the data to be collected is from the active construction sites, it is important that MTO play a more active coordination role for effective data collection. More than 30% of the earlier identified sites could not be visited on time due to lack of coordination between the contract administrators and the project team. The MTO staff can be very effective in removing those coordination difficulties at sites. It is also recommended to use the automated traffic counting devices along-with the manual traffic count for the data verification. Collection of speed data is strongly recommended from the upstream and downstream of the construction workzone. The speed data can be very effective in accurately estimating the user delay cost and workzone capacity.

There is also a need of evaluating possibilities of smart workzone deployments and dynamic late lane merge techniques at busy construction workzones. There were few sites where the congestion were witnessed at the start of taper due to merging activity of vehicles very early of the workzone in anticipation of the merging difficulty at the end of the taper. This was reducing the capacity at the end of taper for a very short duration. Dynamic late merge technique can smooth out the traffic flow and hence can help reduce the length of the queues at busy construction sites.

It is also recommended that the transportation agencies properly quantify the user delay costs associated with construction workzone. The user delay costs component can be very effectively used in LCCA analysis and for making an informed decision in selecting the competing projects. The user delay cost figures can also be used by the transportation agencies in finalizing the appropriates amount of incentives for early completion of construction work and penalties when there is any delay.

Appendix A: Site Characteristics Form (Site A)

Date	02-Nov
Hwy No.	400 N/B
Location	North of Hwy 89 on Hwy 400
Weather	Clear 1º C
Starting Time	21:00
End Time	01:15
Day of Week	Friday-Saturday
Time of Day	Night
Assigned Lane	1 & 2 (Median lanes)
Lane Width (m)	3.75
Direction of Traffic	NB
Shoulder Type	Fully Paved
Lane Closure	lane 1 closed at 2130, lane 2 at 2230
OPP Presence	No
Time of OPP Presence	N/A
Facility Type	Six lane divided freeway
Driver Population	Peak and off-peak
% Heavy Vehicles	
Grade of Road	Level
Speed Limit (km/hr)	100
Curve of Road	Straight
Duration of Closure	24/7 from Friday 2100 till Monday 0130
Interchange	Hwy 89
Type of Traffic Control	Barrel separated
Pavement Condition	Average-Median repair
Distractions	Bad light
Other Comments	Queue length 200 m from Data collection point

Appendix B: Site Characteristics Form (Site B)

Date	22-Sep
Name of the Site	QEW Toronto bound, NB
Location	Thorold Stone Road to Mountain Road
Weather	Clear
Starting Time	20:00
End Time	02:30
Day of Week	Saturday
Assigned Lane	1&2
Lane Width (m)	3.75
Direction of Traffic	N/B
Shoulder Type	Fully paved
Lane Closure	2 Left lanes (Multi lane)
OPP Presence	Yes
Time of OPP Presence	22:30
Facility Type	Six lane divided freeway
Driver Population	Peak-Off peak
% Heavy Vehicles	2.27
Grade of Road	Flat
Speed Limit (km/hr)	100
Curve of Road	Straight
Duration of Closure	20:00-06:00
Interchange	QEW and Thorold Stone Rd.
Type of Traffic Control	TL-38
Pavement Condition	Milling
List of Photos Taken	4.1,4.2,4.3
Other Comments	Speed 20-30,merge from Hwy 420

Appendix C: Site Characteristics Form (Site C)

Date	27-Sep
Name of the Site	Hwy 401 EB
Location	Oshawa
Weather	Warm, approx. 18°C. Partly cloudy.
Starting Time	20:20
End Time	1:15
Day of Week	Thursday
Time of Day	Night
Assigned Lane	Traffic in North lane; two south lanes closed; see map
Lane Width (m)	3.75
Direction of Traffic	EB
Shoulder Type	Partially Paved
Lane Closure	2 Right Lane
OPP Presence	No
Facility Type	6 lane, divided highway
Driver Population	Mostly trucks, some commuter vehicles, become more heavily
% Heavy Vehicles	
Grade of Road	0
Speed Limit (km/hr)	100
Curve of Road	0
Length of Work Zone	1.4km
Duration of Closure	Evening only. Closed at 7pm
Intersections	Closest egret is Simcoe Rd.
Type of Traffic Control	Barrel Separated.
Pavement Condition	Good
Distractions	Night time. Workers present – patch paving
List of Photos Taken	13.1, 13.2
Other Comments	CZ was after a hill. Queue about 1.8km

Appendix D: Site Characteristics Form (Site D)

Date	09-Oct
Name of the Site	Hwy 401 EB
Location	Oshawa
Weather	Clear
Starting Time	21:15
End Time	22:30
Day of Week	Tuesday
Time of Day	Night
Assigned Lane	Traffic in South lane; two north lanes closed; see map
Lane Width (m)	
Direction of Traffic	EB
Shoulder Type	Partially Paved
Lane Closure	2 Left lane
OPP Presence	No
Time of OPP Presence	
Facility Type	6 lane, divided highway
Driver Population	Mostly trucks, some commuter vehicles
% Heavy Vehicles	
Grade of Road	0
Speed Limit (km/hr)	100
Curve of Road	0
Length of Work Zone	Approx 1.0km
Duration of Closure	Evening only. Closed at 8pm
Intersections	Closure begins shortly 500m West of Park road.
Type of Traffic Control	Barrel Separated.
Pavement Condition	Good
Distractions	Night time. Workers present – patch paving
List of Photos Taken	
Other Comments	CZ was after a hill

Appendix E: Site Characteristics Form (Site E)

Date	12-Oct
Name of the Site	Hwy 410 WB
Location	Oshawa
Weather	Clear
Starting Time	22:15
End Time	0:10
Day of Week	Friday
Time of Day	Night
Assigned Lane	Traffic in South lane; two north lanes closed; see map
Lane Width (m)	
Direction of Traffic	WB
Shoulder Type	Partially Paved
Lane Closure	2 Right Lane
OPP Presence	Yes
Time of OPP Presence	Approx 22:45
Facility Type	6 lane, divided highway
Driver Population	Mostly trucks, some commuter vehicles
% Heavy Vehicles	
Grade of Road	0
Speed Limit (km/hr)	100
Curve of Road	0
Length of Work Zone	2.7km
Duration of Closure	Evening only. Closed at 10pm
Intersections	Closure begins 50m West of Simcoe Rd.
Type of Traffic Control	Lane arrow lighted signs. Barrel Separated.
Pavement Condition	Good
Distractions	Night time. Workers present
List of Photos Taken	13.3,13.4
Other Comments	Queue length estimated throughout. See map for details.

Appendix F: Site Characteristics Form (Site F)

Date	20-Sep
Name of the Site	Hwy 427
Location	427 South onramp onto QEW East
Weather	Sunny
Starting Time	10:30
End Time	15:00
Day of Week	Thursday
Time of Day	Mid-day
Assigned Lane	West lane
Lane Width (m)	
Direction of Traffic	EB
Shoulder Type	Paved
Lane Closure	1 Left lane
OPP Presence	No
Time of OPP Presence	
Facility Type	2 Lane onramp
Driver Population	Mostly commuter vehicles
% Heavy Vehicles	
Grade of Road	Downhill, graded as an off ramp from an overpass
Speed Limit (km/hr)	100
Curve of Road	Yes
Length of Work Zone	1.0km on ramp. 2.5km in advance of CZ
Duration of Closure	24 hours/day for multi-month project
Intersections	On-ramp from 427 to EB QEW (see map)
Type of Traffic Control	Lane markings and concrete barriers
Pavement Condition	Good
Distractions	Workers and high traffic
List of Photos Taken	14.1,14.2
Other Comments	Queue 2.5km from start of CZ.

Appendix G: : Site Characteristics Form (Site G)

Date	21-Sep
Name of the Site	Hwy 427
Location	427 South onramp onto QEW East
Weather	Slightly overcast, becoming sunny
Starting Time	7:15
End Time	16:20
Day of Week	Friday
Time of Day	Morning to Afternoon
Assigned Lane	West lane (becomes South lane after turn was open to
Lane Width (m)	
Direction of Traffic	EB
Shoulder Type	Paved
Lane Closure	1 Left lane
OPP Presence	No
Time of OPP Presence	
Facility Type	2 Lane onramp
Driver Population	Mostly commuter vehicles
% Heavy Vehicles	
Grade of Road	Downhill, graded as an off ramp from an overpass
Speed Limit (km/hr)	100
Curve of Road	Yes
Length of Work Zone	1.0km on ramp. 2.5km in advance of CZ
Duration of Closure	24 hours/day for multi-month project
Intersections	On-ramp from 427 to EB QEW (see map)
Type of Traffic Control	Lane markings and concrete barriers – onramp refurbishing
Pavement Condition	Good
Distractions	Workers and high traffic
List of Photos Taken	14.3,14.4
Other Comments	

Appendix H: Site Characteristics Form (Site H)

Date	24-Sep
Name of the Site	Hwy 427
Location	427 South onramp onto QEW East
Weather	Slightly overcast, becoming sunny
Starting Time	7:05
End Time	11:45
Day of Week	Monday
Time of Day	Morning
Assigned Lane	West lane (becomes South lane after turn was open to
Lane Width (m)	
Direction of Traffic	EB
Shoulder Type	Paved
Lane Closure	1 Left lane
OPP Presence	No
Time of OPP Presence	
Facility Type	2 Lane onramp
Driver Population	Mostly commuter vehicles
% Heavy Vehicles	
Grade of Road	Downhill, graded as an off ramp from an overpass
Speed Limit (km/hr)	100
Curve of Road	Yes
Length of Work Zone	1.0km on ramp. 2.5km in advance of CZ
Duration of Closure	24 hours/day for multi-month project
Intersections	On-ramp from 427 to EB QEW (see map)
Type of Traffic Control	Lane markings and concrete barriers – onramp refurbishing
Pavement Condition	Good
Distractions	Workers and high traffic
List of Photos Taken	
Other Comments	

Appendix I: Site Characteristics Form (Site I)

Date	02-Oct
Name of the Site	QEW Niagara bound
Location	St. Catharine's
Weather	Warm and clear, road wet due to earlier rain
Starting Time	20:30
End Time	21:00
Day of Week	Tuesday
Time of Day	Night
Assigned Lane	Traffic in South lane; North lane closed. On/Off ramp lane
Lane Width (m)	
Direction of Traffic	EB
Shoulder Type	Paved
Lane Closure	1 left lane
OPP Presence	No
Time of OPP Presence	
Facility Type	4 lane, divided highway
Driver Population	Mostly trucks, some commuter vehicles, becoming more
% Heavy Vehicles	
Grade of Road	Slightly uphill
Speed Limit (km/hr)	100
Curve of Road	0
Length of Work Zone	300m taper. 1.0km closure (Ontario to Lake St.)
Duration of Closure	Evening only. Closed at 8:30pm
Intersections	Closure begins shortly after 7th. 7th onramp closest access.
Type of Traffic Control	Lane arrow lighted signs. Barrel separated
Pavement Condition	Good
Distractions	Night time. Workers present – barrier adjustments
List of Photos Taken	15.1,15.2
Other Comments	

Appendix J : Raw Data Site-A

St.Time	F. Time	Lag Time	PV	HV	PV Vol	HV Vol	T. Vol
22:55:00	23:10:00	0:15:00	263	23	1052	92	1236
23:10:00	23:25:00	0:15:00	247	26	988	104	1196
23:25:00	23:40:00	0:15:00	277	35	1108	140	1388
23:40:00	23:55:00	0:15:00	269	35	1076	140	1356
23:55:00	0:10:00	0:15:00	228	30	912	120	1152
0:10:00	0:25:00	0:15:00	282	21	1128	84	1296

Appendix K: Raw Data Site-B

St.Time	F.Time	Lag	PV	HV	PV Vol	HV Vol	T.Vol
20:00:00	20:15:00	0:15:00	289	11	1156	44	1244
20:15:00	20:30:00	0:15:00	272	9	1088	36	1160
20:45:00	21:00:00	0:15:00	256	10	1024	40	1104
21:15:00	21:30:00	0:15:00	284	9	1136	36	1208
21:30:00	21:45:00	0:15:00	256	10	1024	40	1104
21:45:00	22:00:00	0:15:00	297	6	1188	24	1236
22:30:00	22:45:00	0:15:00	278	11	1112	44	1200
22:45:00	23:00:00	0:15:00	307	5	1228	20	1268
23:15:00	23:30:00	0:15:00	302	3	1208	12	1232
23:30:00	23:45:00	0:15:00	291	5	1164	20	1204
23:45:00	0:00:00	0:15:00	275	2	1100	8	1116
0:15:00	0:30:00	0:15:00	298	4	1192	16	1224
0:30:00	0:45:00	0:15:00	311	7	1244	28	1300
0:45:00	1:00:00	0:15:00	268	9	1072	36	1144
1:00:00	1:15:00	0:15:00	283	10	1132	40	1212

Appendix L : Raw Data Site-C

St.Time	F.Time	Leg	PV	HV	PV Vol	HV Vol	T. Vol
20:20:00	20:35:00	00:15:00	287	64	1148	256	1660
20:40:00	20:55:00	00:15:00	214	89	856	356	1568
20:55:00	21:10:00	00:15:00	225	82	900	328	1556
21:10:00	21:25:00	00:15:00	263	68	1052	272	1596
21:25:00	21:40:00	00:15:00	266	67	1064	268	1600
21:40:00	21:55:00	00:15:00	197	75	788	300	1388
22:05:00	22:20:00	00:15:00	144	67	576	268	1112
22:20:00	22:35:00	00:15:00	214	63	856	252	1360
22:35:00	22:50:00	00:15:00	217	60	868	240	1348
23:30:00	23:45:00	00:15:00	263	64	1052	256	1564
23:45:00	00:00:00	00:15:00	215	58	860	232	1324
00:00:00	00:15:00	00:15:00	232	86	928	344	1616
00:15:00	00:30:00	00:15:00	217	65	868	260	1388
00:30:00	00:45:00	00:15:00	224	80	896	320	1536

Appendix M : Raw Data Site-D

St.Time	F.Time	Leg	PV	HV	PV Vol	HV Vol	T. Vol
21:15:00	21:30:00	00:15:00	227	98	908	392	1692
21:35:00	21:50:00	00:15:00	189	130	756	520	1796
21:50:00	22:05:00	00:15:00	227	122	908	488	1884
22:05:00	22:20:00	00:15:00	229	104	916	416	1748
22:20:00	22:35:00	00:15:00	215	82	860	328	1516

Appendix N : Raw Data Site-E

St.Time	F.Time	Leg	PV	HV	PV Vol	HV Vol	T. Vol
22:15:00	22:30:00	00:15:00	301	37	1204	148	1500
22:30:00	22:45:00	00:15:00	262	46	1048	184	1416
22:45:00	23:00:00	00:15:00	264	31	1056	124	1304
23:00:00	23:15:00	00:15:00	241	51	964	204	1372
23:15:00	23:30:00	00:15:00	226	52	904	208	1320

Appendix O : Raw Data Site- F

St.Time	F.Time	Leg Time	PV	HV	PV Vol	HV Vol	T.Vol
10:40:00	10:55:00	00:15:00	360	78	1440	312	2064
10:55:00	11:10:00	00:15:00	326	62	1304	248	1800
11:10:00	11:25:00	00:15:00	343	87	1372	348	2068
11:25:00	11:40:00	00:15:00	353	67	1412	268	1948
11:45:00	12:00:00	00:15:00	403	42	1612	168	1948
12:00:00	12:15:00	00:15:00	377	62	1508	248	2004
12:15:00	12:30:00	00:15:00	393	63	1572	252	2076
12:30:00	12:45:00	00:15:00	370	74	1480	296	2072
12:45:00	13:00:00	00:15:00	388	55	1552	220	1992
13:00:00	13:15:00	00:15:00	351	60	1404	240	1884
13:15:00	13:30:00	00:15:00	348	67	1392	268	1928
13:30:00	13:45:00	00:15:00	410	56	1640	224	2088
13:45:00	14:00:00	00:15:00	405	44	1620	176	1972
14:00:00	14:15:00	00:15:00	381	66	1524	264	2052
14:25:00	14:40:00	00:15:00	446	43	1784	172	2128

Appendix P : Raw Data Site- G

St.Time	F.Time	Leg	PV	HV	PV Vol	HV Vol	T.Vol
07:15:00	07:30:00	00:15:00	360	57	1440	228	1896
07:30:00	07:45:00	00:15:00	376	56	1504	224	1952
07:45:00	08:00:00	00:15:00	374	60	1496	240	1976
08:00:00	08:15:00	00:15:00	341	61	1364	244	1852
08:15:00	08:30:00	00:15:00	347	72	1388	288	1964
08:35:00	08:50:00	00:15:00	365	57	1460	228	1916
08:50:00	09:05:00	00:15:00	365	77	1460	308	2076
09:05:00	09:20:00	00:15:00	316	79	1264	316	1896
09:20:00	09:35:00	00:15:00	357	73	1428	292	2012
09:35:00	09:50:00	00:15:00	363	75	1452	300	2052
09:50:00	10:05:00	00:15:00	381	70	1524	280	2084
10:10:00	10:25:00	00:15:00	399	54	1596	216	2028
10:25:00	10:40:00	00:15:00	356	71	1424	284	1992
10:40:00	10:55:00	00:15:00	370	62	1480	248	1976
10:55:00	11:10:00	00:15:00	405	58	1620	232	2084
11:10:00	11:25:00	00:15:00	404	66	1616	264	2144
11:25:00	11:40:00	00:15:00	388	52	1552	208	1968
11:40:00	11:55:00	00:15:00	378	47	1512	188	1888
11:55:00	12:10:00	00:15:00	362	54	1448	216	1880
12:10:00	12:25:00	00:15:00	367	44	1468	176	1820
12:25:00	12:40:00	00:15:00	362	29	1448	116	1680
15:40:00	15:55:00	00:15:00	412	19	1648	76	1800
15:55:00	16:10:00	00:15:00	424	29	1696	116	1928
16:10:00	16:25:00	00:15:00	433	29	1732	116	1964

Appendix Q : Raw Data Site- H

St.Time	F.Time	Leg	PV	HV	PV Vol	HV Vol	T.Vol
07:05:00	07:20:00	00:15:00	341	42	1364	168	1700
07:20:00	07:35:00	00:15:00	335	44	1340	176	1692
07:35:00	07:50:00	00:15:00	322	43	1288	172	1632
07:50:00	08:05:00	00:15:00	323	32	1292	128	1548
08:05:00	08:20:00	00:15:00	302	47	1208	188	1584
08:20:00	08:35:00	00:15:00	331	40	1324	160	1644
08:35:00	08:50:00	00:15:00	408	52	1632	208	2048
08:50:00	09:05:00	00:15:00	324	69	1296	276	1848
09:05:00	09:20:00	00:15:00	341	62	1364	248	1860
09:20:00	09:35:00	00:15:00	395	49	1580	196	1972
09:35:00	09:50:00	00:15:00	361	66	1444	264	1972
09:50:00	10:05:00	00:15:00	379	61	1516	244	2004
10:05:00	10:20:00	00:15:00	367	60	1468	240	1948
10:20:00	10:35:00	00:15:00	364	55	1456	220	1896
10:35:00	10:50:00	00:15:00	341	69	1364	276	1916
10:55:00	11:10:00	00:15:00	341	66	1364	264	1892
11:10:00	11:25:00	00:15:00	356	61	1424	244	1912
11:25:00	11:40:00	00:15:00	389	76	1556	304	2164

Appendix R : Raw Data Site-I

St.Time	F.Time	Time	PV	HV	PV Vol	HV Vol	T. Vol
21:20:00	21:35:00	00:15:00	271	52	1084	208	1500
21:40:00	21:55:00	00:15:00	242	48	968	192	1352
22:00:00	22:15:00	00:15:00	228	49	912	196	1304

Appendix S : Summary Output

Regression Statistics						
Multiple R	0.985					
R Square	0.970					
Adjusted R Square	0.952					
Standard Error	49.8					
Observations	9.000					
ANOVA	***df***	***SS***	***MS***	***F***	***Sig. F***	
Regression	3	398003	132667	53	0.000	
Residual	5	12407	2481			
Total	8	410410				
	Coefficients	***St. Error***	***t Stat***	***P-value***	***Lower 95%***	***Upper 95%***
Intercept	1612.1	53.8	29.9	0.000	1473.8	1750.4
3 Lanes	258.3	57.5	4.4	0.006	110.4	406.1
Left Lane(s) Closed	228.4	45.4	5.0	0.004	111.5	345.3
Barrels	-534.2	57.5	-9.2	0.000	-682.0	-386.3

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